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Eliciting Expert Judgment on the Probability of Loss of an AUV Operating in Four Environments

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ABSTRACT

Assessing the risk in the operation of complex systems is based on the subjective judgment and knowledge of human experts as much as on hard statistics. The Autosub3 is an Autonomous Underwater Vehicle (AUV) designed and operated by the National Oceanography Centre, Southampton. The AUV is used to support studies carried out by scientists supported by the Natural Environment Research Council. Autosub3 will undertake campaigns in ice-covered seas, where we consider the risk of loss to be significant. Our aim here is to quantify that risk.

This study reports on an expert judgment elicitation project, where a group of ten world experts in AUV operation were asked to assign a probability of AUV loss given the emergence of a particular fault, a total of sixty three faults were considered. Reasons given by experts for their assessments are analyzed, and the differences of opinion noted. The annexes contain the full text of expert judgments. After discussing methods of aggregation and analysis, the aggregated risk estimates obtained from the expert judgments were used to estimate the AUV survival in four different environments (open water, coastal, sea ice and ice shelf).

The Autosub3 survival function was used to estimate the risk of a campaign to the Antarctic, planned for January-March 2009. Below is the probability of loss for four mission sets using the risk model derived from the independent expert judgments. On the right is the risk acceptable to the responsible owner of Autosub3.

In summary, the reasoning for accepting risk was stated as:

Minimum set, no sea ice in front of glacier	P(loss) = 10%	*Accept 10%*
Minimum set + 30km of sea ice in front of glacier	P(loss) = 17%	*Accept 17%*
Desired set with no sea ice in front of glacier	P(loss) = 20%	*Accept 20%*
Desired set + 30km of sea ice in front of glacier	P(loss) = 23%	*Accept 23%*

The estimates presented above are based on the motor fault on D306 being retired, as demonstrated by the Norway trials, but with the new high impact fault on those trials included. These results are based on a risk mitigation strategy that requires the vehicle to be operated for an optimal monitoring distance in a area where recovery could be achieved prior to each and every mission. The optimal monitoring distance for scenario 1 is 28km, scenario 2 is 33km, scenario 3 is 43km and finally scenario 4 is 48km. The results above are also based on modeling the increased reliability of the vehicle after each successful mission.

KEYWORDS

Autosub, Autonomous Underwater Vehicle, risk management, expert judgment elicitation, probability judgment aggregation, product limit estimator.

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Terms and Definitions

Campaign	A set of Autosub3 missions.
Censored survival distance	A censored survival distance (or mission) is recorded only if fault has not occurred prior to termination of the study.
Death	AUV loss due to a High Impact fault.
Decision maker	The person or group of people that guide and implement the elicitation process.
Expert	An expert is defined here as someone with special knowledge about an uncertain event, which in this case is the probability for AUV loss given the emergence of a particular fault or failure.
Failure	Failure is an event. This definition works well for software systems where a human failure gives rise to a fault. However in hardware systems a component fault (or latent fault) may give rise to a system failure to perform a given task.
Fault	A system state that results from a design defect.
High impact faults	A fault that will give rise to AUV loss.
Mission	A discrete AUV run, which may include parts in different environments, e.g. launch in open water transit under sea ice, study under ice shelf and return.
Model	Mathematical or graphical representation of a physical system or phenomenon in a consistent level of abstraction.
Optimist expert	Expert whose cumulative probability judgment distribution forms a narrow 'S' shape. Most of the expert's judgments are in the lower probability ranges.
Pessimistic expert	Expert whose cumulative probability judgment distribution forms a broad 'S' shape. A significant amount of the expert's judgments are in the higher probability ranges.
Risk	The probability of loosing the AUV given the emergence of a fault.
Responsible Owner	Person or institution accountable for the AUV operation and maintenance. The responsible owner varies with the type of operator. For a commercial operator of an AUV the responsible owner with regard to risk management is the chief financial officer. In a research environment, in case the AUV was purchased with a grant and the legal ownership of the grant is resting with an institution (rather than the grant awarding body) the responsible owner is likely to be the principal investigator perhaps with oversight of the head of department. When the vehicle is part of a facility – whether the vehicle is owned by the facility or by the body that funded the vehicle, the responsible owner is typically the director in charge of the facility.

Abbreviations

2AFC	Two alternative forced choice.
AUV	Autonomous Underwater Vehicle.
ECOR	Engineering Committee on Oceanic Resources.
NERC	Natural Environment Research Council.
NOC	National Oceanography Centre.
USL	Underwater Systems Laboratory.

Symbols

θ	Uncertain event.
$p(\theta)$	Probability of an uncertain event taken place.
$S(t)$	Survival function.

1. Introduction

Managing AUV operational risk is a complex task that relies heavily on subjective expert judgment and knowledge. Capturing this knowledge quantitatively is imperative in order to: 1) build consensus amongst individuals involved in the AUV development and operations and 2) support risk management strategies at the early phases of the product design as well as in system operation and maintenance.

In previous work Griffiths (Griffiths, et. al, 2003) conducted a personal judgment and knowledge elicitation exercise concerning the AUV probability of loss given a set of operational faults. He was the sole expert. This has been criticised as too insular, and as a consequence, this study has involved more people, and a more formal approach has been taken. In this study a total of 28 Autosub3 missions and 63 faults were considered by ten experts in AUV operations[1]. The missions varied in distance, the minimum distance was 1.5 km while the maximum reached 302.5 km. The faults were caused by different factors such as human, operational and maintenance errors, and software and hardware design errors. These types of errors were analysed in detail in Griffiths (2006) where he concluded that AUV failures can potentially be represented using a Weibull statistical model.

In this report we study the faults in (Griffiths, 2008), however the aim of this report is to estimate the AUV survival given the experts judgments. Analysing and combining the expert probability judgments is a research field in its own right (O'Hagan, et al., 2003). Methods to combine expert probability judgments are divided in two groups: Behavioural methods and Mathematical methods. A behavioural method for combining expert probability judgments was used in the Autosub3 loss inquiry (Strutt, 2006). This method involves eliciting probability judgments from a group of experts, where experts must all agree on each judgment. Mathematical methods make use of analytical algorithms to combine individual expert's probability judgements; in this case experts are kept separate during the elicitation process. In the research presented in this report we used two mathematical methods to combine the expert judgments, linear opinion pool and the logarithmic opinion pool (Clemens and Winkler, 1999).

The experts' combined opinion concerning the risk for AUV loss can be used to estimate the probability of survival with range and environment. Methods such as Kaplan-Meier or Weibull can be used to estimate mission survival with range. In previous work, Griffiths (2008) used both Kaplan-Meier and Weibull to estimate AUV survival given censored data concerning missions 384 to 422. There are clear benefits for using these methods. The AUV survival distribution with range can be used to support decision making concerning future missions. Griffiths (2008) applied the Kaplan-Meier method to estimate the risk associated with a campaign to the Antarctic (Jenkins, 2007).

The Kaplan-Meier method is tailored to model censored data; this means that for a given fault distribution all faults are classified on whether or not they may result in a AUV loss (these are denoted high impact faults). Prior to this report, this judgment was binary – either a fault was considered to lead to certain AUV loss or not. That is, no probability (other than 0 or 1) was assigned. We have now removed this constraint. The data obtained from our experts is in the form of probability judgments for each fault on a scale of $0 \rightarrow 1$, therefore traditional methods such as Kaplan-Meier and Weibull must be modified to represent the data set. Modifications to the Kaplan-Meier and Weibull methods were derived. This report gives details concerning the new formulations and also how the new methods can be used to estimate the risk of an AUV mission and campaign, focusing on the under ice campaign proposed in Jenkins (2007).

1.1 Objectives

The central objective of this report is to model AUV survivability with mission distance given its history of faults and the experts' judgments on the criticality of the same faults and to use this survival model to assess the risk of the forthcoming scientific campaign to the Antarctic. The model should also be able to estimate the effect of different mitigation strategies on the AUV risk. In order to meet this central objective the following subsidiary objectives must be met:

- Comprehensive analysis of individual expert judgments. Expert judgments are constrained

[1] Over the period of these missions, a further 10 missions showed no faults; there was no need for expert judgment and, in later analyses these missions have been included as censored data.

by their experiences (Tversky and Kahneman, 1974). Thus understanding the reasons why the experts assign a given probability of loss to a particular system failure is imperative in order to highlight differences in opinion. This study addresses a series of relevant questions such as: Do experts' judgments group in different schools of thought? What characteristics in their experience separate existing groups? How can we capture distinct views in the risk model? The analysis of expert reasons can be conducted at different levels of detail. At this stage our primary aim is to analyse the data in a way that makes real impact to those involved in the AUV design and operation.

- Construct probabilistic risk model that is consistent with the expert judgments. Expert opinion aggregation methods are studied for suitability. There are several mathematical methods for multiple experts' probabilistic judgment aggregation. We select the most appropriate method to combine different expert judgments. The selection criteria should focus on ease in its application and its correlation with experts' judgments.
- Extend statistical methods for supporting AUV survivability study. The non-parametric Kaplan-Meier statistical method for survivability analysis is used for computing AUV survivability with range based on the AUV risk obtained from the expert's judgments. The data used for AUV risk analyses is presented in a non conventional format. Statistical methods such as Kaplan-Meier or Weibull must be tailored in order to capture this new data.
- Using a conditional probability approach to model the risk reduction from being able to recover the vehicle during a set distance at the start of a mission.

1.2 Outline

This report is organised as follows.

Section 2 describes the knowledge elicitation process. This is a formal and interactive process that consists of seven phases. In order to capture as many diverse judgments as possible two questionnaires were created and separate groups of experts answered each questionnaire. Details concerning these questionnaires and also information about the experts used in this exercise are given in this section.

Section 3 presents the analysis of the expert judgments. This analysis corresponds to phase five of the elicitation process. Judgments provided by experts are analysed with respect to change in environments in order to identify whether discrepancies in judgments are defensible and thus should be included in the risk model. Frequency analyses of expert judgments are carried out in order to assess individual experts' variability.

Section 4 presents a study concerning the possible mathematical methods that can be used to aggregate experts risk judgments. The mathematical formulation and practical implications of two methods (namely linear pool and log pool) are analysed in detail. Limitations of each method are discussed. The linear weighted opinion pool is chosen as the most suitable method for expert judgment aggregation.

Section 5 presents the risk model. Risk distributions are obtained using the linear opinion pool. Two risk models are presented for each operational environment. An extended version of the Kaplan-Meier method is introduced. The new method is applied to estimate Autosub3 survival with range. Section 6 presents the Weibull survival function tailored to the expert judgments. The Weibull survival function and the conditional probability function are used to estimate the effect of different risk mitigation strategies on the probability of losing Autosub3 in the forthcoming campaign to the Antarctic. Conclusions are presented in section 7 and further work outlined in section 8.

Annex A comprises the judgments provided by experts that responded to annex A of Griffiths and Trembranis (2007) whilst Annex B comprises the judgments provided by experts that responded to annex B. Annex C presents brief biographies of the experts that participated in the elicitation exercise. Annex D contains the graphs depicting the probability judgment distributions, for all four environments. Annex E presents the linear and log aggregated judgments for Annex A. In annex F are the optimistic and pessimistic risk models. Annex G presents a summary of the survival estimates for Dr. Jenkins' campaign to the Antarctic. Annex H presents the results of the risk mitigation analyses using the Weibull survival function. Annex I presents the probability judgments distributions for the experts that responded to Annex B questionnaire.

2. The Elicitation Process and Context of Expert Judgments

Expert probability judgments may be elicited through either an informal or formal expert judgment elicitation exercise (Otway and Winterfeldt, 1992). Their formal elicitation process consisted of seven steps: 1) identification and selection of experts; 2) training in probability judgments; 3) presentation and discussion of uncertain events and quantities; 4) analysis and data collection; 5) presentation and discussion of results of the previous step; 6) elicitation; 7) analysis, aggregation, and documentation. Keeney and Winterfeldt (1991) followed a similar process to elicit expert knowledge with regard to the probability of catastrophic failure in two American nuclear power stations namely Surry and Sequoyah following the individual or combined failure of two check valves that connect the reactor cooling system and the residual heat removal system. They elicited probability estimates from approximately 40 experts concerning 50 possible events.

Section 2.1 describes the formal process we adopted to elicit expert judgments. Expert judgments were elicited with respect to four operating environments. Details concerning these environments are presented in section 2.2.

2.1 The Elicitation Process

The goal of our expert elicitation exercise is to capture judgments from a sufficient set of experts with diverse background. Provided that the reasoning supporting the probability judgments are plausible and defensible they must be somehow captured in our analysis. Biases introduced by either an expert or a decision maker can harm the validity of an elicitation exercise. The purpose of adopting a formal process was to reduce these types of biases. The elicitation process consisted of the following seven steps.

2.1.1 The Issues

Given the set of facts on faults and incidents with Autosub3 throughout its life to date, we seek to predict the probability of loss of the vehicle in different operating environments. At issue is how likely is it that each fault or incident, taken in isolation, but with the expert's knowledge of the wider issues, could lead to loss in the four example environments. The actual question to be asked of each fault or incident is set out formally in section 2.1.3.

2.1.2 Selecting Experts

For many (but by no means all) of the judgments sought on individual faults or incidents there is likely to be a degree of uncertainty over the response. It is here that the experience, background, and insight of the individual expert are most important. As a consequence, the success (or not) of the elicitation process is strongly dependent on the knowledge of the experts. Ideally, according to O'Hagan et al. (2006:27), each expert (a) has specific technical and domain knowledge (e.g. closely involved in AUV design or operations), (b) is able to approach a problem via formal principles (e.g. through causal reasoning – the analysis of cause and effect), (c) uses established strategies (e.g. questioning/reviewing first assessments) and (d) relies more on procedural knowledge (e.g. relationships and an appreciation of what is important) and less on declarative knowledge (e.g. facts and simple rules). At the highest level of expertise, there is agreement in the literature that judgement is intuitive, with "an automaticity of action deriving from a wealth of knowledge and experience", that may typically take ten years to gather (O'Hagan et al., 2006:54). Experts should also have a realistic view of their competence for each particular problem.

Clemen and Winkler (1985) examined the precision and value of information elicited from dependent and independent sources. If the experts within a pool have limited diversity or a strong dependence (e.g. from one organisation, or all academics), they concluded that this would "have a serious detrimental effect on the precision and value of the information". Our aim is to maximize expert's independence from the Autosub3 design, development or operation, by using experts from different backgrounds, areas of expertise, nationality etc.

Table 1 lists some details concerning the experience of the experts that participated in this exercise. All experts have experience in one or more areas of AUV concept design, development and operation. Apart from the number of years of experience, the differences between experts lie in the specific area of expertise and also on the nature of their application. Short biographies of experts involved in this study are given in Annex C.

Table 1 Expert experience data. Annex A and Annex B are two separate questionnaires.

Group	Expert	Main subject	Application area	Total years of experience
Annex A	Tom Curtin (TC)	Technology management	Scientific research, Military and Commercial	20
	Barbara Fletcher (BF)	Systems control	Military	8
	Clayton Jones (CJ)	Automation, control and antenna design	Scientific research and Military	11
	Rob McEwen (RM)	Control systems design	Scientific research	9
	Mark Moline (MM)	Operation	Scientific research	6
	Adam Skarke (AS)	Operation	Scientific research	1.5
	Chris Williams (CW)	Hydrodynamics	Scientific research	10
	Dana Yoerger (DY)	AUV design, operations, control systems	Scientific research	15
Annex B	Robert Bogucki (RB)	Adaptive navigation and mapping	Scientific research	3
	Neil Bose (NB)	Propulsion and hydrodynamics	Scientific research and Commercial	24
	Adam Skarke (AS)	Operation	Scientific research	1.5

2.1.3 Clearly define issues

The definition of the problem or issue to be judged is one of the key phases of the elicitation process. The stated issue must be presented as clear and concise as possible. Experts were divided in two groups, one answered the straightforward question: "*What is the probability of loss of the vehicle in the given environment X given fault/incident Y*?" also referenced as Annex A. The second group addressed the second question: "*Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? If you answered that it is loss what is the probability of loss? If you answered that it is survival, what is the probability of survival?"* also referred to as Annex B.

These questions are the key yardstick for the evaluation process and a strict and consistent adherence to the questions will help to maintain a level of consistency between responses and respondees. It is important also to note that our interest in this matter is with respect to the impact of the fault on loss of the vehicle, not, for instance, on the impact that the given fault might have on science delivery, but rather, will this fault lead to the loss of the vehicle as a complete system given the environmental information and one's own expert opinion.

2.1.4 Training the Experts and Eliciting Judgements

The experts completing Annex A (except AS) were briefed on the background and method of eliciting expert judgment at a presentation at the Unmanned Untethered Submersible Technology symposium at Durham, New Hampshire in August 2007. NB was briefed on the progress at a meeting of the ECOR specialist panel on underwater vehicles at Southampton in September 2007. AS and RB were briefed personally by Art Trembanis.

The literature of expert elicitation acknowledges that the precision of estimates is improved if experts have access to independent information, to allow a degree of calibration. We have sought, with limited success, such independent information. First, for open water and coastal environments Leviathan, a leading marine insurance binding authority, stated that they have not paid out on an AUV loss in the last two years[2] as of June 2007. Second, out of some 150 vehicles produced by Hydroid, and

[2] Personal communication, Keith Broughton of Leviathan with Griffiths, June 2007.

used in open and coastal waters, and under sea ice, we believe that none were lost[3] as of August 2007. Third, through the early stages of Seaglider development and operations, eight out of the first ten vehicles were lost, in environments that ranged from open water to areas infested with sea ice and of the next twelve built, two were lost as of September 2005[4].

The questionnaire was envisioned, and was tested by our graduate students, to take approximately 3-4 hours to complete although it was stressed that there was no time constraint for its completion. The fault/incident descriptions, it should be noted, are the distillation of trials and science missions reports (by Griffiths) and thus are by nature concise. Where our students felt the initial draft was too terse, we expanded the fault/incident descriptions. If for some reason one expert did not feel that sufficient description was available we suggested they reflect this in both the confidence level of the probability assessment and the comments after each assessment.

2.1.5 Analyzing and Aggregating

Research has shown that many experts, when asked to use the full probability range, tend too often to opt for values close to 1 or 0[5], termed 'anchoring', O'Hagan et al. (2006: 68). Furthermore, there is evidence that an expert's ability to provide unbiased estimates shows no correlation with the expert's technical or domain expertise. However, if experts are aware that particular types of faults or incidents have led to loss, or not, their subjective judgments may be less biased. This outcome feedback is clearly important, and it argues for open dissemination of faults and loss within the AUV community.

Our analysis of the expert judgments was in two steps, first we looked at the distribution of probability judgments over all faults. This first assessment was necessary in order to identify and understand the main differences between judgments. In the second part of the analysis we try to understand how experts assign their judgments. An expert that uses a wide range of probabilities is less likely to manifest bias due to anchoring. However the expert judgments variability may vary with change in environment. Our observations concerning these analyses are presented in section 3.1.

Combining experts' judgments is easier than identifying bias. In their review of combining probabilities from experts, Clemen and Winkler (1999) describe mathematical and behavioural combination techniques. The Autosub Loss Inquiry used a behavioural approach, requiring the experts gathered together to interact and produce a single, agreed, group judgment (Strutt, 2006). This approach is not without its problems, including group polarisation (or 'group-think').

Where experts do not exchange information, mathematical combining techniques are appropriate. While current research considers Bayesian methods to provide a mathematically defensible, rigorous and effective way of combining judgments (O'Hagan et al., 1998; Sigurdsson et al., 2001), they are challenging to implement. As a consequence, our initial approach is to use a simple linear or logarithmic opinion pool, Clemen and Winkler (1999). Section 3.3 gives a more detailed review of the two methods considered for aggregation; results using both approaches and their limitations are also discussed.

2.1.6 Complete analysis and write up

This version of our report presents the first draft of the complete analyses. It will be reviewed by the experts and we will take their comments into account in preparing a final version. The final report will document the aggregated experts' judgments on the probabilities of leading to loss for each fault and each environment as opinion pool means and a measure of spread. Importantly, the reasons why experts arrived at their judgments will be summarised. Using these sets of probabilities, and example AUV campaigns for each environment, we will model the overall probability of losing a vehicle in each campaign using Kaplan-Meier and Weibull methods as used in Griffiths et al. (2003a). Probabilities of loss will be compared with data from independent sources (if available) for coastal/open water environments, and with earlier single-expert predictions in Griffiths and Trembanis (2007) for under ice.

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[3] Personal communication, Graham Lester of Hydroid with Griffiths, July 2007. This was the case after a REMUS 100 AUV 'lost' for 10 months was recovered, essentially intact.

[4] Personal communication Charles Eriksen with Griffiths, September 2005.

[5] Indeed Griffiths et al. (2003a) *only* considered 1 or 0 as possible outcomes, while Griffiths and Trembanis (2007) considered only 0, 0.25 or 1.

2.2 Environments

We have chosen four contrasting environments as examples for this study. They were chosen because they are well known to us and they represent both common and challenging AUV operating environments. Clearly the method can be applied in other settings, such as near the seabed, in complex terrain, or within enclosed environments such as pipes, cenotes, or lakes. In the following sub-sections are concise notes on key factors from each environment that may effect experts' judgments on probability of faults or incidents leading to loss.

There are some factors that are common to one or more environments. Perhaps the most significant is the process of launch and recovery, frequently from a ship. Incidents during launch and recovery are not uncommon; they can, and have, led to loss or write-off. The occurrence and impact of such incidents has been sufficiently high that some insurance providers have suggested co-insurance, or risk sharing, during these specific parts of a mission (Griffiths et al., 2007).

2.2.1 Open Water

Open water, away from the coast and traffic lanes, where the water depth is less than the crush depth of the vehicle, forms a relatively benign operating environment. An emergency response of rising to the surface, or descending to the seabed, is feasible, and from either location telemetry of data and position is possible. Clearly the risks are higher if the water depth exceeds the crush depth. While hazards mid-water are few, on the surface high winds and/or waves, fog and other vessels may increase risk and the consequences of technical failures in navigation or communication systems may be more severe. Operating close to the seabed can be hazardous, placing reliance on collision avoidance or altitude-sensing hardware, algorithms and software.

2.2.2 Coastal

Coastal settings, defined as waters from the shelf edge (150-200 m water depth) and landward towards the shore, and including inland waters, can be challenging locations for AUV operations. While usually well below crush depth, many challenges remain. This setting includes shipping lanes and bay mouths as well as the near-shore (just outside of the surf zone), and estuaries. Physical hazards in this setting include high density ship traffic comprising, among others, commercial, military, and personal watercraft; divers (recreational and commercial) (Patterson et al., 2001); engineering structures (e.g. bridges, breakwaters, piers, jetties, groins); fishing gear (e.g. pound nets, lobster/crab pots). Environmental hazards include turbid waters and strong fluid flows (currents and waves) that make search and recovery problematic. Coastal settings do, however, afford a host of launch/recovery options including ships, boat ramps, docks and piers, which can be used in tandem or switched to mid-mission as conditions require.

Shallow depths and strong hydrodynamic flow present increased risk for collision and thus place added importance on collision avoidance systems. The rapid spatial and temporal changes to environmental conditions in coastal settings also place a premium on navigation and communication systems. The proximity to logistical centres, however, does provide advantages for operational adjustments (e.g. operations can be moved to more benign locations and additional support supplies can be more readily acquired). For the purposes of the questionnaire, we asked experts to consider a semi-open, highly developed coastal embayment with depths of 40 m maximally, relatively sheltered from waves but subject to tidal currents of ~1-1.5 $m.s^{-1}$. Vessel traffic to consider included commercial and recreational vessels and occasional personal watercraft.

2.2.3 Sea ice and icebergs

Sea ice and icebergs pose a wide spectrum of risk that merits an expert elicitation study in its own right. There are numerous classes or types of sea ice, and each may pose a threat of some magnitude to AUV operations. Ice types are described by Wadhams (2000), and MacDonald (1969) described how ice affects vessel operations. More specific information on ice types and their effect on AUV operations is available on the Polar AUV Guide website[6].

Sea ice and icebergs pose a hazard to AUV operations for several reasons:

[6] www.srcf.ucam.org/polarauvguide/environment/icetypes.php

- Ice can form a rigid lid to the ocean, hampering or even preventing recovery after a technical failure or incident.
- Afloat, deep ice keels and icebergs pose collision hazards. If in shallow water, especially if they are grounded, ice keels and icebergs may test severely the collision avoidance and path planning systems within an AUV.
- Thin ice may pose different hazards: semi-transparent grease ice may be sufficient to hamper visual sighting on recovery; nilas, up to 10 cm thick, may damage appendages such as antennas.
- Continuous multiyear ice, such as fast ice or sikussak can form a barrier as effective as an ice shelf should an AUV become stranded, especially if the support vessel has limited icebreaking capability.
- Ice need not be continuous to pose a threat; brash ice can be a hazard during launch and recovery, especially to appendages and propeller blades.

An important factor affecting the level of risk posed by sea ice is the icebreaking capability of the support vessel as this affects the likelihood of success or failure should recovery from under ice become necessary. The risk appetite and time allocated for search and recovery are also factors, as are the availability of supporting tools such as an emergency location beacon on the vehicle and whether an ROV is on board the vessel to aid recovery. Because of the wide range of risks, for the purpose of this study, we asked that experts focus on a scenario where first year ice dominates (0.3–2.0m thick), with ice keels to 15m, sporadic icebergs and a support vessel able to break 2 m ice at 2kt. Perhaps not surprisingly (because of its complexity), this environment produced a wide range of responses.

2.2.4 Shelf Ice

Ice shelves are the floating edges of continental ice sheets, and, with a typical thickness of 180 m at the seaward edge, form an impenetrable barrier. If an AUV becomes stranded under an ice shelf through a fault or incident, the chance of recovery must be almost zero. An ROV recovery might be possible if the stranding was no more than a few hundred metres from the ice front. Further in, it is possible to drill through the ice (e.g. using hot water), and if the AUV position is known accurately a recovery might be possible. However, such operations are very costly and involve complex logistics.

Experts were asked to bear in mind, as outcome feedback, that only two AUVs have ever attempted under ice shelf missions, and both were lost, one on its first such mission, the other (Autosub2) on its second.

2.3 Summary

The elicitation process was explained to the experts. It is a formal elicitation process that is widely applied in research. It is an interactive process and this report closes the first loop of this process where analyses of the expert judgments carried out in order to remove bias. The results of this analysis are presented in section 3. Experts provided probability judgments for Autosub3 probability of loss in light of a given fault. The question was asked in two different ways, which we denote as 'Annex A questionnaire' and 'Annex B questionnaires' (Griffiths and Tembranis, 2007). In Annex A we asked the straight forward question "*What is the probability of loss of the vehicle in the given environment X given fault/incident Y*?" In Annex B we used a two alternative forced choice to elicit the probability of loss, the question asked was: "*Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? If you answered that it is loss what is the probability of loss? If you answered that it is survival, what is the probability of survival?*".

We found that by separating the experts in two groups and asking each group to answer only one question it would allow us to capture a more diverse set of judgments. Ten experts participated in this exercise (see Table 1 for more detail). Expert AS kindly accepted to answer both questionnaires. This gives us some insight on whether or not the way we put the question affects the outcome judgment.

3. Analysing and Aggregating

The analysis and aggregation task corresponds to phase five of the judgments elicitation exercise (see section 2.1.5). Prior to combining the expert judgments we need to understand whether there are significant disagreements in judgments and also we must identify the best way to aggregate these judgments. Two types of analyses are relevant to this process. First, the failure judgments distribution for all four environments visually highlights major discrepancies in judgments. Second, the individual expert frequency distribution gives us information concerning the variability of the expert judgments. The analyses supported by these graphs are presented in the following sections, where we also draw upon the written comments of the experts, especially where there are major differences in interpretation.

3.1 Experts judgments and the fault distribution

3.1.1 Annex A

With eight experts, sixty three faults and four environments, we have a possible total of 2016 expert judgments. In practice, we have 1863 as not all combinations were completed. Our intention in this section is not to suppress differences of opinion, or to introduce our own views, or to bias the results, but to draw our experts' attention to those faults where there appear to us to be resolvable differences of opinion, misunderstandings or typographical errors. Of the 1863, we query some opinions in: 8 faults in open water, 4 in coastal waters, 7 under sea ice and 6 under shelf ice. This is 10% of faults, meaning that in 90% of cases we feel no need to draw attention to differences between experts' opinions. The risk judgment distribution for all eight experts that answered Annex A are presented in Annex D of this report.

3.1.1.1 Open water

For open water, there are eight faults of particular interest: 385_1_1[7], 389_1_3, 389_2_3, 418_1_1, 406_5_7, 406_7_7, 407_1_2 and 407_2_2. Figure 1 depicts the judgment distribution for faults 385_1_1, 389_1_3 and 389_2_3 by expert by expert designated by their initials, with probability of loss on the y axis.

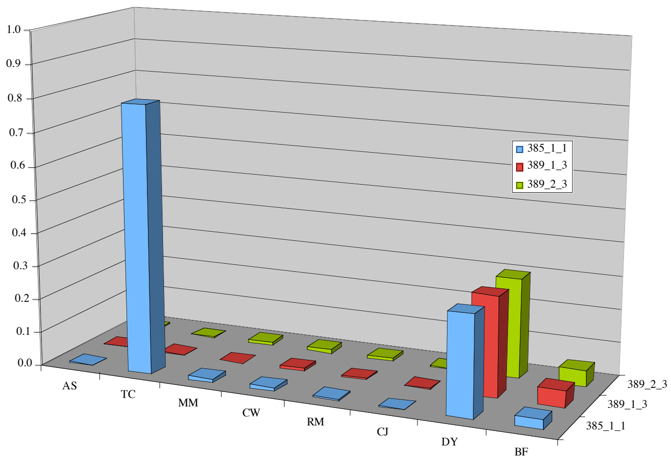


Figure 1 Probability judgments for failures 385_1_1 (blue), 389_1_3 (red) and 389_2_3. These judgments concern open water operations only.

Expert TC assigns a very high probability of loss to fault 385_1_1. Fault 385_1_1 concerns a failure in the navigation system due to the removal of the Acoustic Doppler Current Profiler (ADCP). This causes the AUV to travel on the wrong heading. Expert TC assumes that this fault takes place after 15km into the mission and that the navigation failure is further compounded with failure of the AUV monitoring system or indeed any other system that could be used to issue an abort-to-surface command. In contrast to expert TC, experts AS, RM, CW and CJ assumed that such backup systems

[7] Our nomenclature is as follows: failure 389_1_3 represents the first failure assessed by the experts concerning mission 389. The last digit, i.e., number 3, stands for the total number of failures recorded during the mission.

were still available at the time of the fault. There is some evident disagreement between experts and as highlighted, this is mainly due to the assumptions on the availability of backup systems.

The experts comments highlighted several variables that could be taken into account in the assessment of this fault, some of these variables are: 1) Time at which the fault took place (e.g. phase in the mission, whether or not the mission time was exceeded); 2) battery depletion; 3) weather conditions (e.g. fog, size of the waves and currents).

Recommendation 1: Autosub3 has backup systems that can be used to issue the abort to surface command and, in addition, the Autosub3 also has systems that enable the support ship to track the AUV position at real time during the initial phase of the mission. We should assume that such systems are available at the time of this fault. Thus in order to build expert consensus, it is recommended that expert TC should re-assess failure 385_1_1 in light of the assumptions highlighted above.

Failure 389_1_3 concerns a fault during the homing phase which caused an incorrect setting in the AUV speed and heading. As a result the AUV headed in the wrong direction just before dive. Expert DY assigns a higher risk to this event than any other expert. According to DY, whilst recovery would depend on the types of surface localisation available (Strobes or RF beacon), being able to catch the AUV would depend on weather conditions and the capacity of the support ship to chase the AUV. Expert DY also argues that a GPS-iridium combination or a timeout in the homing process would significantly reduce the likelihood of loss. Other experts consider that systems for monitoring the AUV position and abort are available and therefore recovery should be straightforward. The time out process in Autosub3 forces the AUV to check for homing signal after every 2 minutes. In case there is no signal the AUV will remain circling until it receives another signal. An abort to surface command would facilitate the recovery.

Recommendation 2: Request a revised judgment from DY concerning fault 389_1_3. It is recommended that expert DY should assume that Autosub3 is equipped with a timeout system and that engineers on the support ship can trace the AUV position.

Failure 389_2_3 also occurred during homing mode. The Autosub did not exit homing mode after 2 minutes as expected. As a result the Autosub continued on the last specified heading. Similarly to failure 389_1_3 the risk associated with this fault depends on whether or not tracking is maintained and also depends on the vessel's top speed. These risks were clearly highlighted in RMs comments, shown below.

> ***" I think this is a dire situation - when the propulsion is on, and the guidance is dead. #385 and #387 are similar. We've had this happen to us also, but only in Monterey Bay. Risk depends, among other things, on if the ship can catch the AUV, and also if the ship can maintain tracking."***

RMs views are similar to those of experts AS, CJ, CW and TC. These experts assume that it is possible to track the Autosub and therefore it would be possible to intercept the vehicle. Expert DY says that the performance characteristics of the Autosub play a key role on the risk. DYs comments are below:

> ***"Again, a high-speed drive-off is very scary for a vehicle with the speed and endurance of Autosub. Does the homing mode have a timeout? If so, the consequences of this failure would be less severe..."***

Recommendation 3: For the same reasons as highlighted in recommendation 1, it is recommended that expert DY should provide new judgment for failure 389_2_3.

CW's judgments regarding failures 406_5_7, 406_5_7, 407_1_2 and 407_2_2 for open water (which are not captured in Figure 1) are also quite extreme when compared to the judgments provided by remaining experts. CW uses as baseline for his judgments the graph in Figure 6.a of Griffiths, et al. (2003). Figure 6.a depicts the Autosub survival plot in light of its high impact underway fault history. The method used to derive this graph relies on censored data based on Griffiths personal assessment of the criticality of these faults. Hence, the graph should not be used for faults that do not have a high probability of leading to loss. In this exercise we are asking independent experts to generate their own assessments.

Recommendation 4: After a debate amongst decision makers we can conclude that CW's judgment should not use the graph in Figure 6a of (Griffiths et. al, 2003) as a reference for his personal judgments. Thus it is recommended that CWs should re-assign judgments to faults 406_5_7, 406_5_7, 407_1_2 and 407_2_2.

3.1.1.2 Coastal

The probability of loss judgment distribution for Coastal water shows that in general there is an increase in risk as the vehicle moves from open water to coastal water. Interestingly for fault 385_1_1, TC assigns a higher probability of loss in open water than in coastal water. TC assigns P(loss) = 0.8 for open water and P(loss) = 0.7 for coastal water. TCs rationale is that the closer the AUV is to the coast the most likely one is to find the AUV. TCs comment is presented in the box below.

> ***"If it's out of control 15 km out, the chances of loss are pretty high unless it is still being tracked somehow. If the vehicle remains water tight (no seal leaks, collisions, …), the chances of ultimate recovery are slightly higher in coastal regions due to the likelihood of its being found on a beach ."***

In contrast to TC's views, experts AS, CW and DY argue that the closest the vehicle is to shore the more exposed the vehicle is to additional risk (such as collision with another vessel or rocks). Comments made by these experts with reference to fault 385_1_1 are presented below:

> ***AS: "…Coast: uncontrolled headway risk collision with other vessels as well as the shore. …"***
> ***CW: "…If this event occurs in coastal waters, P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, …"***
> ***DY: "…more potential problem scenarios near the coast, the vehicle could end up running aground which could make the vehicle harder to find and complicate the recovery considerable. …"***

Although RMs comments do not reference the change in environment, the probability judgments provided by RM show that this expert is in agreement with the rationale presented above by experts AS, DY and CW. For fault 385_1_1, RM assigns Ploss = 0.005 for open water, and Ploss = 0.01 for coastal water. When it comes to the change in environments from open water to coastal water in particular, it is evident that there are three schools of thought. Whilst all experts seem to be aware of the risks involving the AUV operation in these environments, some experts choose to take an optimistic view of the problem whilst other group of experts seem to adopt a pessimistic view. The third school of thought comprises those experts that are indifferent to the change in environment from open water to coastal water, namely CJ and BF. CJ assigns the same risk to open and coastal water for all 63 faults whilst BF assigns the same risk to 62 faults (fault 384_1_1 being the exception). MM assigns the same P(loss) to 63% of the failures.

For coastal water, there are four faults of particular interest, and these are faults 385_1_1, 388_2_2, 389_1_3 and 389_2_3. Figure 2 shows the expert judgments for these faults. Both experts TC and DY assign a high risk to failure 385_1_1. The reasons for their assessments were discussed in the previous section. Failure 388_2_2 is only assessed high risk by DY; we believe that the high P(loss) may be due to 'anchoring'. According to DY, the risk should be small because, "depth instability would not affect the function of the surface localization aids". This rationale is also shared by CW, CJ, AS and TC, their comments are below:

CW: "Assuming that the AUV can be located via the acoustic pinger, strobe light or ARGOS position, and, that the ship can get to the location of the AUV, then P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3."
CJ: "1m oscillation not mission recovery critical."
AS: "Ice / seafloor collision possible if the AUV course was planed with less than 1 meter of vertical clearance (which would be imprudent). Otherwise no loss risk."
TC: "This amplitude oscillation is low risk for loss unless operating near the surface, especially if the surface is ice covered."

The probability judgment provided by DY does not reflect the argument present in his comments. We believe that DYs judgment for coastal water is anchored to the judgment for open water.

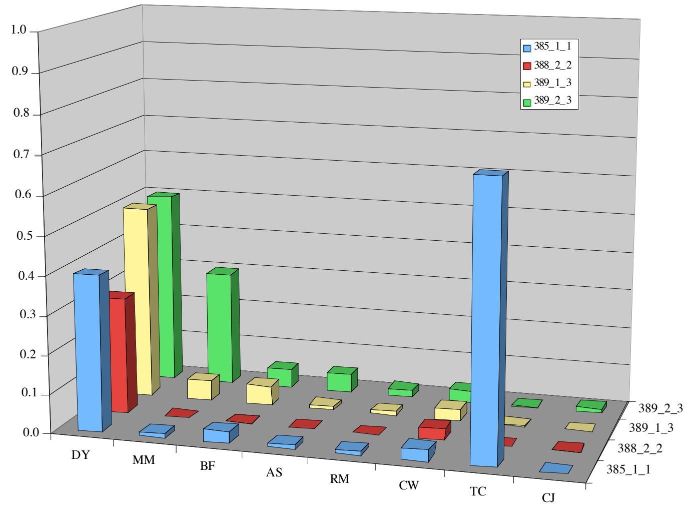


Figure 2 Expert judgment assessments for failures 385_1_1 (blue), 388_2_2 (red), 391_1_3 (yellow) and 389_2_3 (green).

Recommendation 5: Despite the fact that DY shows some coherence in his judgments there is a significant discrepancy between his judgments for failure 388_2_2 and the judgments provided by the remaining experts. Given this discrepancy in judgments it is recommended that expert DY should re-assess failure 388_2_2.

Failure 389_1_3 and 389_2_3 were discussed in the previous section. Analyses concerning these failures for open water resulted in **recommendations 2 and 3 for open water.** Similarly to recommendation 5, for these failures we argue that the high Ploss judgment provided by DY may also be due to anchoring bias. Expert MM also assigned a high Ploss to the same failure. However, there is no evidence of anchoring bias in his judgment. MM's judgments for this failure varies from P(loss) = 0.01 for open water to P(loss) = 0.3 for coastal water. This may be a typing error given that for most judgments the same expert varies from 0.01 for open water to 0.03 for coastal water. Unfortunately MM did not provide any comment concerning this failure. A future update of this document should include MM's comments for this failure.

Recommendation 6: For the reasons mentioned in previous paragraph, it is recommended that expert DY should re-asses faults 389_1_3 and 389_2_3, for coastal water. Furthermore, given the high risk judgment assigned to failure 389_2_3 by expert MM, it is recommended that MM should re-assess this fault and provide the reasons for his judgment.

3.1.1.3 Sea Ice

Our perception was that sea ice poses a greater hazard to AUV operation than the previous two environments (Griffiths and Tembranis, 2007) and this is substantiated in the expert judgments. The risks of loosing the vehicle are greater when the vehicle comes to surface. The AUV has several antennas that can be damaged by the ice on the surface, damage to any of these antennas can result in navigation problems or problems in locating the vehicle. Sea ice can also make it difficult for the support ship to reach a stranded vehicle.

The probability judgment distribution shows that for the majority of failures two or more experts assign probability of loss greater than 0.2 (P(loss) ≥ 0.2). Only faults where one or two experts assign a P(loss) equal or greater than 0.5 are considered in this exception analysis. According to this criterion, failures that show a greater disagreement between experts' judgments are: 389_1_3, 394_1_1, 395_1_1, 397_1_1, 402_1_5, 403_1_3 and 416_1_1. Figure 3 shows the experts' judgments for all these faults.

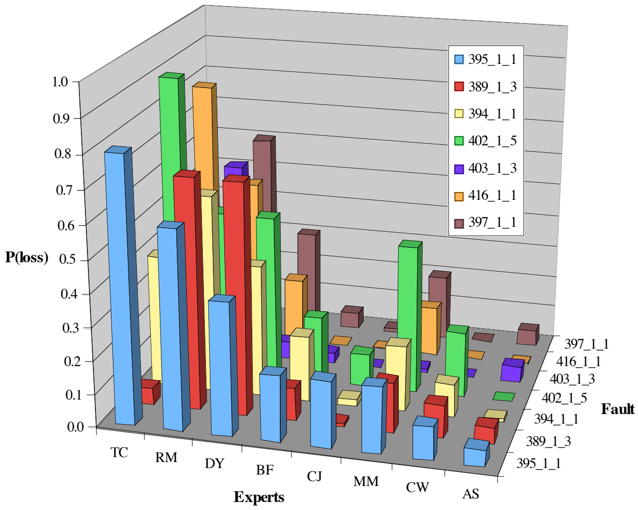


Figure 3 Comparison of expert judgments for sea ice. Expert judgment assessments for failures 395_1_1 (blue), 389_1_3 (red), 394_1_1 (yellow), 402_1_5 (green), 403_1_3 (dark blue), 416_1_1 (orange) and 397_1_1 (brown).

For failure 394_1_1, RM is to be the only expert whose P(loss) judgment exceeds the threshold of 0.5. Failure 394_1_1 concerns a problem with the Jack-in-the-box float system. The Jack-in-the-box system is suppose to operate when the AUV is at surface after completing a mission. The system is used to check and to support its recovery. Here, the jack-in-the-box float came out and its line wrapped around the Autosub propeller, jamming it. This led to consequential damage to the upper rudder frame and the GPS antenna as the recover was made more difficult. According to RM's comments, his judgment reflects the worst scenario where the vehicle is heading under, rather than away from, the ice. This fault is significantly risky under sea ice, four experts assign a P(loss) ≥ 0.2. The judgments provided by RM for this fault do not show any evidence of bias due to anchoring nor representativeness.

Failure 389_1_3 was previously discussed for open and coastal waters. Prior to the start of the mission, the AUV is put in a holding mode. This means that the AUV is set circling around a pre-defined area whilst engineers on board the vessel carry out relevant checks. Usually this operation occurs directly underneath the support vessel. Here, when the AUV exited from holding mode and dived, it was noticed that the AUV was heading in the wrong direction. At this point the vehicle mission was stopped by acoustic command.

Experts DY and RM assigned a high P(loss) to this failure under sea ice; both assigned P(loss) = 0.7. For this fault all remaining experts assign a P(loss) < 0.15, in fact three experts (AS, CJ and TC) assign P(loss) ≤ 0.05. This shows some significant disagreement between experts. Whilst DYs judgment can be explained by the fact that it is anchored to the judgment that he provided for open water, RMs judgment does not seem to be anchored to any previous judgment. RMs judgments for this fault across different environments are as follows {P(Loss|Open water) = 0.005, P(Loss|Coastal water) = 0.005, P(Loss|Sea ice) = 0.7, P(Loss|Ice shelf) = 0.9}. The comment provided by RM does not allow us to infer whether his judgment contains bias due to representativeness or availability.

Recommendation 7: There is strong disagreement in judgments for failure 389_1_3. The brevity of the description may have contributed. As this happened immediately after first dive it was close to the ship. Thus it is recommended that if possible, experts DY and RM should re-assess their judgments. Expert DY has shown some evidence of anchoring and thus if possible expert DY should re-assess this fault for all four environments. Expert RM's judgments do not show any evidence of bias. However expert RM's judgment is significantly higher than those of the rest of the group. In order to understand the reasoning underpinning his judgment it is recommended that RM should add a comment with reference to the environment change and its effect on the judgment.

Failure 395_1_1 is similar to failure 394_1_1, both are a result of the Jack-in-the-box line wrapped around the AUV propeller. The main differences between these two faults are: 1) the mission distance; 2) the damage caused on recovery to the AUV control panels and GPS antenna, this occurred for failure 394_1_1 but not for failure 395_1_1. Experts MM, BF, CW and DY assigned the same probability judgment for both faults, regardless of the operational environment. Expert TC on the other hand considers the mission distance as a major factor and thus assigns a high P(loss) to failure 395_1_1 when compared with failure 394_1_1. For failure 395_1_1 the highest P(loss) are assigned by experts TC (P(loss) = 0.8) and RM (P(loss) = 0.6). These judgments seem plausible, given that at least four other experts assigned a P(loss) equal or greater than 0.2.

All experts received information concerning how the AUV was recovered following failure 394_1_1. Experts RM, AS and CJ seem to take this information into account when providing their assessments. Since no information concerning the recovery was provided (implying no additional damage) for failure 395_1_1; the way in which the details of the fault were presented may have introduced bias into the expert judgment. Below are the comments made by AS, CJ and RM with respect to failure 394_1_1.

CJ: "Given recovery, albeit with damage, the AUV must have been clear of the shelf ice. In ice conditions, small boat may not be launch able."
AS: "Risk of loss in all situations is associated with recovery difficulties. Increased risk includes potential collision with boat and compromising of watertight appendages."
RM: "…. Also, the risk of losing the vehicle is increased in open water because the difficult recovery could be further complicated by incoming weather, fog, etc."

Recommendation 8: It is possible that by adding details concerning the recovery procedure following a particular fault, we may be directing the expert into a specific rationale, one that would inevitably contain bias. This is particularly true with faults 394_1_1 and 395_1_1, where details concerning the recovery seem to have more influence on the differences in expert judgments than any other factor, such as mission distance and damage to the vehicle. Thus it is recommended that experts CJ, AS and RM should re-assess faults 394_1_1 and 395_1_1. Details concerning the AUV recovery should be removed from the description of fault 394_1_1.

Fault 397_1_1 concerns the Autosub3 lifting system; as a result of a human failure the main lifting lines became loose. One possible consequence of this failure was that the lifting lines could have jammed the motor. RM seems to be the only expert to assign a high probability of losing the AUV in light of this fault. RM judged this fault identical to fault 395_1_1 where the Jack-in-the-box becomes loose and jams the motor. However, the two faults are different in the sense that fault 397_1_1 took place whilst Autosub3 was in the process of being brought alongside the vessel and not in the middle of a mission.

One additional observation is that expert CW argues that failure 397_1_1 is not applicable to sea ice or indeed to the ice shelf scenario. CW's rationale is that when this fault took place, the Autosub is very close to the boat and thus the true environment is open water rather than sea ice or shelf ice, and so of low risk. This notwithstanding, we are asking experts to consider the surrounding environment. Therefore, for fault 397_1_1, we are asking the experts to consider that the vehicle just returned from an operation in all four environments.

Recommendation 9: It is recommended that expert RM should re-assess failure 397_1_1 in light of the fact that the AUV was close to the vessel when this failure took place. As highlighted above, this failure differs from failure 395_1_1 and thus they should have different judgments.

In failure 403_1_3 the recovery line was wrapped around the propeller whilst the AUV was at surface. Six experts assigned P(loss) < 0.05. CW did not assign a judgment to this fault on the grounds that when this fault took place the AUV could not have been under sea ice (same as for failure 397_1_1). RM assigned the highest P(loss) for this fault (P(loss) = 0.6). Expert RM deems this fault identical to faults 395_1_1 and 397_1_1, but as previously discussed this assumption is not entirely correct. Expert DY states that "any departure from normal recovery procedure increases likelihood of loss, especially if the weather is bad". However he assigned the same judgment to all environments.

Recommendation 10: Given the differences in judgments, it is recommended that expert RM should re-assess failure 403_1_3.

Failure 416_1_1 consisted of a loss of communication with the AUV at a depth of 1180m. This resulted in an unplanned surfacing from a holding pattern. Given that the acoustic telemetry maximum range was 500m for digital data, there are two potential risks, one is Autosub3 collision with surface hazards and the second is the actual loss of communications at surface. Whilst the majority of experts consider this operation of low risk, TC and RM both assign P(loss) > 0.5. Apart from the Acoustic telemetry, the RF communication can also be used to locate and update Autosub position. However the RF range is also approximately 500 metres. The differences in judgments depend on whether an expert has an optimistic or pessimistic view of the problem and therefore there is no recommended rectification for these discrepancies in judgments.

3.1.1.4 Ice Shelf

This environment is interesting and challenging for two reasons, 1) not many people have experience in working in this environment and 2) this is a very unforgiving environment, where a failure deemed insignificant under open water may be considered mission critical and fatal under ice shelf.

Only faults where one or two experts assign a P(loss) equal or greater than 0.5 are considered in this exception analysis. According to this criterion, failures that show a greater disagreement between experts' judgments are: 391_2_3, 403_1_3, 404_7_7, 405_1_2, 405_2_2 and 408_1_5. Figure 4 shows the experts' judgments for all these faults.

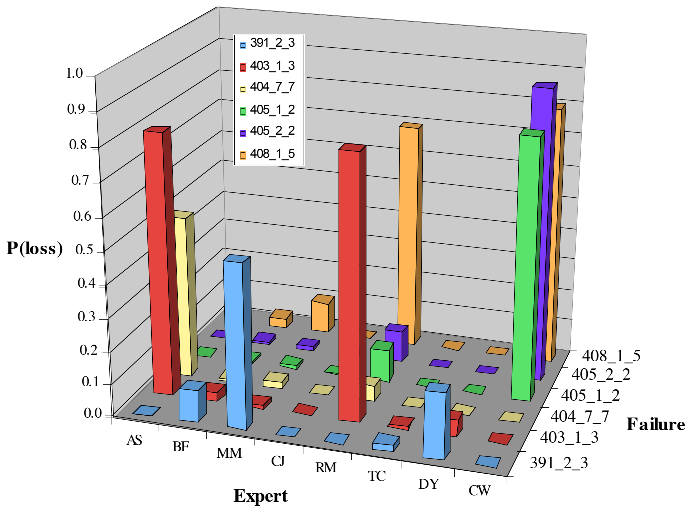


Figure 4 Comparison of expert judgments for ice shelf. Expert judgment assessments for failures 391_2_3 (blue navy), 403_1_3 (red), 404_7_7 (yellow), 405_1_2 (green), 405_2_2 (dark blue), 408_1_5 (orange).

Failure 391_2_3 concerns a fault with the GPS antenna. The GPS antenna became flooded near the end of a mission. The GPS plays a role in post-mission localisation however its role can be performed by location beacons. This would have been a very critical failure if the AUV did not have other means to communicate its position. Both the UHF RDF and the acoustic telemetry could locate the AUV. Whilst no judgment is provided by CW, four experts (AS, CJ, RM and TC) assign a P(loss) < 0.02 and MM assigns a P(loss) = 0.5. This probability is rather high given that the AUV is right at the end of its mission.

Recommendation 11: Although there is no evidence of bias, MM's P(loss) judgment following failure 391_2_3 is significantly higher than the judgments provided by all other experts. It is therefore here recommended that expert MM should re-assess fault 391_2_3.

In failure 403_1_3 the AUV propeller was jammed by the recovery line whilst the AUV was at surface. Five experts assign P(loss) < 0.05. Both AS and RM assign P (loss) = 0.8. In his comments AS argues that the same P(loss) should be attributed to sea ice and ice shelf. However for this failure he assigns P(loss) = 0.05 for sea ice and P(loss) = 0.8 for ice shelf. We believe that this may be a simple typo, one that should be addressed by AS. Expert RM considers this failure to have the same criticality as failure 395_1_1, where the Jack-in-the-box line came out, wrapped around the propulsion motor, jamming it. However as previously noted, these failures are different because for failure 403_1_3 the AUV is at surface and in reach of the ship, the same cannot necessarily be said for failure 395_1_1.

Recommendation 12: For the reasons stated above, it is recommended that failure 403_1_3 should be re-assessed by experts RM and AS.

In failure 404_7_7, a collision with the vessel caused damage to the AUV acoustic telemetry transducer. Six experts judged P(loss) < 0.05. AS assigned P(loss) = 0.5. In his comments AS highlights the criticality of this fault in case the AUV needed to manoeuvre in order to be retrieved by the vessel. In contrast to AS's views, most experts assume that the AUV is next to the ship and thus recovery should be straightforward. Comments made by three of our experts validate this hypothesis.

BF: If caught and corrected pre-launch, then low risk of loss

CJ: Given pre-launch identification, then low expectation of loss.

RM: This situation and the above two seem similar and low risk in that the vehicle is on the surface next to the ship

CW: This incident occurred in open water, at the end of the mission, during recovery. What is P(loss) during recovery after this incident occurred? It is no different that a normal open-water recovery, hence P(loss) is 0.01, confidence is 4. Ensure that the transducer is checked, and, repaired or replaced and tested prior to the next deployment.

Recommendation 13: Given the discrepancy in judgments for fault 404_7_7 and also given that this discrepancy is due to differences in assumptions. It is recommended that expert AS should re-assess this failure. For the new assessment expert AS should consider that the AUV does not need to manoeuvre in order to be retrieved.

Failure 405_2_2 concerns a fault found during pre-launch, the starboard lower rudder and sternplane were loose. This fault was detected and corrected whilst the AUV was on-board, thus the risk should be low. Six experts (namely AS, MM, BF, CJ, TC and DY) assigned a risk lower than 0.01. Two experts (namely RM and CW) went beyond the assumptions present in the fault description. Both assumed that either the fault went undiscovered or that the fault was only discovered whilst the AUV was in the middle of a mission.

Recommendation 14: Failure 405_2_2 was detected and corrected whilst the AUV was still on-board the vessel. In order to reduce discrepancies in judgments, this assumption should be considered by all experts. It is therefore recommended that experts RM and CW should re-assess this fault, assuming that there was a high probability that it was detected and corrected whilst the AUV was on-board.

Similar to the previous failure, failure 408_1_5 was discovered whilst the AUV was on board of the vessel. The failure description states: "Propulsion motor felt rough when turned by hand – bearings replaced before deployment". Five experts (namely DY, AS, BF, CJ and TC) assigned a low probability of loss (P(loss) < 0.03). In a similar fashion to failure 405_2_2, experts RM and CW seem to be the only experts to assign a very high probability of loss. Again both experts assume that the failure was discovered whilst the AUV was in the middle of a mission. On a separate issue, MM assigned P(loss) = 0.1. This is a significant increase from the assessment that he provided for failure 405_2_2. Failures 408_1_5 and 405_2_2 are different; however they were both discovered and rectified whilst the AUV was on board of the vessel. MM did not provide a comment for this failure but perhaps MM's reasoning is that he considered the case where the fault was not correctly rectified. Below are the comments provided by DY, AS, BF, CJ and TC.

DY: This problem was diagnosed so it did not put the vehicle at risk. However, this could mean that the bearing could wear prematurely, which could result in a problem during a long mission.
AS: If bearings were problem, than there is no risk of loss as they were replaced prior to deployment.
BF: If caught and corrected pre-launch, then low risk of loss
CJ: Pre-launch check, mitigates loss risk.
TC: Since fault found pre-launch and fixed, risk is negligible. If fault not found or repair unreliable, the risk is higher.

Recommendation 15: Given that failure 408_1_5 was discovered and rectified whilst the AUV was on-board and that this was the assumption taken by the majority of experts; it is recommended that both RM and CW should re-assess this failure in light of the assumption presented in the failure description that there is a high probability of this fault being caught pre-launch.

3.2 Frequency distribution of experts' judgments

This section looks at two types of variability typically present in expert probability judgments. First we look at expert judgment variability across different environments and secondly we look at variability in the totality of their assessments between experts (variability within contentious fault assessments was discussed in the previous section; here we look at this from a different perspective). The variability in judgments is analysed first in terms of how often experts use different ranges of probability judgments. In our initial analysis we use a total of nine intervals of probability. The cumulative distribution of the relative frequency at which P(loss) lies in any particular range is plotted to support analysis, see Figure 5.

3.2.1 Open water

The cumulative distribution for all experts shows that some experts use a wider range of probability in their judgments than others. A P(loss) of 0 is only assigned by five experts (RM = 4, AS = 5, MM = 25, TC = 10 and DY = 12). The minimum P(loss) assigned by BF and CJ is 0.001 and the minimum P(loss) assigned by CW is 0.01. TC is the only expert to assign P(loss) values between 0.001 and 0 (in four instances TC assigns a P(loss) of 0.0001). For this environment, it can also be observed that 90% of CW's judgments are lower than 0.03 and 92% of DY's judgments are below the same value. All remaining experts have at least 98% of all their P(loss) judgments under 0.03. For open water CJ uses three interval ranges; BF, MM and DY use four; AS,RM,CW and TC use five. One additional observation is the spread of these judgments; are these intervals clustered? 94% of CJ's judgments were in the interval range of]0.0003, 0.001] (CJ assigned P(loss) = 0.001, 59 times), however the other two interval ranges used by this expert are at least one interval range apart. Open water is the most forgiving of all four environments and given that the vast majority of CJ's judgments are in the lower interval ranges, in our view CJ's overall judgments distribution does not represent any problem to the elicitation process.

In contrast to CJs judgments, CW's judgments seem to be clustered in the upper interval ranges. This can be explained by the fact that CW did not provide any judgment for 12 failures (namely 391_3_3, 404_4_7, 404_5_7, 404_6_7, 406_2_7, 408_3_5, 408_5_5, 409_1_1, 410_1_1, 415_2_3, 415_3_3, 416_1_3). CW's comments present a detailed argument on the criticality of each of these faults (see Annex A). CW considers all these failures to be of low risk and that may be the reason why he did not assign a probability judgment to the above failures. In some of CW's comments, the expert quite frequently referenced the graph in Figure 6a of Griffiths, et. al (2003) and recommends a judgment based on this graph. For the reason mentioned in **recommendation 4**, it was decided not to use CW's judgment for these particular faults. As a result, 19% of CW's judgments are omitted from our analyses. Coincidently, these were some of the failures for which the remaining experts assigned a low P(loss) value. It is our belief that if CW re-assesses these failures, a greater range will be exhibited in CW's P(loss) distribution.

Recommendation 16: CW provided insightful comments to failures 391_3_3, 404_4_7, 404_5_7, 404_6_7, 406_2_7, 408_3_5, 408_5_5, 409_1_1, 410_1_1, 415_2_3, 415_3_3, 416_1_3. However CW omitted the probability judgments for each of these failures. These failures are considered of low risk by all experts, including CW. Thus it is recommended that CW should re-assess failures 391_3_3, 404_4_7, 404_5_7, 404_6_7, 406_2_7, 408_3_5, 408_5_5, 409_1_1, 410_1_1, 415_2_3, 415_3_3, 416_1_3 for all operating environments.

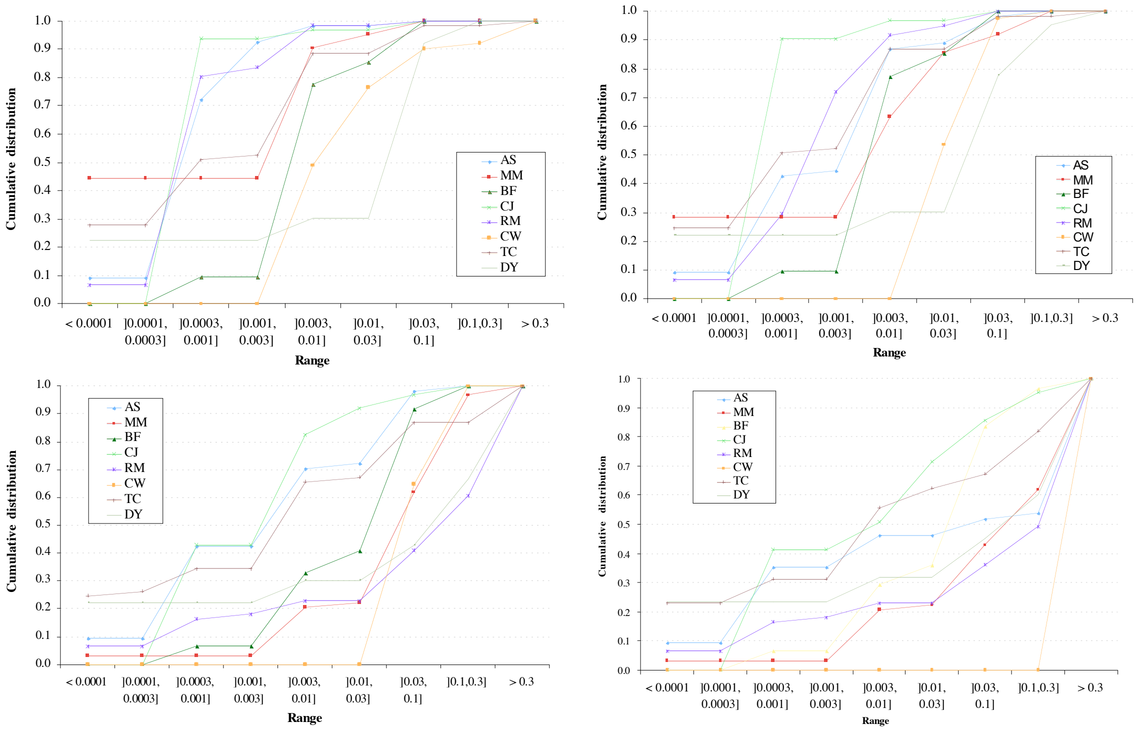


Figure 5 Cumulative probability distributions. Open water (top left), Coastal water (top right), Sea ice (bottom left) and Ice shelf (bottom right).

3.2.2 Coastal water

The spread of the cumulative distribution varies with the operational environment. Considering coastal water, this phenomenon is most notable if we observe the cumulative distribution obtained for MM and TC. Both experts reduce the number of times that they assign a P(loss) < 0.0001 compared with open water. For open water MM assigns P(loss) < 0.0001 in 44% of his judgments whereas for coastal water the same expert assigns P(loss) < 0.0001 in 29% of his judgments. Looking at expert TC's judgments we can also see that the expert reduced the number of times that P(loss) ranges under 0.0001 are used. For open water, TC assigned P(loss) < 0.0001 in 29% of his judgments whereas for coastal water the same expert assigned P(loss) < 0.0001 in 25% of his judgments.

For coastal water, Figure 5 also shows that there is a cluster of experts (formed by AS, MM, BF, RM and TC) that quite frequently use the mid-lower ranges of]0.0003, 0.001] and]0.001, 0.003].

3.2.3 Sea ice and Ice shelf

The reduced slope of the cumulative distributions for sea ice and ice shelf shows that a greater number of probability intervals are used by our experts (see distributions for RM, CW, TC and BF). The shape of the cumulative distribution for sea ice highlights a phenomenon that is not captured in the previous two environments. Whilst some expert's cumulative judgments distribution have a narrow 'S' shape (AS, BF, CJ, CW, MM and TC) others display a broad 'S' shape (DY and RM). Together with the clustering in the median probability, this inspired us to classify experts into two groups, those that are optimist (namely experts whose judgments cumulative distribution follows a narrow 'S' shape) and another group formed by the pessimist (namely, those experts whose judgments cumulative distribution displays a broad 'S' shape). We do not intend to be judgmental in using these terms; our observation that there may be two "schools of thought", especially for operations under sea ice means that caution is needed when using an average over all experts.

The main difference between the judgments provided for sea ice and ice shelf are in the number of judgments that lie in the range of]0.3, 1.0]. RM, DY, AS, MM, CW and DY seem to be the experts who most frequently assign P(loss) values in this range when assessing ice shelf scenario. Looking at the shape of the cumulative distribution, it is visible that two experts form the group of optimistic (namely BF and CJ), the other experts who were in the optimistic group for sea ice moved to the pessimistic group for ice shelf. If we compute the un-weighted average of the expert judgments for all four environments we obtain the distribution depicted in Figure 6. The un-weighted average may be interpreted as a single expert.

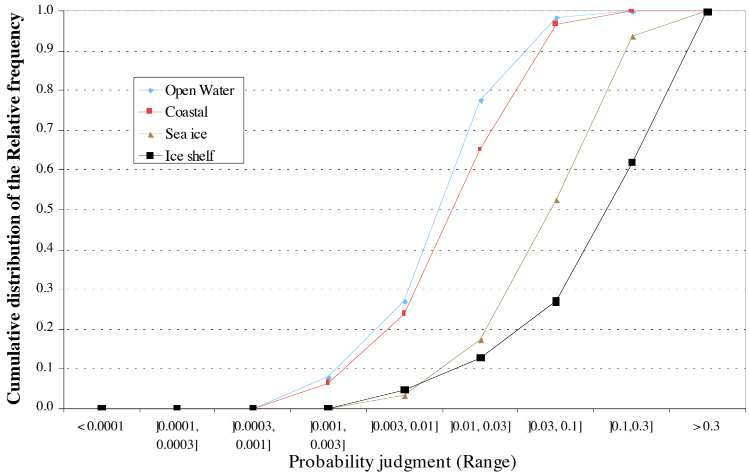


Figure 6 Comparison of the cumulative probability distribution of the un-weighted average for four operating scenarios. Open water (blue), Coastal water (red), Sea ice (brown) and Ice shelf (black).

The distributions across all four environments cluster into two groups. Group 1 formed by the open water and coastal water distribution and group 2, sea ice and ice shelf. These two groups are separated by a significant gap. As previously highlighted for ice shelf the average judgments are dominated by a pessimistic view of the risk. The distributions presented in Figure 6 do not capture the influence of the expert's confidence on his risk assessment. The following section will look into how the experts' self assessment influences the aggregated opinion of the risk perception associated with each of the four environments.

3.3 Summary

The purpose of this chapter was to identify major discrepancies in judgments and to raise recommendations whenever we felt that these discrepancies could be resolved. People employ different types of instinctive processes when making judgments under uncertainty (Tversky and Kahneman, 1974). Thus, first we were looking to see whether discrepancies in judgments were caused because our experts introduced bias whilst following a particular instinctive process (anchoring, representativeness or availability) also denoted as heuristics. Secondly we were also interested to see whether some discrepancies in judgments were caused by misunderstandings or typographical mistakes. We raised sixteen recommendations and a summary of our recommendations is presented in Table 2. On one occasion we believe that one expert may have introduced bias due to anchoring and this raised recommendation 5, all remaining fifteen recommendations were raised to tackle misunderstandings in the assumptions.

Table 2 Summary of recommendations for Annex A. No recommendations were raised due to expert BF's judgments.

Recommendation Number	TC	BF	CJ	MM	RM	AS	CW	DY
	1		8	6	7	8	3	2
				11	8	12	4	3
					9	13	14	5
					10		15	6
					12		16	7
					14			
					15			

4 Knowledge Aggregation

As previously mentioned in section 2.1.5 two mathematical methods were selected to aggregate the experts' judgments. Mathematical approaches construct a single combined assessment per event by applying analytical models that operate on the individual assessments. The aggregated opinion may be viewed as that of a single expert. The methods used for aggregating the expert judgments were the linear weighted pool and the logarithmic opinion pool (Winkler, 1968). The linear and logarithmic pools lead to quite different aggregated distributions. This section gives details concerning these methods, it discusses assumptions and compares results obtained using both methods. A simple non-weighted aggregated mean for all individual assessments is also computed to support arguments. Detailed results for the two aggregated methods are presented in Annex E for all operational environments.

4.1 Linear Weighted Pool

The linear weighted opinion pool was applied to combine expert judgments concerning all 63 faults. Results of the weighted opinion are presented in Annex E. This is the most popular method for expert opinion aggregation (O'Hagan, et al., 2003). A single probability judgment is created by summing the products between an individual expert's weights (w_i) and their judgments ($p_i(\theta)$) for the n experts. Where θ is the uncertain event (which in our case is AUV loss). The weight w_i may be chosen by the decision maker (for example the authors of the report) to reflect their assessment of the relative expertise of the experts, or may be based on the experts self ratings (Genest and McConway, 1990). Some researchers argue that self rating produces better results (e.g. Dalkey, et al., 1969). In this report, where we have used weightings they have been those of experts themselves. We have not altered any self ratings.

Equation 4.1 below captures the mathematical formulation of the linear pool aggregation method.

$$p(\theta)=k\sum_{i=1}^{n} w_i p_i(\theta) \qquad with \quad k=\frac{1}{\sum_{i=1}^{n} w_i} \qquad 4.1$$

The elicitation exercise here presented, considered the weight as a measure of how confident the expert was about their own assessment. The weight varies in a range of 1 to 5, an expert assigns weight 5 to their assessment in case (s)he is very confident about their judgment, in contrast an expert assigns weight of 1 in case (s)he is not very confident about their judgment. Table 3 shows an extract of the expert elicitation table, where the probability judgments provided by eight experts are aggregated into a single judgment using the linear pool method.

Table 3 Fraction of the Expert elicitation table. Eight expert judgments are considered.

Fault/incident description	Open		Coast		Sea Ice		Shelf Ice	
Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.001 0.01 0.001 0.01	0.01 0.001 0.01 0.1	0.01 0.01 0.001 0.01	0.2 0.001 0.03 0.1	0.05 0.07 0.1 0.01	0.2 0.01 0.1 0.5	0.5 0.2 0.2 0.8	0.9 0.01 0.8 0.5
Weights	3, 5, 5, 5, 3, 4, 2,5		4, 4, 5, 5, 1, 3, 2,5		2, 3, 3, 5, 1, 3, 2,4		1, 3, 3, 4, 1, 3, 2,4	
Range	0.001 – 0.1		0.001 - 0.2		0.01 - 0.5		0.01 – 0.9	
Linear Opinion Pool	0.0210		0.0519		0.1470		0.4781	

The linear weighted frequency distribution is depicted in Figure 7 for each of the four environments. Looking at open water first, approximately 46% of all probability judgments are within the range of:]0.01, 0.03]. For the same environment, the linear weighed opinion does not judge any single failure with a P(loss) > 0.3. In addition the graph also shows that approximately 16% of all 63 faults, exactly 9 faults, lie in the region of]0.03, 0.1]. Failure 385_1_1 is the most critical failure in open water with a probability of AUV loss of 0.1109 or probability of survival of 0.85537 (1 - 0.1109). Failure 407_1_2 is the second most critical failure, with P(loss) = 0.05023. The relatively large aggregated P(loss) obtained for failure 385_1_1 may be due to TCs and DYs judgments on this failure (this is discussed in section 3.1.1.1). As previously mentioned, TC assigned a P(loss) of 0.8 and self assessment weight of 2. The weight assigned by TC is small when compared to weights assigned by other experts (for instance DY's weight = 5), however TC's contribution to the linear weighted aggregated judgment is 1.6 (i.e p*w). Having assigned a P(loss) of 0.3 and a self assessment weight of 5, DYs contribution to the weighted sum is 1.5. The combined weighted distribution of both TC and DY is approximately 14 times the combined contribution of all remaining 6 experts put together (which is 0.228). This discrepancy between different weighted contributions, for failure 385_1_1, may be reduced if **recommendation 1** (proposed in section 3.1.1 of this report) is addressed in a future work. Similarly, failure 407_1_2 is also significantly influenced by the weighted contribution provided by CW (which equals 1.2). Again the aggregated P(loss) for this fault may be reduced if **recommendation 4** (proposed in section 3.1.1) is addressed in future work.

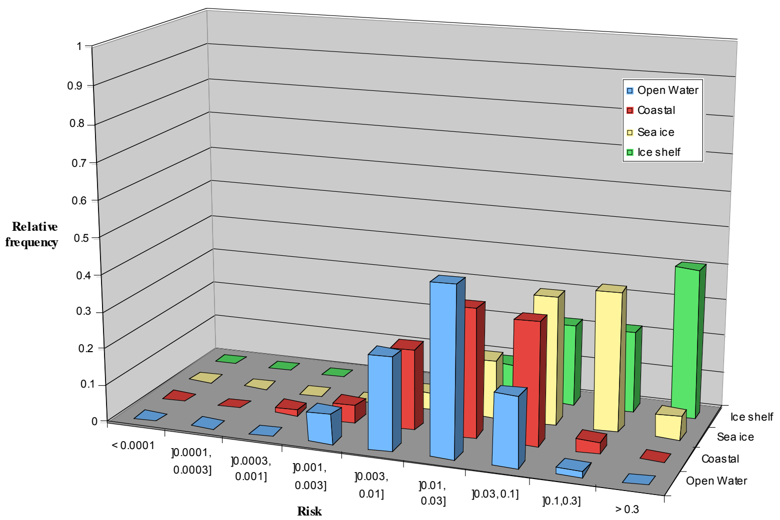


Figure 7 Relative frequency for the linear weighted mean

Comparing the relative frequency of the judgments for open and coastal water, the distribution shows that whilst the shape of both distributions are similar, the coastal water distribution presents a shift of judgments towards greater risk. Similarly to open water, the majority of probability judgments for coastal water lie in the range]0.01, 0.03]. However there was 17% increase in judgments in the range]0.03, 0.1] and a 2% increase in judgments in the range]0.1, 0.3]. The latter implies that two failures are assigned a P(loss) greater than 0.1 and lower than 0.3. These are namely failures 385_1_1 (P(loss) = 0.124) and 389_2_3 (P(loss) = 0.118). The P(loss) for these failures will reduce significantly if recommendations 1 and 6 are addressed in future work. Interestingly failure 407_1_2 (deemed the second most critical failure for open water) for coastal water is considered a failure of low criticality (P(loss) = 0.0104 instead of 0.0502). The reason for that is because, for coastal water, CW did not assign a P(loss) for this failure whilst for open water the expert assigned a very high P(loss). The linear aggregated opinion on this judgment is likely to change if recommendation 4 is addressed in future work.

The shift of probability judgments towards greater risk becomes more evident if one looks at the relative frequency distribution of the aggregated judgments for the sea ice and ice shelf. Ice shelf is the most severe environment where 41% of all failures are assigned a P(loss) > 0.3.

A summary of the statistical properties of the P(loss) distribution obtained using the linear aggregated opinion pool is presented in Table 4.

Table 4 Statistical properties of the linear aggregated opinion pool.

	Environment			
	Open water	Coastal	Sea ice	Ice shelf
Quantile 25%	0.0083	0.0083	0.045	0.072
Median	0.018	0.021	0.088	0.17
Quantile 75%	0.026	0.037	0.17	0.40
Quantile 95%	0.049	0.090	0.36	0.75

4.2 Logarithmic Weighted Pool

The logarithmic weighted pool was introduced to tackle an important theoretical limitation of the linear weighted opinion pool. Analytical methods for combining expert judgments are expected to comply with axioms of probability theory such as marginalization and Bayesian theory. Unlike the linear weighted opinion pool the logarithmic opinion pool complies with the principles of Bayesian theory (Genest, 1984). This is better explained if we consider the scenario where, in light of new evidence, one expert (let us call him expert A) wants to update his judgment and thus a new aggregated judgment must be computed. The decision maker has two alternatives as to how to achieve this; the decision maker can remove expert A's previous judgment and re-combine all judgements (including expert A's new judgment) or alternatively, the decision maker can update the old aggregated judgment using Bayes theory. An aggregation method that complies with the Bayesian theory would provide the same results regardless of the process followed by the decision maker to update the aggregated opinion. The logarithmic opinion pool is mathematically captured with the following equation:

$$P(\theta)=\sqrt[n]{\prod_{i=1}^{n} p_i^{w_i}(\theta)}^{\left[\frac{n}{\sum_{i=1}^{n} w_i}\right]} \qquad 4.2$$

The equation presented above differs slightly from the logarithmic opinion pool equation presented in the literature (Clemen and Winkler, 1999). Although mathematically equivalent, equation 4.2 makes the normalization factor explicit. An evident detail encapsulated by the equation is that if one expert assigns a probability of 0 to an event, this expert's judgment will overrule all other experts' judgments. This reflects a characteristic of the logarithmic opinion pool denoted by right of vetoing. One expert has the right to veto the remaining experts' opinions by assigning 0 to a probability of an event taking place. In practical terms this may be an unacceptable limitation of the logarithmic aggregation method. As previously discussed, on many occasions an expert may be inclined to assign probability of 0 instead of 0.0001 for instance. Training provided to experts prior to the elicitation exercise should cover this situation, however, unlike behavioural methods, mathematical methods rely on data provided by single experts, and the experts are not monitored nor guided through this process. Table 5 shows an extract of the expert elicitation table, where the logarithmic opinion pool is used to aggregate the probability judgments provided by eight experts (the same extract as in Table 3). Note that in each environment the log opinion pool leads to a lower estimate of loss.

Table 5 Fraction of the Expert elicitation table. Eight expert judgments are considered.

Fault/incident description	Open		Coast		Sea Ice		Shelf Ice	
Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.001 0.01 0.001 0.01	0.01 0.001 0.01 0.1	0.01 0.01 0.001 0.01	0.2 0.001 0.03 0.1	0.05 0.07 0.1 0.01	0.2 0.01 0.1 0.5	0.5 0.2 0.2 0.8	0.9 0.01 0.8 0.5
	3, 5, 5, 5, 3, 4, 2,5		4, 4, 5, 5, 1, 3, 2,5		2, 3, 3, 5, 1, 3, 2,4		1, 3, 3, 4, 1, 3, 2,4	
Range	0.001 – 0.1		0.001 - 0.2		0.01 - 0.5		0.01 – 0.9	
Logarithmic Opinion Pool	0.0065		0.0156		0.0646		0.2425	
Linear Opinion Pool	0.0210		0.0519		0.1470		0.4781	

Figure 8 depicts the relative frequency distribution for aggregated probability judgments, using the logarithmic pool. It should be noted that the relative frequency distribution only takes into account those failures that were not vetoed. For open water 35 events were vetoed by at least one expert thus the figure shows the relative distribution for the 28 events that were not vetoed. The logarithmic pool for open water uses only two classes of probability ranges, namely:] 0.003, 0.01] and] 0.01, 0.03], with] 0.003, 0.01] used in 79% of all non vetoed judgments (23 judgments).

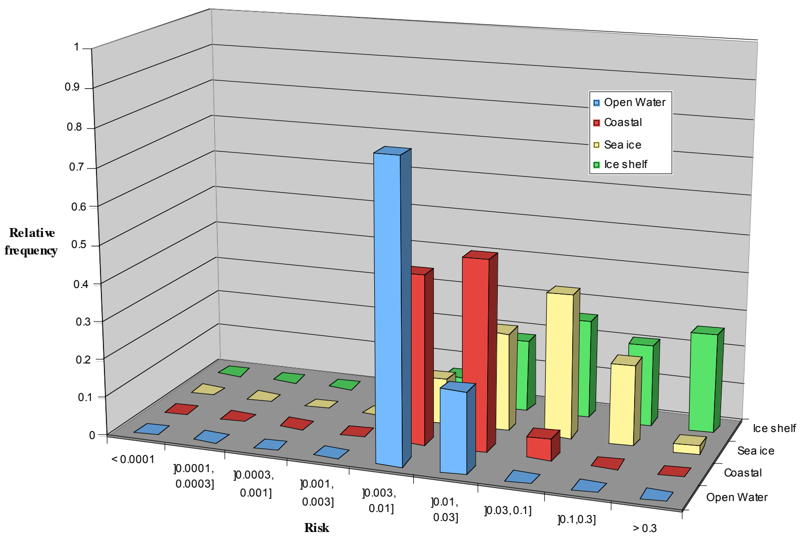


Figure 8 Relative frequency for the logarithmic weighted pool

Approximately 50% of the probability judgments for coastal water lie in the range]0.01, 0.03]. There is a significant decrease of probability judgments in the range of]0.003, 0.01]. The figure also shows that 5% of all judgments are in the range of]0.03, 0.1]. Failure 389_2_3 is assigned the maximum probability of loss, this failure was caused by a mission control error. The P(loss) for this fault is 0.037 which is still quite small given that the maximum value for its class (interval range) is 0.1.

The coastal water logarithmic weighted distribution is significantly more pessimistic than the distribution obtained for open water. According to experts there is an evident increase in risk by moving an operation from open water to coastal water, this is discussed briefly in section 3.1. The aggregated distribution for coastal water makes use of three probability ranges:] 0.003, 0.01],] 0.01, 0.03] and] 0.03, 0.1]. We note that the median for open water is 0 because more than 50% of the judgments were vetoed by one expert or other.

The distribution obtained for sea ice denotes a significant increase in risk when compared to open and coastal water. The spread of the distribution highlights the effect of the environment change on the risk assessment, and there is more uncertainty. Whilst some faults are still deemed of low risk, perhaps because these faults took place when the AUV was close to the vessel, other faults are considered of high risk, for example fault 402_2_5. This fault was caused by network failure, the AUV was 274 km into the mission; the logarithmic aggregated opinion assigns a P(loss) of loss of 0.31.

The logarithmic distribution obtained for ice shelf is quite optimistic when compared to the linear weighted and non-weighted distributions obtained for the same environment. Whilst the logarithmic pool assigns P(loss) > 0.3 to 26% of all non-vetoed faults (42 faults) the linear weighted pool assigns P(loss) > 0.3 to 41% of the faults and the non-weighted pool assigns P(loss) > 0.3 to 38% of all faults. Failure 395_1_1 is classified as the second worst failure for sea ice, for ice shelf the same failure is deemed the worst failure, with a P(loss) = 0.81. The average expert self-assessment weight for this failure is 3.14, this is smaller than the average self-assessment weight for failure 402_2_5 (which is the second worst failure with an average self-assessment weight of 3.42); this shows that experts were slightly more confident in assessing fault 402_2_5 than fault 395_1_1. However, for this particular environment failure 395_1_1 was generally assigned a higher probability of loss, the non-weighted probability of loss of 0.82 is almost 20% higher than the non-weighted probability of loss assigned to fault 402_2_5. This numerically explains why failure 395_1_1 is classified as the most critical failure for ice shelf. A summary of the statistical properties of the P(loss) distribution obtained using the aggregated logarithmic pool is presented in Table 6.

Table 6 Statistical properties of the logarithmic opinion pool.

Statistics	Environment			
	Open water	Coastal	Sea ice	Ice shelf
Quantile 25%	0.0000	0.0000	0.000	0.000
Median	0.0000	0.0054	0.018	0.023
Quantile 75%	0.0065	0.012	0.062	0.15
Qunatile 95%	0.014	0.028	0.20	0.65

4.3 Other Mathematical Opinion Aggregation Methods

Methods that apply Bayesian formalism have been continuously gaining reputation amongst researchers. Such methods required the definition of a likelihood function which is typically elicited from the human experts. The likelihood combined with the prior belief in the probability of an event taken place is used to compute a posterior belief (Clemen and Winkler, 1990). Future extension to this work would be to study the feasibility of applying such techniques to our problem. The current expert data seems to be insufficient to apply successfully any of the Bayesian methods.

4.4 Top Risks following Aggregation

The aggregated judgments for all 63 failures is presented in Annex F, an extract of the table containing the five most critical faults for each environment is presented in Table 7.

Except for fault 385_1_1 the single expert analysis (Griffiths, 2008) identified the same most critical faults as in Table 8 for the Ice shelf environment, and these we discussed in detail with the AUV leader.

Interestingly, the pessimistic group deem failures 407_1_2 and 407_2_2 as the two most critical failures for open water but not for the remaining environments. This is related to recommendation 4, highlighted in section 3.1.1.1 of this report. CW is one of three experts that form the pessimistic group for open water. As discussed earlier CW assigns a very high probability of loss to these failures. Future work may see the removal of these faults from the top five risks.

Table 7 List of the five most critical failures for each of the four environments.

Experts	Open water		Coastal		Sea ice		Ice shelf	
Failure	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic
384_1_2	------	------	------	------	0.1944			0.8389
385_1_1	0.0981	0.1277	0.1127	0.1329	------	------	0.6500	0.7842
388_2_2	------	------	------	0.0937	------	------	------	------
389_1_3	------	0.1339	------	0.1788		0.3375	------	------
389_2_3	------	------	------	0.2136	------	------	------	------
391_2_3	0.0285	------	------	------		0.4706	------	------
392_1_1	------	------	0.0600		------	------	------	------
394_1_1	------	------	------	0.0925		0.3063	------	------
395_1_1	------	------	------	------	0.4100		0.9786	0.8293
402_1_5	------	------	------	------	0.3549	0.3750	0.8929	
402_2_5	0.0268	------	0.0436		0.6667		0.7333	0.7611
402_3_5	------	------	------	------		0.3125		0.7250
407_1_2	------	0.1417	------	------	------	------	------	------
407_2_2	------	0.1356	------	------	------	------	------	------
415_1_3	0.0387	------	0.0298		------	------	0.4143	
415_2_3	0.0404	------	------	------		0.3150	------	------
416_1_1	------	------	------	------	0.2673		------	------
418_1_1	------	0.1322	0.0454		------	------	------	------

4.5 Summary

Mathematical methods for aggregating experts' judgments were reviewed in this section; the feasibility of applying such methods to aggregate experts' probability judgment concerning the probability of loosing the AUV was also assessed. The point is not that one or another method is more appropriate overall, but that different models may be appropriate for different situations, depending on the nature of the situation and an appropriate description of the experts' probabilities. The linear and logarithmic opinion pool, have the advantage of being simple and practical. In contrast, methods based on Bayesian theory are quite complex to apply and require expert data that was not elicited during our survey.

The cumulative distribution shows that the logarithmic pool generally provides a better fit than the linear pool (this was discussed in section 3.2). Other authors agree with our views (O'Hagan et. al., 2006). However for our problem the benefit of using logarithmic pool comes at the expense of ignoring failures for which the logarithmic pool results in the vetoing by a single expert. For open water it means that approximately 50% percent of all failures are vetoed. The percentage of failures vetoed decreases as the risk posed by the environment increases, thus open water has more vetoes than coastal, and coastal has more vetoes than sea ice and sea ice more vetoes than ice shelf. The number of failures that were vetoed for open water is large, results in a median of 0, and therefore it is not practical to create our risk model using the logarithmic opinion pool. Thus, from hereafter the linear opinion pool will be used to generate our risk model.

Our analyses also highlighted that experts often cluster in different groups that represent different perceptions of risk. For reasons of simplicity we decided to treat separately those that are optimistic from those that are pessimistic. The terms are not used with the intention of criticizing the expert views. The goal here is to help us to build a more detailed model of the AUV mission risk. We do keep in mind that by choosing the linear opinion pool we are choosing the most pessimistic aggregation model.

5. Risk Model and Survival Analysis

The AUV risk model consists of an aggregated opinion of the risk of loosing the AUV given its history of faults. In order to capture the expert judgments in a more realistic form than forming a single opinion pool it was decided to aggregate experts in two schools of thought, the optimists and the pessimists. Table 8 shows the different groups for each environment.

Table 8 Experts groups description.

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

Arguably, it is also possible to create three groups of experts, one formed by the optimists, another by the pessimists and a third group formed by 'moderate' experts, i.e. experts that are neither optimistic nor pessimistic. However, whilst the discrimination of these three groups is easy for open and coastal water environments, for sea ice and ice shelf it is only possible to create two groups (for more detail see cumulative distribution presented in Figure 5).

5.1. AUV Survival Analysis using Kaplan-Meier

Statistical methods for estimating survival functions use a sample of observations to infer the survivability distribution for the system of interest. Early application of such methods was in the field of statistical medicine where many parametric and nonparametric survival models were developed to estimate patient survival over time (Gross and Clark, 1975). Results obtained using such models were used by medical doctors to manage the frequency of patient visits, type of analysis and the drugs prescription regime. The product-limit method derived by Kaplan and Meier (also referred as the Kaplan-Meier approach) is a well established nonparametric model for estimating and displaying survival functions based on a small or medium sample of data (Kaplan and Meier, 1958). With medical statistics the formulation of the Kaplan-Meier survival estimator is typically presented as a function of time. In the context of AUV risk management, the Kaplan-Meier approach has been used to estimate the AUV survival as a function of range. Using the survival estimator in its usual form, we can only deal with losses (death), as was done in the simplified analysis in Griffiths (2006).

Given a set of data comprising ordered mission ranges, and whether each mission ended with a fault that would lead to certain loss (a "death") or not, the survivor function S*(r)* with range *r* is defined as:

$$\hat{S}(r) = \prod_{r_i < r} \frac{n_i - d_i}{n_i} \qquad 5.1$$

where n_i is the number (of missions) at risk immediately prior to range r_i and d_i is the number of losses at range r_i. The process followed to apply the Kaplan-Meier approach to an AUV is described in detail in Griffiths (2008). A summary of the results obtained using this approach to estimate the risk of a campaign to the Antarctic, planned for January-March 2009, using a single expert and a simple 'loss'/'no loss' approach is presented in section 5.2. Section 5.3 details the mathematical manipulation needed in order to extend the Kaplan-Meier approach to estimate AUV survival based on any probability between 0 and 1 of a fault leading to loss, with the results presented in section 5.4. Section 5.5 presents the summary.

5.2 Autosub3 Survival Under Ice Shelf – Single Expert Kaplan-Meier Assessment

The Kaplan-Meier approach was previously used to model Autosub3 survival with distance (e.g. Griffiths et al., 2003a, 2003b) and most recently in (Griffiths, 2008). Historical fault data was censored by a single expert (GG). Recognizing that only assigning 'loss' or 'no loss' to each fault was an oversimplification, GG derived two sets of outcomes. The first set ('optimistic') marked as 'loss' only those missions for which he was very sure of the outcome (P(loss) > 0.7). The second set ('pessimistic') also marked as loss those missions for which there was an estimated probability of > 0.25 of the fault leading to loss under ice shelf. GG assessed 63 faults which occurred during missions 384-422, ten of these missions did not record any failure and hence were always censored. An unpublished analysis (Griffiths, 2008) resulted in the survival estimates shown in Figure 9 for the under ice shelf environment. In this analysis, 34 missions out of 39 were censored in the optimistic case and 30 in the pessimistic. Where more than one fault occurred on a mission, only the most severe was considered.

The survival function obtained from this analysis was used to estimate the risk of a scientific campaign to the Antarctic. The scientific campaign proposed by Dr Adrian Jenkins (BAS) (Jenkins, 2007) consisted of several open water, under sea ice in the Amundsen u.c.ea and under ice shelf missions on Pine Island Bay glacier.

The following four scenarios were derived from the operational requirements:

- Scenario 1 – Minimum set with no fast ice
  - Three 60 km open water missions
  - Three 60 km missions under outer half of the ice shelf cavity
- Scenario 2 – Minimum set with fast ice
  - Three 120 km under fast ice missions
  - 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
  - Three 60 km open water missions
  - Three 60 km missions under outer half of the ice shelf cavity
  - Three 120 km missions under ice shelf cavity
- Scenario 4 – Desirable set with fast ice
  - Three 120 km under fast ice missions
  - Three 120 km missions: 60 km under fast ice and 60 km under outer half of the ice shelf cavity
  - Three 180 km missions: 60 km under fast ice and 120 km under ice shelf cavity

The survival distributions depicted in figure 9 in blue were used directly to estimate the probability of loss for the missions stated. For each under ice shelf mission, of a required range r, the probability of survival was read off the Kaplan-Meier graph. However the campaign also involved missions under open water and sea ice. For these missions GG used an empirical factor, based in his own judgment, that would reflect the decrease in risk from ice shelf to sea ice and from ice shelf to open water, with under Shelf ice weighted as 1, the risk factor for under sea ice was 0.3 and 0.1 for open water. These were selected before the expert judgment exercise, and compare with 1:0.53:0.11 for the medians of the linear opinion pools. Table 9 presents the summary of the overall campaign risk obtained for each scenario.

Table 9 Probability of losing Autosub3 based on Kaplan-Meier analyses for each scenario (GG assessment). The optimistic estimate is the first number in each cell, the pessimistic is the second.

Analysis Model	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Kaplan-Meier	0.33 – 0.48	0.44 – 0.64	0.54 – 0.80	0.65 – 0.84

The results in table 10 correspond to the unmitigated risk assessment. These high estimated probabilities of loss led to a number of risk mitigation measures, including those set out in section 6.

5.3 Extending the Kaplan-Meier Approach

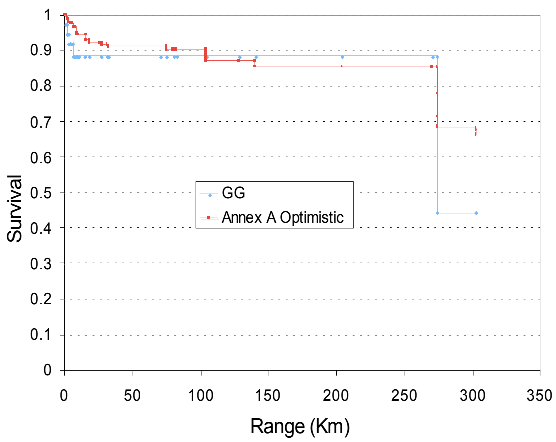
The aggregated expert judgments presented in section 4 contain a representation of uncertainty on whether or not a given failure would lead to loss, represented as a probability. The conventional Kaplan-Meier approach was modified in order to model this uncertainty (Griffiths, et. al., in prep.), leading to the expression:

$$\hat{S}(r) = \prod_{r_i < r} 1 - \left(\frac{1}{n_i}\right) P(e_i) \qquad 5.2$$

For the survival function, where n_i is the number of events at risk at range r_i, and $P(e_i)$ the probability of fault leading to loss. Thus if $P(e_i)$ is zero we have what is called a censored case, i.e. no death is observed during the interval of interest. Else if $P(e_i)$ equals one, death is observed during the interval of interest. The approach reduces to the original version of the Kaplan-Meier method. One additional advantage of the new method is that it is now possible to capture the effect of one or more failures at a particular distance. In the original version of the Kaplan-Meier method if we had more than one failure at a particular range we would only consider the most critical one. The new version allow us to capture the contribution of each failure.

5.4 Using the Extended version of the Kaplan-Meier method

The mathematical formulation in equation 5.2 was implemented in a Visual Basic program running on Excel 2003. Figure 9 presents the survival distribution obtained for the ice shelf environment in red and GG's single expert (loss/ no loss) assessments in blue.



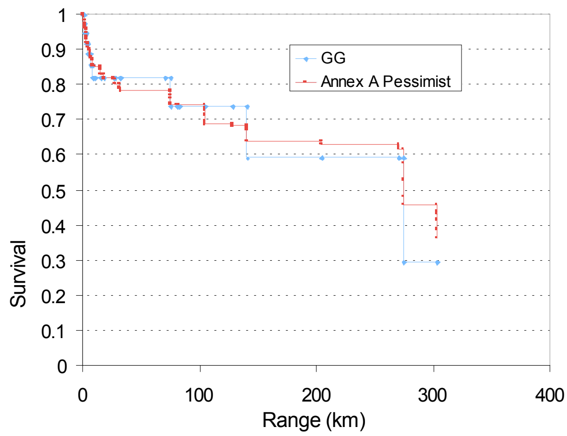


Figure 9 Kaplan-Meier (left) optimistic assessment and (right) pessimistic assessment. In red is the estimate provided by the independent experts that answered Annex A whereas that in blue is the assessment provided by GG.

Whilst differences in shape of the survival distributions are visible, and the number of steps (events) in GG's analysis are fewer, the actual probabilities of survival at a given range are quite similar. If we consider optimistic predictions first, from GG's survival distribution it is possible to see that for ranges between 25 km and 274 km the probability of survival is 0.89 whereas for the same range the probability of survival using the independent experts assessment varies from 0.91 to 0.85. GG probability of survival between 100 km and 274 km is slightly greater than the probability of survival obtained using the independent experts. For ranges lower than 100 km and greater than 274 km GG's probability of survival is more pessimistic. For the pessimistic assessment, GG provided the most pessimistic probability of survival for ranges greater than 140 km and lower than 18 km.

The differences in shape between survival distributions can be explained by the fact that in case of the independent experts' survival distribution any interval range can have more than one fault and any fault within this range can cause a decrease on the probability of survival (provided that the aggregated

P(loss) is greater than zero). In contrast, for the survival distribution in GG's assessment, only one fault per interval range can cause a decrease in the probability of survival.

5.4.1 Dr. Jenkins Pine Island Bay plans – Expert Judgment Kaplan-Meier Assessment

The extended survival function was used to compute the probability of Autosub3 loss for the four scenarios provided by Dr. Jenkins for the Pine Island Bay glacier campaign (see section 5.1 for more detail). For each scenario a probability of loss was computed using an optimistic and pessimistic model of the expert judgments, the results are presented in Table 10.

Table 10 Probability of losing Autosub3 based on Kaplan-Meier analyses for each scenario. The optimistic assessment is the first number in each cell, the pessimistic the second. The second row presents the difference in estimates using Annex A experts and GGs personal assessment, where a (-) signifies the EEJ estimates are less than GG.

Analysis Model	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Kaplan-Meier	0.26 – 0.56	0.40 - 81	0.53 – 0.86	0.64 – 0.96
Difference EEJ-GG	(-)0.07 - (+)0.11	(-)0.04 - (+)0.17	(-)0.01 – (+)0.06	(+)0.01 – (+)0.12

Considering the optimistic prediction, the results show that the probability of loss for scenarios 1, 2 and 3 are lower than the probability of loss obtained using GG's assessment. For scenario 4 the probability of loss provided by Annex A is slightly higher than the one estimated by GG's model. For the pessimistic case, the differences are greater, with the experts predicting a greater likelihood of loss.

5.5 Summary

This chapter presented a real application of the expert judgment elicitation exercise described in chapters 2 to 5. A new version of the Kaplan-Meier approach was introduced. The extended Kaplan-Meier method allows us to estimate AUV probability of survival with range using expert judgment. The method was applied to assess the risk of the upcoming scientific campaign to the Antarctic (this campaign will take place in January 2009). An estimate of the risk for this campaign was previously produced by GG using his own judgments and very simple loss/ no loss model. Pessimistic estimates provided by GG's model are slightly less pessimistic than those estimates provided by our independent experts that answered Annex A. In contrast the optimistic estimates provided by the independent experts are slightly more optimistic than the estimates provided by the GG's personal assessment. This notwithstanding, the results here presented used the first probability judgments elicited from our experts. And as highlighted in section 3 and 4 the elicitation process is iterative. If recommendations 1 to 16 are addressed they will significantly influence the estimates presented in this chapter. It is our expectation that a more optimistic outcome would be forthcoming, as all of our queries have been on risks marked high by individual experts compared with the others.

6. Risk Mitigation

The probability of loss estimated in Section 5.4.1 exceeds the risk acceptance limits defined by the Autosub3 responsible owner, even after the Norway trials of 2007. In a previous exercise the Autosub3 responsible owner defined the following risk acceptance levels for Dr Jenkins' Antartic mission to the Pine of Island Bay: for scenario 1 the acceptable risk is 10%, scenario 2 is 17%, scenario 3 is 20% and scenario 4 is 23%[8]. A list of mitigation measures is given in Griffiths (2008). These include rectification of the faults found, ensuring that the recovery lines cannot became tangled in the propeller and using penetrators for critical connections.

The survival distribution gives a good insight concerning the AUV risk with range and as previously mentioned, this information is important to support strategic decision making. The survival distribution obtained using the failure data presented in this report takes one of many possible shapes (Kalbfleisch

[8] The difference in risk acceptance comes from a risk model (Griffiths and Trembranis, 2007a) that takes into account the different mission environments, the number of missions etc. Scenario 1 only requires three under ice missions while scenario 4 calls for nine.

and Prentice, 1980). As discussed in section 5 and highlighted in Figure 9, the survival distribution for ice shelf shows a steep decline in the probability of survival at shorter distances, whereas at mid distances the survival distribution is almost flat. In terms of managing the risk, this means that if we can monitor the AUV at shorter ranges and address any problems if they emerge, than we will significantly reduce the risk posed by those failures and thus reduce the mission probability of loss. In practical terms this means that if the AUV is about to undertake an under shelf ice operation, the AUV should cover some distance in open water before diving under the ice shelf. Section 6.1 shows how it is possible to model the effect of the monitoring distance on the AUV probability of loss. The method is applied to estimate the optimal monitoring distance for the forthcoming scientific campaign to the Antarctic.

6.1 Modeling the effect of mitigation

The flat shape of the non-parametric Kaplan-Meier survival distribution does not lend itself to an analysis to quantify the effect of mitigation measures such as the increase of the monitoring distance. This effect is better captured if a parametric survival distribution is used instead, for example a Weibull distribution (Griffiths, 2008). Similarly to the Kaplan-Meier survival distribution defined in 5.4 and 5.5, the Weibull survival function was derived from the failure data and the expert judgments on the probability of loss for each failure.

We took a simulation-based approach to deriving the Weibull parameters for the case of loss given our expert's judgments. For each fault or incident we generated 1000 copies, with (1 – $P(e_i)$)*1000 entries censored, the others marked as losses. The scale (alpha) and shape (beta) parameters of the Weibull distribution were obtained using JMP tool from SAS, results are presented in Annex H. The Weibull survival distribution was first used to compute the unmitigated probability of AUV loss for the four missions proposed by Dr. Jenkins. Results of this exercise are presented in Table 11. The Weibull survival distribution for ice shelf environment is presented in Figure 10.

Table 11 Probability of losing Autosub3 based on Weibull analyses for each scenario. The optimistic assessment is the first number in each cell, the pessimistic the second. The second row presents the difference in estimates using Weibull survival function based on Annex A judgments and the Weibull survival function based on GGs personal judgment, where a (-) signifies the EEJ estimates are less than GG. The third raw presents the difference in estimates provided by Weibull survival function based on Annex A judgments and the Kaplan-Meier survival function also based on Annex A judgments.

Analysis Model	Scenario 1	Scenario 2	Scenario 3	Scenario 4
EEJ Weibull	0.29 – 0.63	0.47 – 0.85	0.57 – 0.90	0.72 – 0.97
Difference EEJ Weibull – GG Weibull	(-)0.16 - (-)0.03	(-)0.13 - (+0.05)	(-)0.17 – (+)0.02	(-)0.12 - (+)0.01
Difference EEJ Weibull – EEJ Kaplan-Meier	(+)0.03 - (+)0.07	(+)0.07 - (+)0.04	(+)0.03 - (+)0.04	(+)0.08 - (+)0.01

One obvious observation that can be drawn from Table 10 is that the optimistic predictions provided by the independent experts are more optimistic than GG optimistic predictions for all four environments.

The conditional probability of the AUV surviving distance X given that it has survived distance Y, where distance Y corresponds to the monitoring distance, is mathematically captured in equation 6.1.

$$P(X < x \mid X > y) = \frac{F(x) - F(y)}{1 - F(y)} \qquad 6.1$$

Where *F(·)* is the Weibull cumulative distribution function.

The Weibull survival function was used to estimate the effect two mitigation strategies (we denote these as mitigation strategy A and B) on Dr. Jenkins' mission scenarios described in section 5.2. The description for each strategy and a summary of the results are as follows:

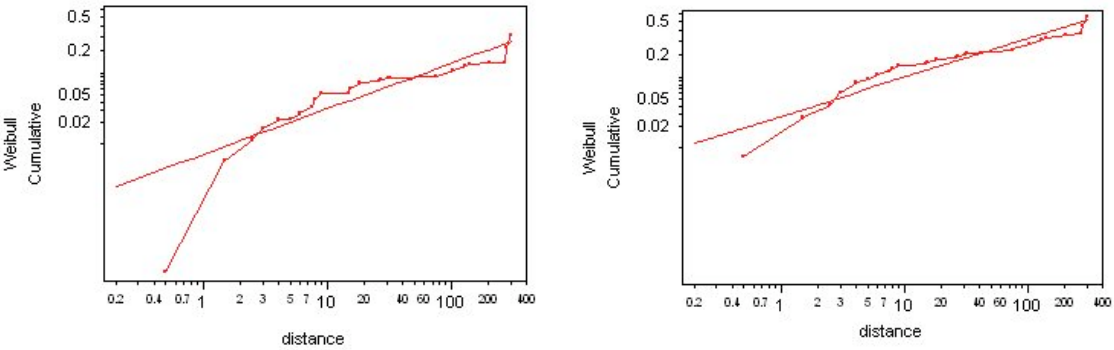


Figure 10 EEJ Weibull survival distribution (left) optimistic assessment and (right) pessimistic assessment. The straight red line is the best fit used to estimate the Weibull parameters alpha and beta.

<u>Mitigation A</u>

Dr Jenkins' scenarios with the following assumptions:

- The faults on mission 402 removed. These faults have been understood and completely rectified. The other faults have been left in.
- Where successful open water/under sea ice runs are assumed pre ice shelf, and the Weibull parameters recalculated.
- Also includes Conditional probability - where vehicle monitored for first 25km.
- Optimistic scenario only.

The calculations in Annex H show that for scenario 3 (optimistic) the probability of loss would be reduced to 0.30 and for scenario 4 to 0.39. While these are indicative of a significant risk reduction, these risk estimates are higher than the acceptable limits defined by the Autosub3 Responsible Owner. An increase of the monitoring distance from 25km to 50 km would allow compliance with the risk levels established by the responsible owner. Results presented in Annex I show that if the AUV is monitored for the first 48km the probability of loss would be 0.035 for scenario 1, 0.09 for scenario 2, 0.18 for scenario 3 and 0.23 for scenario 4. A monitoring distance of 48km is optimal for scenario 4 but not for scenarios 1, 2 and 3. The P(loss) of 0.04 obtained for scenario 1 is well below the acceptable P(loss) of 0.10 and would result unnecessary use of ship time. A monitoring distance of 28km for scenario 1 would provide a P(loss) estimate of 0.10. For scenario 2, a monitoring distance of 33km would provide a P(loss) estimate of 0.17, whereas for scenario 3, a monitoring distance of 43km would provide a P(loss) estimate of 0.20. These are all within the acceptable risk margins defined by the responsible owner.

<u>Mitigation B</u>

Dr Jenkins' scenarios with the following assumptions:

- The faults on mission 402 were removed i.e. their cause established and retired for future missions.
- Simulates completion of summer 2008 reliability demonstration trials: one short 0.5km mission and missions of 15, 53, 181 km with only one high impact faults underway.
- Also includes Conditional probability - where vehicle monitored for first 25 km.
- Optimistic scenario only.

The calculations presented in Annex H show that for scenario 3 (optimistic) the probability of loss of 0.33 would be obtained whereas for scenario 4 the probability of loss would be reduced to 0.43. Similarly to what was discussed for Mitigation A, these risk levels would not be accepted by the Responsible owner. The probability of loss can be brought down to acceptable levels if the monitoring distance is increased to 53km. For such conditions the probability of loss for scenario 1 would be

0.022, scenario 2 would be 0.08, scenario 3 would be 0.17 and for scenario 4 would be 0.23. Whilst this monitoring distance is optimal for scenario 4, for the remaining scenarios this would result in unnecessary use of ship time. Similar to what was discussed for Mitigation A, each scenario has an optimal monitoring distance; for scenario 1 is 30km, scenario 2 is 34km and scenario 3 is 48km.

6.2 Summary and Further Analyses of the Results

The Weibull survival distribution was used to estimate the effect of two potential risk mitigation strategies on the probability of losing Autosub3 in the forthcoming Pine Island Bay glacier campaign, which is taking place in January 2009. The results show that an acceptable risk reduction would be achieved if an AUV monitoring distance of 50km is covered prior to the start of an under shelf ice mission. This estimate doubles the figure of 25km obtained using GGs assessment of the same campaign (Griffiths, 2008). This discrepancy can be explained by comparing the shape of GGs survival distribution to that of EEJs survival distribution (Figure 9). The optimistic GG Kaplan-Meier survival distribution depicted in Figure 9 (in blue) shows that there is a steep decline of probability of survival within the first 7km of the mission. GG's survival distribution is constant from 7km to up to 274km. Thus, according to GG's Kaplan-Meier survival distribution, a monitoring distance greater than 7km would significantly reduce the probability of losing the vehicle. The EEJ survival distribution (in red) does not fall as steeply within the first 7km, it takes approximately 110km for the survival distribution to fall to the value that reads in the first 7km of GG's survival distribution. Thus our experts' optimal monitoring distance should be expected to be much greater than the optimal monitoring distance obtained using GG's personal assessment.

7. Conclusions

This report uses independent expert judgments concerning the probability of faults leading to AUV loss to create a risk model that can be used to compute the AUV probability of survival with range for a series of science missions under different operating environments (Open water, Coastal, Sea ice and Ice shelf). The method was applied to assess the risk of loosing Autosub3 in the forthcoming Pine Island Bay glacier campaign, which is taking place in January 2009.

A formal judgment elicitation process consisting of six sequential steps was adopted. Ten experts provided their judgments considering the probability of AUV loss over sixty three faults under four operating environments. All experts had previously received training on how to assign probability judgments to uncertain events. Graphical methods were used to analyse and identify discrepancies in judgments. A total of sixteen recommendations concerning possible misunderstandings were raised from our analyses. On only six occasions did one expert judgment strongly disagree with the others. These disagreements were discussed in section 3.2. TC provided a sound argument supporting his two judgments where there is an obvious disagreement with all other experts' judgments. The remaining four major disagreements in expert judgments concerns CW judgments on faults 406_5_7, 406_5_7, 407_1_2 and 407_2_2. As highlighted in section 3.2, CW's judgments were based on assumptions that were not entirely correct; he used GG's previous assessment of the faults to create his own probability judgments. This would inevitably introduce bias into the elicitation exercise and thus it is highly recommended that CW should re-assess his judgments concerning these four faults.

Two mathematical methods were considered for aggregating experts' probability judgments. The results obtained using the expert opinion aggregation methods are encouraging since both methods provide plausible estimates for the probability judgments. The linear weighted and the logarithmic opinion pools have been extensively discussed in the literature. The aggregated judgment distribution obtained using the linear weighted pool shows a greater variability. In contrast the distribution obtained using the logarithmic opinion pool shows an over-confidence in the judgments (see Figures 5 and 6 for more detail). However, the log opinion pool allows one expert to veto all remaining experts' judgments. For open water environment, this means that 35 faults out 63 would have an aggregated probability of loss equal to zero, and this was not acceptable. Therefore, the risk model presented in this report is a result of using the linear weighted pool to aggregate the expert judgments.

In light of the cumulative judgment distributions obtained for sea ice and ice shelf and also in order to have a more detailed AUV risk model it was decided to aggregate the experts in two schools of thought, the pessimists and the optimists (details are given in section 5). Thus, for each environment, two risk models were created by aggregating the pessimists and the optimists using the linear weighted pool. The top risks for each operational environment are presented in section 4.4. For ice shelf environment, both pessimists and optimists agree on three of the top five risks. Whilst fault 402_2_5 (which concerns a problem with the rudder actuator) has been addressed for Autosub3 by re-designing the system; faults 385_1_1(Jack in the box line wrapped around the propeller) and 395_1_1 (problem with the navigation system due to the removal of the ADCP system) are still of some concern for this environment.

The Autosub3 survival function with range based on the expert judgments (risk model) was formulated using the extended version of the Kaplan-Meier model, Griffiths et al. (2008). The method was applied to estimate the probability of the Autosub3 surviving the forthcoming Pine Island Bay glacier campaign. This scientific campaign involves four series of missions (or scenarios) and these take place in a mix of open water, sea ice and ice shelf conditions. Initial risk estimates were unacceptable to the Autosub3 responsible owner, this is in agreement with the analyses previously conducted by Griffiths (2008). In a previous discussion with members of the Autosub team it was agreed that mitigation measures would include rectification of the faults found, ensuring that the recovery lines could not become tangled in the propeller, use penetrators for critical connections and also use of a pre-defined distance for monitoring the Autosub performance prior to start of a mission. The conditional probability function permits us to capture quantitatively the effect of the monitoring distance on the risk reduction. The shape of the Kaplan-Meier survival distribution is not suitable for applying the conditional probability function (Griffiths, 2008). Thus, the Weibull survival function was derived based on the expert judgments on the fault history (section 6). Results show that different monitoring distances had to be set for different scenarios. In conclusion, the optimal monitoring distance for scenario 1 is 28km, scenario 2 is 33km, scenario 3 is 43km and finally scenario 4 is 48km.

8. Future work

The task of eliciting expert probability judgments is not an exact science. This report presents our first attempt to framework our independent experts' risk assessments in a concise model that can be used to estimate AUV survival for a series of science missions or campaigns. Probability judgment elicitation exercise is an iterative process where the number of iterations depends on the level of detail carried out in the analyses of the same judgments. We raised 16 recommendations where we think that differences in experts' opinion can be resolved by re-assessing particular judgments. The next phase of this project is to update the risk estimates according to future changes in our experts' judgments. Research has shown that the way in which a question is presented results in different risk models (O'Hagan, et al., 2003). We elicited expert probability judgments using a direct and an indirect approach (the two alternative forced choice (2AFC), discussed in 2.1.3). The model obtained using the 2AFC was not considered in our analyses for removing biases and misunderstandings. Only three experts participated in this exercise. The probability judgments obtained through the 2AFC were nevertheless processed and a risk model was created, results are presented in appendix I. However as a future extension to the work here presented we would like to ask more experts to answer the questionnaire presented in Annex B. The experts' judgments will then be analysed in order to remove bias and build consensus in the assumptions.

The risk register is a live document that must be frequently updated. Likewise the Autosub fault history should be updated according to future missions or campaigns. This information could then be sent to our independent experts in order to update the risk model.

9. Acknowledgment

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Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.001	0.004	0.05	0.8	Open: fault would have to combine with failure of acoustic beacon to result in loss. Coast: Free floating on surface exposes AUV to hazards of vessel traffic and shoreline. Sea Ice: Surfacing under ice could result in damage to AUV, though recovery is likely. Ice Shelf: Surfacing under ice make loss very likely if the vessel is way from the shelf edge.
			3	4	2	1	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.001	0.004	0.05	0.8	Assuming the AUV is positively buoyant, risk arises from uncontrolled surfacing and assessment is same as above. If the AUV is negatively buoyant, loss risk increases to 1 if operating in depth greater than crush depth, or under ice away from shelf edge. Otherwise risk remains the same. If the AUV retains neutral buoyancy Open risk remains the same. Coast risk decreases to 0.001 because vessel is not exposed to surface hazards. Sea ice risk decreases because there is no surfacing hazard. Shelf ice risk remains the same.
			3	4	2	1	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.001	0.01	0.05	0.5	Open: fault would have to combine with failure of acoustic beacon to result in loss. Coast: uncontrolled headway risk collision with other vessels as well as the shore. Sea ice: if surrounded by icebergs risk of collision is high. Ice shelf: If vessel heads in the direction of the shelf, collision with ice or transit under ice may result in loss.
			3	4	2	1	
386	26	GPS antenna failed at end of mission.	0.001	0.001	0.001	0.001	Because this fault occurred at the end of the mission, I assume the AUV is on the surface and near the launch / recovery ship. If so risk arises if there is reduced visibility (night, fog, high seas) and the support vessel pilot relies on a GPS fix to know where the AUV is in relation to the ship. If so, collision with the ship is possible.
			3	4	2	1	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.001	0.01	0.05	0.5	The risk factors are the same as No. 385.
			3	4	2	1	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.001	0.004	0.01	0.01	The AUV should not have travelled far from the ship in 4 minutes, resulting in a very low loss risk. Risk in Sea ice and Ice shelf would be associated with surfacing at an unplanned location after aborting the mission.
			3	4	2	1	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0	0	0	0	Ice / seafloor collision possible if the AUV course was planed with less than 1 meter of vertical clearance (which would be imprudent). Otherwise no loss risk.
			3	4	2	1	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.002	0.01	0.05	0.5	Open: low risk assuming the support ship can chase and catch the AUV. Coast: holding an unplanned course risk collision with other vessels and the shoreline. Sea ice: holding an unplanned course risk collision with icebergs. Ice shelf: If vessel heads in the direction of the shelf, collision with ice or transit under ice may result in loss.
			3	4	2	1	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.002	0.05	0.05	0.7	Open: low risk assuming the support ship can chase and catch the AUV. Coastal: High risk of collision with other vessels and shoreline. The ship may be limited in its ability to give chase by depth and navigational restrictions (such as channels). Sea ice: holding an unplanned course risk collision with icebergs. The ship might be limited in ability to give chase by the ice field. Ice shelf: indefinite course holding in the direction of the shelf, will result in collision with ice or transit under ice.
			3	4	2	1	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.002	0.01	0.01	0.5	Open: Loss of telemetry introduces risk of collision when trying to retrieve the AUV with ship. Coast: There is a risk of collision with support ship as well as other vessels and shoreline. Sea ice: There is a risk of collision with the support ship as well as icebergs. Shelf Ice: Loss of telemetry while the AUV is under the ice could result in the inability to modify AUV behaviour if a system error occurs.
			3	4	2	1	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches. (Cont.)							
No.	**Distance km**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.001	0.05	0.05	0.5	Open: minimal risk from reduces navigation ability. Coast: minimal risk of collision with vessel traffic or shoreline. Sea Ice: minimal risk of collision with iceberg. Shelf ice. If navigation error places AUV under ice shelf risk of loss is significant.
			3	4	2	1	
		GPS antenna flooded. No fix at end point of mission.	0.001	0.001	0.001	0.001	This fault must be combined with a fault in location beacons on AUV to risk loss of vessel. Secondary risk arises if there is reduced visibility (night, fog, high seas) and the support vessel pilot relies on a GPS fix to know where the AUV is in relation to the ship. If so, collision with the ship is possible.
			3	4	2	1	
		EM2000 swath sonar stopped logging during mission.	0	0	0	0	There is no risk from this fault unless the swath sonar is used for navigation.
			4	4	4	4	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.005	0.25	0.25	0.5	Open: minimal risk of loss. Coast: Significant risk of collision with vessel traffic or shoreline. Sea Ice: Significant risk of collision with iceberg. Shelf ice. If end position is under ice loss is certain, if not recovery is likely.
			3	4	2	1	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.002	0.01	0.01	0.5	Open: Loss of telemetry introduces risk of collision when trying to retrieve the AUV with ship. Coast: There is a risk of collision with support ship as well as other vessels and shoreline. Sea ice: There is a risk of collision with the support ship as well as icebergs. Shelf Ice: Loss of telemetry while the AUV is under the ice could result in the inability to modify AUV behaviour if a system error occurs.
			3	4	2	1	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.01	0.01	0.01	0.01	Risk of loss in all situations is associated with recovery difficulties. Increased risk includes potential collision with boat and compromising of watertight appendages.
			4	4	4	4	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.001	0.004	0.05	0.8	Assuming the AUV is positively buoyant, risk arises from uncontrolled surfacing and assessment is same as above. If the AUV is negatively buoyant, loss risk increases to 1 if operating in depth greater than crush depth, or under ice away from shelf edge. Otherwise risk remains the same. If the AUV retains neutral buoyancy Open risk remains the same. Coast risk decreases to 0.001 because vessel is not exposed to surface hazards. Sea ice risk decreases because there is no surfacing hazard. Shelf ice risk remains the same.
			3	4	2	1	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches. (Cont.)

No.	Distance km	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.001	0.001	0.001	0.001	Given short duration of mission, risk of navigation errors from lack of current data, and associated risk seems minimal.
			4	4	4	4	
397	4	Main lifting lines became loose, could have jammed motor.	0.001	0.004	0.05	0.8	Assuming the AUV is positively buoyant, risk arises from uncontrolled surfacing and assessment is same as above. If the AUV is negatively buoyant, loss risk increases to 1 if operating in depth greater than crush depth, or under ice away from shelf edge. Otherwise risk remains the same. If the AUV retains neutral buoyancy Open risk remains the same. Coast risk decreases to 0.001 because vessel is not exposed to surface hazards. Sea ice risk decreases because there is no surfacing hazard. Shelf ice risk remains the same.
			3	4	2	1	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.001	0.005	0.005	0.5	Open: Very minimal risk. Coast: Risk of ending mission in a hazardous location. Sea Ice: Risk of ending mission at a location resulting in collision with iceberg. Shelf ice: risk if mission ended prematurely under ice. Otherwise no risk.

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.001	0.02	0.02	0.5	Navigation error exposes AUV to risk of collision with vessels, shorelines and icebergs. If error places AUV under ice risk of loss is significant.
			3	4	2	1	
		Damaged on recovery, “moderately serious” to sternplane, shaft bent.	0.001	0.001	0.001	0.01	In all situations AUV is in recovery and so loss of vehicle is minimal. The only risk of loss would arise from compromising the water tight status of the sternplane.
			4	4	4	4	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.001	0.001	0.001	0.001	There should be minimal risk of loss unless flooding of actuator makes the vessel positively buoyant, or introduces water into critical part of hull
			4	4	4	4	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.					There is not enough information for me to asses risk with my level of understanding about the AUV
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive					The fault stated is not clearly written.
		Only one position fix from tail mounted ARGOS transmitter.	0.001	0.001	0.001	0,001	As long as the vehicles position is known, the ARGOS transmitter is unnecessary and its malfunction wouldn’t lead to a loss.
			4	4	4	4	
		GPS antenna damaged on recovery.	0.001	0.001	0.001	0.001	This fault must be combined with a fault in location beacons on AUV to risk loss of vessel. Secondary risk arises if there is reduced visibility (night, fog, high seas) and the support vessel pilot relies on a GPS fix to know where the AUV is in relation to the ship. If so, collision with the ship is possible.
			4	4	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic (Cont.)

No.	Distance	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.001	0.004	0.05	0.8	Assuming the AUV is positively buoyant, risk arises from uncontrolled surfacing and assessment is same as above. If the AUV is negatively buoyant, loss risk increases to 1 if operating in depth greater than crush depth, or under ice away from shelf edge. Otherwise risk remains the same. If the AUV retains neutral buoyancy Open risk remains the same. Coast risk decreases to 0.001 because vessel is not exposed to surface hazards. Sea ice risk decreases because there is no surfacing hazard. Shelf ice risk remains the same.
			3	4	2	1	
		Took over 1 hour to get GPS fix at final waypoint.					This fault must be combined with a fault in location beacons on AUV to risk loss of vessel. Secondary risk arises if there is reduced visibility (night, fog, high seas) and the support vessel pilot relies on a GPS fix to know where the AUV is in relation to the ship. If so, collision with the ship is possible.
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.					The fault stated is not clearly written.
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0.001	0.01	0.01	0.25	If weight is dropped during mission it could result in an unplanned surfacing. Open: minimal risk of loss. Coast: exposure of AUV to surface hazards. Sea ice: risk of collision with icebergs. Shelf ice: If weight is dropped under ice loss is certain, if not risk of loss is moderate.
			3	4	2	1	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0.001	0.001	0.001	0.001	In all environments, the risk nominal because the problem was discovered before the AUV was launched.
			4	4	4	4	
		Propeller speed showed same problem as on m402 and 403.					The fault stated is not clearly written.
			3	4	2	1	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic (Cont.)							
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	0	0	0	0	Loss of instrument not critical to navigation presents no risk of loss.
			4	4	4	4	
		M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.					The fault stated is not clearly written.
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0.001	0.001	0.001	0.001	Since the AUV is captured, loss of vehicle could only occur if the rudder cut the lift line and released the AUV
			4	4	4	4	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0.002	0.01	0.01	0.5	Open: Loss of telemetry introduces risk of collision when trying to retrieve the AUV with ship. Coast: There is a risk of collision with support ship as well as other vessels and shoreline. Sea ice: There is a risk of collision with the support ship as well as icebergs. Shelf Ice: Loss of telemetry while the AUV is under the ice could result in the inability to modify AUV behaviour if a system error occurs

Table 4 ***Terschelling*** **July 2006 – Turbulence studies in the Irish Sea**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0.001	0.001	0.001	0.001	In all environments, the risk nominal because the problem was discovered before the AUV was launched.
			4	4	4	4	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0.001	0.001	0.001	0.001	In all environments, the risk nominal because the problem was discovered before the AUV was launched.
			4	4	4	4	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.001	0.002	0.005	0.01	A drop in speed may result in navigational errors or the inability to remain submerged leading to risk of collision with vessels, the shoreline, or icebergs. Loss of speed when retuning from under an ice shelf may result in a loss if the AUV expends all energy before emerging.
			4	4	2	1	
		Current spikes of 3A and voltage drops in first part of mission.	0.001	0.005	0.005	0.005	Voltage drops could result in loss of instruments necessary to navigation such as the DVL or GPS. Additionally, voltage drops could interrupt critical systems such as the CPU of computers.
			3	3	2	1	
		Propulsion motor failed 500V Megger on recovery on windings to case.					I don't have enough knowledge of the Autosub to understand the fault.
		One battery pack out of four showed intermittent connection.	0.001	0.005	0.005	0.005	Loss of battery could result in voltage drops. These could lead to loss of instruments necessary to navigation such as the DVL or GPS. Additionally, voltage drops could interrupt critical systems such as the CPU of computers
			3	3	2	1	
		Acosutci telemetry unit gave no replies.	0.002	0.01	0.01	0.5	Open: Loss of telemetry introduces risk of collision when trying to retrieve the AUV with ship. Coast: There is a risk of collision with support ship as well as other vessels and shoreline. Sea ice: There is a risk of collision with the support ship as well as icebergs. Shelf Ice: Loss of telemetry while the AUV is under the ice could result in the inability to modify AUV behaviour if a system error occurs.
			3	4	2	1	
		On surfacing first GPS fix was 1.2km out.	0.001	0.001	0.001	0.001	This fault must be combined with a fault in location beacons on AUV to risk loss of vessel. Secondary risk arises if there is reduced visibility (night, fog, high seas) and the support vessel pilot relies on a GPS fix to know where the AUV is in relation to the ship. If so, collision with the ship is possible.
			3	4	2	1	
		Spikes in indicated motor rpm	0.001	0.001	0.001	0.001	Risk is very minimal since navigation is independent of motor rpm. Only risk arises from possible failure of motor, which would result in the risk associated with an unplanned surfacing.
			4	4	4	4	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea (Cont.)

No.	Distance (Km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.002	0.01	0.01	0.5	Open: Loss of telemetry introduces risk of collision when trying to retrieve the AUV with ship. Coast: There is a risk of collision with support ship as well as other vessels and shoreline. Sea ice: There is a risk of collision with the support ship as well as icebergs. Shelf Ice: Loss of telemetry while the AUV is under the ice could result in the inability to modify AUV behaviour if a system error occurs.
			3	4	2	1	
		Noise spikes on both channels of turbulence probe data.	0	0	0	0	Assuming that the turbulence probe data is not incorporated into the navigation or control of the AUV, there is no risk of loss.
			4	4	4	4	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0	0	0	0	If bearings were problem, than there is no risk of loss as they were replaced prior to deployment.
			4	4	4	4	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem, this would show itself immediately on first dive.	0.001	0.004	0.05	0.05	Minimal risk since problem is evident immediately. Only risk is from un planed surfacing after 50 m which introduces risk of collision with vessels, shoreline, or iceberg.
			3	4	2	1	
		No telemetry from Acoustic telemetry unit.	0.002	0.01	0.01	0.5	Open: Loss of telemetry introduces risk of collision when trying to retrieve the AUV with ship. Coast: There is a risk of collision with support ship as well as other vessels and shoreline. Sea ice: There is a risk of collision with the support ship as well as icebergs. Shelf Ice: Loss of telemetry while the AUV is under the ice could result in the inability to modify AUV behaviour if a system error occurs.
			3	4	2	1	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.05	0.05	0.05	0.05	Relatively high risk in all environments. The inability to stop the AUV when it is headed for a collision with the ship, other vessels, the shoreline, or ice is potentially catastrophic.
			4	4	4	4	
		Still spikes on motor rpm that need investigating.	0.001	0.001	0.001	0.001	Risk is very minimal since navigation is independent of motor rpm. Only risk arises from possible failure of motor, which would result in the risk associated with an unplanned surfacing.
			4	4	4	4	

Mark Moline

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.01	0.01	0.1	0.7	
			5	5	3	2	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.01	0.01	0.1	0.95	
			5	5	3	4	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.01	0.01	0.1	0.95	
			5	5	3	4	
386	26	GPS antenna failed at end of mission.	0.03	0.03	0.1	0.2	
			4	4	3	2	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.01	0.2	0.2	0.9	
			5	4	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0	0	0.1	0.75	
			5	5	4	3	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0	0	0.15	0.8	
			5	5	4	3	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0	0.05	0.15	0.8	
			5	5	4	3	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.01	0.3	0.5	0.5	
			5	4	3	2	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0	0	0.2	0.9	
			4	4	4	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches. (cont.)							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0	0.03	0.1	0.8	
			5	4	3	3	
		GPS antenna flooded. No fix at end point of mission.	0.1	0.15	0.2	0.5	
			5	4	4	4	
		EM2000 swath sonar stopped logging during mission.	0.01	0.01	0.15	0.1	
			3	3	3	3	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.01	0.01	0.15	0.1	
			3	3	3	3	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.02	0.02	0.2	0.6	
			3	3	3	3	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.01	0.05	0.2	0.96	
			5	5	4	4	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.01	0.05	0.2	0.96	
			5	5	4	4	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches. (cont.)							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0	0	0.1	0.15	
			5	5	4	3	
397	4	Main lifting lines became loose, could have jammed motor.	0.01	0.05	0.2	0.96	
			5	5	4	4	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0	0.01	0.05	0.1	
			5	5	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0	0.01	0.05	0.1	
			5	5	4	4	
		Damaged on recovery, “moderately serious” to sternplane, shaft bent.	0	0	0	0	
			5	5	4	4	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.01	0.01	0.45	0.95	
			5	5	4	4	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.01	0.01	0.1	0.6	
			5	5	4	4	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.01	0.01	0.2	0.8	
			5	5	4	4	
		Only one position fix from tail mounted ARGOS transmitter.	0.01	0.01	0.01	0.01	
			5	5	4	4	
		GPS antenna damaged on recovery.	0	0	0	0	
			5	5	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0	0	0.01	0.01	
			5	5	4	4	
		Took over 1 hour to get GPS fix at final waypoint.	0	0	0.01	0.01	
			5	5	4	4	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.01	0.01	0.2	0.8	
			5	5	4	4	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0	0.01	0.1	0.5	
			5	5	4	4	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0	0.01	0.1	0.5	
			5	5	4	4	
		Propeller speed showed same problem as on m402 and 403.	0.01	0.01	0.2	0.8	
			5	5	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic (cont.)							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Propeller speed showed same problem as on m402 and 403.	0.01	0.01	0.2	0.8	
			5	5	4	4	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	0	0	0.01	0.01	
			5	5	4	4	
		M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	0.01	0.01	0.01	0.01	
			5	5	4	4	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0.01	0.01	0.01	0.01	
			5	5	4	4	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0.02	0.02	0.02	0.02	
			5	5	4	4	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0.01	0.01	0.01	0.01	
			5	5	4	4	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0.01	0.01	0.01	0.01	
			5	5	4	4	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0	0	0.1	0.1	
			5	5	4	4	
		Current spikes of 3A and voltage drops in first part of mission.	0	0	0.1	0.1	
			5	5	4	4	
		Propulsion motor failed 500V Megger on recovery on windings to case.	0.01	0.01	0.01	0.01	
			5	5	4	4	
		One battery pack out of four showed intermittent connection.	0	0.02	0.15	0.3	
			5	5	4	4	
		Acosutci telemetry unit gave no replies.	0	0.02	0.15	0.3	
			5	5	4	4	
		On surfacing first GPS fix was 1.2km out.	0	0	0.1	0.1	
			5	5	4	4	
		Spikes in indicated motor rpm	0	0	0.1	0.1	
			5	5	4	4	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
	(km)						
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0	0.02	0.15	0.3	
			5	5	4	4	
		Noise spikes on both channels of turbulence probe data.	0	0	0.1	0.1	
			5	5	4	4	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0	0	0.1	0.1	
			5	5	4	4	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	0	0	0.1	0.1	
		this would show itself immediately on first dive.	5	5	4	4	
		No telemetry from Acoustic telemetry unit.	0	0	0.1	0.1	
			5	5	4	4	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.01	0.02	0.15	0.3	
			5	5	4	4	
		Still spikes on motor rpm that need investigating.	0	0	0.1	0.1	
			5	5	4	4	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	0.01	0.01	0.01	0.01	
			5	5	4	4	
410	9	No acoustic telemetry or transponding.	0.01	0.01	0.01	0.01	
			5	5	4	4	
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	0.01	0.02	0.1	0.15	
			5	5	4	4	
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	0.01	0.02	0.1	0.15	
			5	5	4	4	
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	0.01	0.02	0.1	0.15	
			5	5	4	4	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway. (cont.)							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
	(km)						
415	6	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.	0.1	0.12	0.17	0.25	
			5	5	4	4	
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system	0.1	0.12	0.17	0.25	
			5	5	4	4	

		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.	0.01	0.02	0.1	0.15	
			5	5	4	4	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway. (cont.)							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.	0.01	0.02	0.15	0.8	
			5	5	4	4	
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a “stay here” mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	0	0.03	0.15	0.5	
			5	5	4	4	

Barbara Fletcher

Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.01	0.005	0.1	0.5	Limited experience with ice conditions
			4	4	3	3	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.01	0.01	0.05	0.07	Depends on if it actually did entangle the propeller- obviously, much higher risk if it did.
			4	4	3	3	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.03	0.03	0.1	0.5	Depends on when the uncontrolled heading was noted and whether the mission could be aborted.
			4	4	3	3	
386	26	GPS antenna failed at end of mission.	0.01	0.01	0.05	0.05	
			5	5	3	3	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.01	0.01	0.07	0.2	
			5	5	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.005	0.005	0.01	0.05	
			4	4	3	3	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0.001	0.001	0.01	0.02	
			4	4	3	3	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.05	0.05	0.1	0.1	
			4	4	3	3	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.05	0.05	0.2	0.2	
			4	4	3	3	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.001	0.001	0.01	0.01	
			3	3	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches. (cont.)

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.03	0.03	0.07	0.07	Dependent on degree of reduced accuracy and amot of accuracy required
			4	4	2	2	
		GPS antenna flooded. No fix at end point of mission.	0.05	0.05	0.1	0.1	
			4	4			
		EM2000 swath sonar stopped logging during mission.	0.001	0.001	0.001	0.001	Assuming this is a data collection sensor rather than a mission-critical sensor
			3	3	3	3	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.01	0.01	0.1	0.2	Depends on whether the position was under ice or not!
			4	4	3	3	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.01	0.01	0.05	0.05	So what else is new? A common problem… sigh
			4	4	3	3	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.07	0.07	0.2	0.2	
			4	4	2	2	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.07	0.07	0.2	0.2	Was the wrapped line the same as in No. 394?
			4	4	2	2	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.005	0.005	0.01	0.01	Depends on how critical current estimation is to navigation accuracy
			4	4	3	3	
397	4	Main lifting lines became loose, could have jammed motor.	0.01	0.01	0.05	0.05	Of course if a line "could" jam a motor, it WILL jam it sooner or later…. Murphy's law of vehicles
			4	4	3	3	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.001	0.001	0.001	0.001	Better safe than sorry!
			5	5	5	5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.05	0.05	0.1	0.15	
			4	4	3	3	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	0.01	0.01	0.01	0.01	If damaged on recovery, then chance of loss due to this specific is low provided that it is fixed
			4	4	4	4	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.05	0.05	0.2	0.3	Here's where I see the risk of loss….
			4	4	3	3	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.05	0.05	0.2	0.2	Concern with getting stuck under ice
			4	4	2	2	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.01	0.01	0.05	0.05	
			3	3	2	2	
		Only one position fix from tail mounted ARGOS transmitter.	0.01	0.01	0.05	0.05	
			4	4	3	3	
		GPS antenna damaged on recovery.	0.01	0.01	0.05	0.05	Gotta protect that antenna better!
			4	4	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.03	0.03	0.03	0.03	Vehicle is on surface, so risk of loss is low
			4	4	3	3	
		Took over 1 hour to get GPS fix at final waypoint.	0.01	0.01	0.05	0.05	
			4	4	3	3	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.01	0.01	0.05	0.05	
			3	3	2	2	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0.001	0.001	0.001	0.001	If caught and corrected pre-launch, then low risk of loss
			4	4	3	3	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0.001	0.001	0.001	0.001	If caught and corrected pre-launch, then low risk of loss
			4	4	3	3	
		Propeller speed showed same problem as on m402 and 403.	0.01	0.01	0.05	0.05	
			3	3	2	2	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	0.01	0.01	0.01	0.01	Depends on criticality of data for mission execution
			4	4	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic. (cont.)							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	0.005	0.005	0.005	0.005	On recovery, does not appear to imperil vehicle
			5	5	5	5	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0.005	0.005	0.005	0.005	On recovery, does not appear to imperil vehicle
			5	5	5	5	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0.005	0.005	0.005	0.005	If caught and corrected pre-launch, then low risk of loss
			5	5	5	5	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0.005	0.005	0.005	0.005	If caught and corrected pre-launch, then low risk of loss
			5	5	5	5	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0.01	0.01	0.01	0.01	If caught and corrected pre-launch, then low risk of loss
			5	5	5	5	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.01	0.01	0.05	0.05	Depends on criticality of expected speed for navigation
			3	3	2	2	
		Current spikes of 3A and voltage drops in first part of mission.	0.01	0.01	0.05	0.05	Unknown impact
			2	2	2	2	
		Propulsion motor failed 500V Megger on recovery on windings to case.	0.01	0.01	0.05	0.05	Unknown impact
			2	2	2	2	
		One battery pack out of four showed intermittent connection.	0.01	0.01	0.05	0.05	Depends on planned safety margin of battery life during mission
			4	4	2	2	
		Acosutci telemetry unit gave no replies.	0.005	0.005	0.005	0.005	Hard on the observer, but not directly threatening to vehicle safety (unless I'm missing something)
			5	5	5	5	
		On surfacing first GPS fix was 1.2km out.	0.01	0.01	0.03	0.05	How were subsequent fixes?
			4	4	2	2	
		Spikes in indicated motor rpm	0.01	0.01	0.05	0.05	Depends on criticality of expected speed for navigation
			3	3	2	2	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.005	0.005	0.005	0.005	Hard on the observer, but not directly threatening to vehicle safety (unless I'm missing something)
			5	5	5	5	
		Noise spikes on both channels of turbulence probe data.	0.01	0.01	0.05	0.05	Unknown impact
			2	2	2	2	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0.01	0.01	0.02	0.03	If caught and corrected pre-launch, then low risk of loss
			4	4	3	3	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem, this would show itself immediately on first dive.	0.01	0.01	0.02	0.04	
			4	4	3	3	
		No telemetry from Acoustic telemetry unit.	0.005	0.005	0.005	0.005	Hard on the observer, but not directly threatening to vehicle safety (unless I'm missing something)
			5	5	5	5	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.01	0.01	0.02	0.03	If on surface, relatively low chance of loss
			5	5	4	4	
		Still spikes on motor rpm that need investigating.	0.01	0.01	0.05	0.05	Unknown impact
			2	2	2	2	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	0.005	0.005	0.005	0.005	Hard on the observer, but not directly threatening to vehicle safety (unless I'm missing something)
			5	5	3	3	
410	9	No acoustic telemetry or transponding.	0.005	0.005	0.005	0.005	Hard on the observer, but not directly threatening to vehicle safety (unless I'm missing something)
			5	5	3	3	
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	0.01	0.01	0.05	0.05	The antenna strikes again!
			4	4	3	3	
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	0.01	0.01	0.05	0.05	
			4	4	3	3	
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	0.01	0.01	0.05	0.05	Unknown impact
			3	3	3	3	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	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.	0.02	0.02	0.05	0.05	
			4	4	2	2	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system	0.02	0.02	0.05	0.05	
			4	4	2	2	
		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.	0.05	0.05	0.1	0.1	Is acoustic the only stopping technique for the sub?
			4	4	2	2	
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.					
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a "stay here" mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	0.01	0.01	0.05	0.05	Since it stopped with acoustic command, "all's well that ends well", but could be issue with ice or other obstacles.
			4	4	3	3	

Clayton Jones

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.001	0.001	0.01	0.1	Surfacing under ice may lead to damage of propeller and/or control surfaces upon acoustic mission homing command. Any surface constraint inherently increases risk of successful recovery.
			5	5	5	4	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.001	0.001	0.01	0.02	If a tangle renders the propeller inoperable, the vehicle would surface, however, have no means for shelf ice extrication. Yet, as described, it did not tangle and therefore is not an issue.
			5	5	5	4	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.001	0.001	0.01	0.5	Presume that incorrect flight was being tracked after hardware modification and mission terminated. Flight control is key to getting back out from under ice - this may prove difficult.
			5	5	5	4	
386	26	GPS antenna failed at end of mission.	0.001	0.001	0.001	0.001	Proper mission termination is in open water. Use of ARGOS and UHF RDF should bring to acoustic and visual range.
			5	5	5	5	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.001	0.001	0.01	0.01	Acoustic command is viable, use a bearing and distance to replace acoustic tracking to get out from under ice.
			5	5	5	4	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.001	0.001	0.001	0.02	Presuming that a pre-dive checkout would occur prior to an under ice run.
			5	5	5	4	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0.001	0.001	0.001	0.001	1m oscillation not mission recovery critical.
			5	5	5	5	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.001	0.001	0.01	0.01	3km range should be adequate to stop mission. Comment regarding ship speed belongs in next issue description.
			5	5	5	5	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.001	0.01	0.01	0.01	Given a nominal speed of 2m/s, the unit would have traversed 120 m in the two minutes, still well within the range for an acoustic abort.
			4	4	3	3	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.001	0.001	0.01	0.01	In conjunction with the above faults, this could give tracking issues that may have missed the homing mode issue.
			3	3	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.001	0.001	0.001	0.001	Not the only navigation set. Reduced accuracy will still allow a successful mission and acoustic homing.
			4	4	4	4	
		GPS antenna flooded. No fix at end point of mission.	0.001	0.001	0.001	0.001	Proper mission termination is in open water. Use of ARGOS and UHF RDF should bring to acoustic and visual range.
			5	5	5	5	
		EM2000 swath sonar stopped logging during mission.	0.001	0.001	0.001	0.001	Not the primary collision avoidance sensor.
			4	4	4	4	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.001	0.001	0.05	0.2	If position coincides to ice coverage, could be an issue of surfacing under ice damage to propeller or control actuators.
			5	5	5	4	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.001	0.001	0.02	0.05	Other mission systems should enable successful mission and recovery.
			4	4	3	3	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.001	0.001	0.02	0.02	Given recovery, albeit with damage, the AUV must have been clear of the shelf ice. In ice conditions, small boat may not be launch able.
			5	5	4	4	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.001	0.001	0.2	0.95	Presuming that the line came out while underway in a mission, not during a normal recovery. Smaller boat may not be able to be launched in sea ice.
			5	5	4	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches. (cont.)							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.001	0.001	0.001	0.001	Issue identified and rectified within 4 km.
			5	5	5	5	
397	4	Main lifting lines became loose, could have jammed motor.	0.001	0.001	0.01	0.01	Could have, however, did not.
			5	5	4	4	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.001	0.001	0.001	0.001	Still in control of vehicle.
			5	5	5	5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.001	0.001	0.02	0.05	Wonder if the shelf ice would have been a more stable navigation reference. At 7.5 km distance, acoustic comms and other navigation methods should enable a recovery.
			4	4	3	3	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	0.001	0.001	0.001	0.001	Recovery damage, signifies "no loss".
			5	5	5	5	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.001	0.001	0.1	0.75	Problem with flying up into ice and loss of control capability at a significant range from ship.
			4	4	3	3	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.05	0.05	0.2	0.2	Concern with getting stuck under ice
			4	4	2	2	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.001	0.001	0.01	0.3	If under ice, reduced propulsion could result in not clearing ice in time. The range should be OK given fresh batteries.
			4	4	4	3	
		Only one position fix from tail mounted ARGOS transmitter.	0.05	0.05	0.1	0.05	Have to be out from under the ice. As this is the long range recovery mechanism some concern is due. Iridium availability could mitigate.
			4	4	4	4	
		GPS antenna damaged on recovery.	0.001	0.001	0.001	0.001	Recovered, no loss.
			5	5	5	5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.001	0.001	0.001	0.001	On surface, therefore loss unlikely.
			5	5	4	4	
		Took over 1 hour to get GPS fix at final waypoint.	0.001	0.001	0.01	0.01	Proper mission termination is in open water. Use of ARGOS and UHF RDF should bring to acoustic and visual range.
			5	5	4	4	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.001	0.001	0.01	0.2	If under ice, reduced propulsion could result in not clearing ice in time although 140 km seems well in range with fresh batteries.
			4	4	4	3	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0.001	0.001	0.001	0.001	Low chance of loss given pre-launch checks and that the weight had to be loaded prior to launch.
			4	4	4	4	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0.001	0.001	0.001	0.001	Given pre-launch identification, then low expectation of loss.
			4	4	4	4	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0.001	0.001	0.001	0.001	Damage not leading to loss.
			5	5	5	5	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0.001	0.001	0.001	0.001	Given pre-launch identification, then low expectation of loss.
			5	5	5	5	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0.001	0.001	0.001	0.001	Pre-launch check.
			5	5	5	5	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0.001	0.001	0.001	0.001	Pre-launch check.
			5	5	5	5	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.001	0.001	0.02	0.2	If under ice, reduced propulsion could result in not clearing ice in time although 104 km seems well in range with fresh batteries.
			4	4	3	3	
		Current spikes of 3A and voltage drops in first part of mission.	0.01	0.01	0.01	0.05	Tolerance of system not known.
			2	2	2	2	
		Propulsion motor failed 500V Megger on recovery on windings to case.	0.001	0.001	0.001	0.001	Recovered, no loss.
			4	4	4	4	
		One battery pack out of four showed intermittent connection.	0.001	0.001	0.01	0.05	Energy safety margin used in mission planning?
			4	4	3	3	
		Acoustic telemetry unit gave no replies.	0.001	0.001	0.01	0.02	Only one of the tracking/recovery systems.
			5	5	5	5	
		On surfacing first GPS fix was 1.2km out.	0.001	0.001	0.01	0.02	1.2 km should be in acoustic range.
			4	4	3	3	
		Spikes in indicated motor rpm	0.001	0.001	0.01	0.02	Magnitude and associated navigation error?
			4	4	3	3	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.001	0.001	0.01	0.02	Only one of the tracking/recovery systems.
			5	5	5	5	
		Noise spikes on both channels of turbulence probe data.	0.001	0.001	0.001	0.001	Science, not mission recovery critical.
			5	5	5	5	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0.001	0.001	0.001	0.001	Pre-launch check, mitigates loss risk.
			5	5	5	5	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	0.001	0.001	0.01	0.02	Presume that this would be caught and rectified well within acoustic range if under ice.
		this would show itself immediately on first dive.	4	4	3	3	
		No telemetry from Acoustic telemetry unit.	0.001	0.001	0.01	0.02	Only one of the tracking/recovery systems.
			5	5	5	5	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.001	0.001	0.001	0.001	On surface signifies low probability of loss. WiFi indicates close range, expect that the AUV could have been stopped acoustically.
			5	5	4	4	
		Still spikes on motor rpm that need investigating.	0.001	0.001	0.01	0.02	Magnitude and associated navigation error?
			4	4	3	3	

Rob McEwen

Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.01	0.015	0.5	0.8	I'm assuming that the ARGOS transmitter is independent and pressure activated, and will transmit without an on-board network.
			2	2	3	3	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.005	0.01	0.5	0.8	In this case the vehicle can transmit its location in the normal way, once on the surface.
			2	2	3	3	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.005	0.01	0.7	0.9	It may not be possible for the ship to follow the AUV if it goes under thick ice, whereupon tracking may be lost. (Depends on the directionality of the USBL).
			2	2	3	3	
386	26	GPS antenna failed at end of mission.	0.001	0.003	0.01	0.01	I'm not sure if you typically use GPS to help locate the vehicle after the mission. We usually do.
			3	3	3	3	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.001	0.001	0.1	0.2	I'll assume the mission would have been stopped before it reached the ice edge, and that the location is well known. There is a higher danger near the ice due to possible collisions with ice fragments.
			3	1	1	1	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.001	0.001	0.002	0.002	I'm assuming that only 4 minutes into the mission the vehicle is not yet near ice, and its position is known.
			3	3	1	1	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.					I would have to know if by "instability" you mean a limit cycle, that is, a sustained oscillation of constant amplitude, or you mean in the sense of unbounded and growing amplitude. Also, what was the frequency? High enough to cause damage?
			1	1	1	1	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.005	0.01	0.7	0.9	What was the programmed speed for this mission? Are we to assess risk in a general case of homing mode malfunction, or this specific case, with this specific ship that goes 9 kts? I'll assume the latter.
			2	2	2	2	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.01	0.02	0.7	0.9	I think this is a dire situation - when the propulsion is on, and the guidance is dead. #385 and #387 are similar. We've had this happen to us also, but only in Monterey bay. Risk depends, among other things, on if the ship can catch the AUV, and also if the ship can maintain tracking.
			3	3	4	4	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.001	0.003	0.1	0.1	Does the navigation accuracy depend on surface aiding? For example are USBL fixes telemetered to the AUV?
			2	2	2	2	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.001	0.01	0.3	0.5	It depends on proximity to the shore, and to ice keels or ice bergs.
			4	2	2	2	
		GPS antenna flooded. No fix at end point of mission.	0.001	0.001	0.001	0.001	It depends on whether GPS plays a role in post-mission location.
			2	2	2	2	
		EM2000 swath sonar stopped logging during mission.	0	0	0	0	I'm assuming that the navigation does not rely in any way on the EM2000
			3	3	3	3	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.001	0.003	0.3	0.3	It's unclear how this would happen. How would the GPS failing upon mission completion cause a position error?
			4	4	2	2	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.001	0.05	0.3	0.6	No chance to abort the mission if the operator detects an error.
			4	2	2	2	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.003	0.006	0.6	0.8	I'm assuming that in the under-ice cases the vehicle was heading under, not away, from the ice. Also, the risk of losing the vehicle is increased in open water because the difficult recovery could be further complicated by incoming weather, fog, etc.
			3	3	3	3	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.001	0.003	0.6	0.8	
			3	3	3	3	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.001	0.001	0.1	0.2	Does the navigation accuracy depend on current estimation?
			2	2	2	2	
397	4	Main lifting lines became loose, could have jammed motor.	0.001	0.003	0.6	0.8	I assume this is the same as #395.
			3	3	3	3	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.001	0.01	0.2	0.3	Presumably the operators wouldn't terminate the mission with the AUV under the ice. But if the waypoints were wrong, the vehicle might get trapped in a canyon, or in ice keels.
			3	3	1	1	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.001	0.005	0.5	0.7	The sea ice case depends on wheather you were launching from a lead in the ice, or the ice edge, and if the edge, how well-defined it was.
			3	3	2	2	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	0.001	0.001	0.001	0.001	Once you've got a line on the vehicle, the risk of loss seems small.
			3	3	3	3	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.001	0.003	0.5	0.7	I presume autosub is statically buoyant.
			3	3	2	2	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.001	0.003	0.5	0.7	This appears similar to the above case. I'm assuming the vehicle's position is known at the time of the abort.
			3	3	2	2	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.001	0.003	0.5	0.7	The risk in many of these situations depends on whether the operators can use the acoustic communications to recall the vehicle before the problem worsens. I'm always estimating the risk to be higher near shelf ice than in sea ice because I'm assuming there is probably pieces, if not a brash like cover of ice in addition to the shelf. The risk near shelf ice may actually be lower than that of sea ice, if the shelf terminates in open water and forms a distinct surface.
			3	3	2	2	
		Only one position fix from tail mounted ARGOS transmitter.	0.001	0.003	0.1	0.1	I'm guessing this implies that the AUV is operating normally, but ARGOS has dropped out. I assume that acoustic communications are working. Again, if you have a radio modem, or Iridium, the risk is lower.
			3	3	2	2	
		GPS antenna damaged on recovery.	0.001	0.001	0.001	0.001	

			3	3	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.001	0.003	0.6	0.8	Similar to #395 & #397.
			3	3	3	3	
		Took over 1 hour to get GPS fix at final waypoint.	0.001	0.001	0.001	0.001	
			2	2	2	2	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.001	0.003	0.5	0.7	
			3	3	2	2	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0	0	0	0	The comment is a little confusing. How could it not be spotted or checked if you have to load a weight into the keeper? Also, wouldn't a distorted keeper tend to jam the weight in, not make it drop out?
			1	1	1	1	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0	0	0	0	Wasn't it detected during the pre-launch? Then there is no risk of loss due to this.
			1	1	1	1	
		Propeller speed showed same problem as on m402 and 403.	0.001	0.003	0.5	0.7	
			3	3	2	2	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	0.001	0.001	0.01	0.01	If you have a variable-buoyancy system which relies on CTD data in real time, than the risk is worse. Also, it depends on if the PHINS is using the CTD data to process the Dvl data.
			3	3	1	1	
		M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	0.001	0.001	0.05	0.05	
			3	3	2	2	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0.001	0.001	0.05	0.05	
			3	3	2	2	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0.001	0.001	0.05	0.05	This situation and the above two seem similar and low risk in that the vehicle is on the surface next to the ship
			3	3	2	2	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0.001	0.003	0.1	0.1	But you found the problem pre-launch, so there was no risk! I'll assume that you didn't find it
			1	1	1	1	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0.003	0.006	0.1	0.1	Suppose it was not found in the pre-launch check
			1	1	1	1	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.001	0.003	0.5	0.7	Same as #402 & 3
			3	3	2	2	
		Current spikes of 3A and voltage drops in first part of mission.	0.001	0.003	0.5	0.7	Something is about to short out?
			2	2	1	1	
		Propulsion motor failed 500V Megger on recovery on windings to case.	0.001	0.003	0.5	0.7	
			3	3	2	2	
		One battery pack out of four showed intermittent connection.	0.001	0.003	0.1	0.2	
			2	2	2	2	
		Acosutci telemetry unit gave no replies.	0.005	0.01	0.5	0.7	
			2	2	2	2	
		On surfacing first GPS fix was 1.2km out.					Out from where? From the ship? Or was there a 1.2 km error in GPS position? Or was GPS correct, but the AUV was 1.2 km from the final waypoint?
		Spikes in indicated motor rpm	0.001	0.003	0.3	0.5	
			2	2	1	1	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.005	0.01	0.3	0.5	Same as 406 e)? I assumed there that you meant no replies at all.
			2	2	1	1	
		Noise spikes on both channels of turbulence probe data.	0.001	0.001	0.005	0.005	I assume that there wasn't similar noise on other instruments.
			3	3	2	2	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0.001	0.003	0.5	0.7	
			3	3	2	2	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	0.001	0.003	0.1	0.1	
		this would show itself immediately on first dive.	3	3	1	1	
		No telemetry from Acoustic telemetry unit.	0.005	0.01	0.3	0.5	
			2	2	1	1	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.001	0.003	0.3	0.3	
			2	2	2	2	
		Still spikes on motor rpm that need investigating.	0.001	0.003	0.3	0.5	
			2	2	1	1	

Table 5 ***Terschelling*** **March 2007 – Deep water AUV reliability proving trials in Norway.**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	0.005	0.01	0.3	0.5	
			2	2	1	1	
410	9	No acoustic telemetry or transponding.	0.005	0.01	0.3	0.5	Same situation as previous a-comms losses
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	0.001	0.001	0.001	0.001	Same as #391
			4	2	2	2	
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	0.001	0.001	0.001	0.001	For open water this depends on if you're relying on itermediate surfacing for GPS position fixes. Presumably the AUV can't surface in the ice except at the launch/recovery location. Also I assume that the GPS was working upon launch, and that the INS was correctly initialized.
			4	2	2	2	
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	0.001	0.003	0.3	0.3	
			3	3	2	2	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	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.	0.001	0.003	0.5	0.7	I assume the operator can kill the mission with the acoustic communication. I don't know if you can recall it to the launch point.
			4	4	2	2	
		Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system	0.05	0.05	0.5	0.8	I don't know what the abort system is. Do you mean the drop weight? Also, I would guess loss of the EM and Seabird don't risk the vehicle much, but certainly losing the downward Dvl/Adcp does.
			3	3	2	2	
		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.	0.001	0.003	0.3	0.3	
			3	3	1	1	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.	0.001	0.003	0.5	0.7	Were communications re-estabilished near the surface? Did the AUV come up under power, or was the prop off?
			3	3	1	1	
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a “stay here” mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	0.001	0.05	0.5	0.5	
			3	3	2	2	

Chris Williams

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.01	0.03	0.1	1	Under ice shelf: If the abort decision (operation) does not include an attempt to return to the mother ship or shelf edge, then P(loss) is 1.0. If the required mission length is less than the time taken for the fault to emerge then P(loss) could be reduced to 0.7; confidence is 4. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: For a loss due to an inability to locate the AUV, the observed fault would need to be compounded by the failure to function of one or more of the following devices on the AUV: (a) acoustic pinger, (b) emergency release for drop weight, (c) ARGOS transmitter. P(loss) is 0.01, confidence is 4. Note: We assume longer missions only.
			4	3	3	4	

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**

Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.02	0.05	0.1	0.8	Under ice shelf: If this event occurs under the ice shelf, and the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: If this event occurs under sea ice, the AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV. P(loss) is 0.1, confidence is 3. Coastal: If this event occurs in coastal waters, P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If this event occurs in open water, the recovery should be straight-forward, as long as the procedure to recover the AUV doe
			4	3	3	4	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.01	0.03	0.1	0.8	Under ice shelf: If this event occurs under the ice shelf, and the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: If this event occurs under sea ice, the AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV. P(loss) is 0.1, confidence is 3. Coastal: If this event occurs in coastal waters, P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If this event occurs in open water, the recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4.

							Note: It is not absolutely certain that the line will tangle.
			4	3	3	3	

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
386	26	GPS antenna failed at end of mission.	0.01	0.03	0.1		Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. Under ice shelf: not applicable Under sea ice: The AUV is near the ship but GPS antenna was damaged by sea ice. Recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: The AUV is near the ship but P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is near the ship hence the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		

387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	0.01	0.03	0.1	0.8	Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: If the ship can get to the location of the AUV then recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: If the ship can get to the location of the AUV then P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: If the ship can get to the location of the AUV then the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4. Note: The vehicle is no where near the ice shelf when homing.
			4	3	3	3	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.01	0.03	0.1		Under ice shelf: There is a low probability that the AUV would reach the edge of the ice shelf within 4 minutes of travel time, so this case is not applicable. Under sea ice: Assuming that the signal from the acoustic pinger can be detected through the ice, and, that the ship can get to the location of the AUV, then recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: Assuming that the AUV can be located via the acoustic pinger, strobe light or ARGOS position, and, that the

							ship can get to the location of the AUV, then P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: Assuming that the AUV can be located via the acoustic pinger, strobe light or ARGOS position, and, that the ship can get to the location of the AUV, then the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0.01	0.03	0.1		Under ice shelf: There is a low probability that the AUV would reach the edge of the ice shelf within 7 to 8 minutes of travel time, so this case is not applicable. Under sea ice: Assuming that the signal from the acoustic pinger can be detected through the ice, and, that the ship can get to the location of the AUV, then recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: Assuming that the AUV can be located via the acoustic pinger, strobe light or ARGOS position, and, that the ship can get to the location of the AUV, then P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: Assuming that the AUV can be located via the acoustic pinger, strobe light or ARGOS position, and, that the ship can get to the location of the AUV, then the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.01	0.03	0.1		Under ice shelf: not applicable since the ship caught the AUV. Under sea ice: Recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: Here P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						

389	3	Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.01	0.03	0.1	0.8	Assume the AUV continues travelling until either (a) battery is depleted, or, (b) mission time is exceeded and the abort-to-surface command is executed, at which time the AUV comes to rest and the location of the AUV is known. Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4. Note: The general direction is correct.
			4	3	3	3	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.01	0.03	0.1	0.8	Assuming that the ship-based acoustic telemetry unit can be repaired, then the process to recover the AUV can begin. Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: Assuming that the signal from the acoustic pinger can be detected through the ice, and, that the ship can get to the location of the AUV, then recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: Assuming that the AUV can be located via the acoustic pinger, strobe light or ARGOS position, and, that the ship can get to the location of the AUV, then P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Note: This does not influence the navigation of the system.
			4	3	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.1				This fault should not affect the ability of the AUV to "come home" provided that the AUV can receive that acoustic command, or, that the eventual mission time-out invokes a "come home" action. Figure 6a of [1] shows that the probability of survival from a voyage of length 30 km without a high impact fault is about 0.9, thus P(loss) is 0.1 and confidence is 3.
			3				
		GPS antenna flooded. No fix at end point of mission.	0.01	0.03	0.1		Under ice shelf: The mission was completed so this case is not applicable. Under sea ice: The AUV is near the ship but GPS antenna was damaged. Recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: The AUV is near the ship but P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is near the ship hence the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		
		EM2000 swath sonar stopped logging during mission.					Although this fault will affect the scientific value of the mission, this fault should not affect the ability of the AUV to "come home" provided that the AUV can receive that acoustic command, or, that the eventual mission time-out invokes a "come home" action. Figure 6a of [1] shows that the probability of survival from a voyage of length 30 km without a high impact fault is about 0.9, thus P(loss) is 0.1 and confidence is 3.

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.01	0.03	0.1		This fault should not affect the ability of the ship's crew to recover the AUV. Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. Under ice shelf: The mission was completed so this case is not applicable. Under sea ice: The AUV is near the ship but GPS antenna was damaged by sea ice. Recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: The AUV is near the ship but P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is near the ship hence the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.01	0.03	0.1	0.8	Note that the faults with the acoustic telemetry system may make it difficult to locate the AUV. Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The recovery should be straight-forward unless it is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4. Note: No influence on the vehicle.
			4	3	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.02	0.05	0.1	1	If this incident occurred late in the mission, it may to be difficult or impossible to recover the AUV. Since the tangle is severe enough to prevent the propeller from turning, no attempt to return to the mother ship or shelf edge will be possible. Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4. Note: The jamming happened.
			4	3	3	5	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.02	0.05	0.1	1	If this incident occurred late in the mission, it may to be difficult or impossible to recover the AUV. Since the tangle is severe enough to prevent the propeller from turning, no attempt to return to the mother ship or shelf edge will be possible. Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4.
			4	3	3	5	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.	
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.01	0.03	0.1	0.8	This fault may affect whether the AUV can actually attain the desired waypoints but it should not affect the ability of the AUV to "come home". This P(loss) should be low. Under ice shelf: If the AUV can get itself out beyond the edge of the ice shelf then the usual procedures for recovery in "sea ice" conditions apply. If the AUV can get itself to within say 300 m of the edge of the ice shelf, then recovery by ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The recovery should be straight-forward unless it is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4. Note: The jamming happened.
			4	3	3	3	
397	4	Main lifting lines became loose, could have jammed motor.	0.02	0.05			Under ice shelf: Incident occurred when AUV is at the surface so this case is not applicable. Under sea ice: Incident occurred when AUV is at the surface so this case is not applicable. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4.
			4	3			

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.01	0.03	0.1	0.8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly. Distance travelled was 8 km. Here the location of the AUV (at the instant at which the mission was ended) is the determining factor. Under ice shelf: If the AUV can get itself out beyond the edge of the ice shelf then the usual procedures for recovery in "sea ice" conditions apply. If the AUV can get itself to within say 300 m of the edge of the ice shelf, then recovery by ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The recovery should be straight-forward
			4	3	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.01	0.03	0.1		Here the main problem is to locate the AUV based on its most-recent ded-reckoning position. This mistake should not affect the ability of the AUV to "come home" nor the ability of the ship's crew to recover the AUV once it has been located. Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. Under ice shelf: The AUV can get itself out from under the ice shelf so this case is not applicable. Under sea ice: If the ship can locate the AUV and get near to it, recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: If the ship can locate the AUV and get near to it, P(loss) is assessed higher than for the open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: If the ship can locate the AUV and get near to it, the recovery should be straight-forward unless it is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
		Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.					
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	0.05	0.1	0.2		The issue here is whether an inoperable sternplane affects the recovery procedure, therefore increase P(loss) during recovery; from 0.01 to 0.05 and 0.03 to 0.10 and 0.10 to 0.20. Under ice shelf: The damage occurred near the ship so this case is not applicable. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV is not significantly impaired by an inoperable sternplane. P(loss) is 0.20, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.10; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV is not significantly impaired by an inoperable sternplane, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.05; confidence is 4.
			4	3	3		

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.05	0.1	0.2	1	Due to the sternplane jam, the AUV will either (a) rise to the undersurface of the ice, or, (b) descend toward the seabed. Assume that the "max depth" detection and subsequent dropping of the emergency weight works correctly, no loss will occur due to exceeding the "crush depth". Assume that the ship can communicate acoustically with the AUV and that the "come home" command is issued from the ship. Then the success of the "come home" procedure will depend on the ability of the altimeter, depth sensor, upward-looking sonar, forward-looking sonar and obstacle-avoidance software to work in conjunction with the remaining five control surfaces to "come home" along a constant depth trajectory. The issue here is whether an inoperable sternplane affects the recovery procedure, therefore increase P(loss) during recovery; from 0.01 to 0.05 and 0.03 to 0.10 and 0.10 to 0.20. Under ice shelf: If the AUV cannot extricate itself from under the ice shelf and ends up a long distance from the edge, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.9; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV is not significantly impaired by a jammed sternplane. P(loss) is 0.2, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.1; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV is not significantly impaired by a jammed sternplane, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.05; confidence is 4. Note: complete loss of control.
			4	3	3	5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
402	274	Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.05	0.1	0.2	1	If the release of the emergency drop weight is the issue, then the AUV may have difficulty coming to the surface. Assume that the control surfaces have sufficient control authority so that with some low forward speed the AUV can come to the surface, then the usual recovery procedures can be used. The success of the "come home" procedure while under the ice shelf will depend on the ability of the altimeter, depth sensor, upward-looking sonar, forward-looking sonar and obstacle-avoidance software to work in conjunction with the control surfaces to "come home" along a constant depth trajectory. Increase the usual value of P(loss) due to increased complexity of the recovery process due to the need for some forward speed during recovery. Under ice shelf: If the AUV tries to "come home" but ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, and, how difficult it is to recover a slowly-moving AUV. P(loss) is 0.2, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.1; confidence is 3. Open water: The recovery procedure will be affected by the need to recover a slowly-moving AUV; additional complications will be due to waves, fog or strong tidal currents, hence P(loss) is 0.05; confidence is 4. Note: Complete loss of control.
			4	3	3	5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
402	274	Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.02	0.05	0.2	0.8	Only one position fix from tail mounted ARGOS transmitter. Distance travelled was 274 km. Assume that the alternate devices (acoustic pinger, strobe light) function correctly, or, that the AUV can be located visually. This fault should not affect the usual recovery procedures. Under ice shelf: Failure occurred when AUV is at the surface so this case is not applicable. Under sea ice: The AUV is probably near the ship but the AUV has drifted since its last reported position. Once the AUV has been located, recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: Here P(loss) is assessed to be higher than for the open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is probably near the ship but the AUV has drifted since its last reported position. Once the AUV has been located, the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3	3	

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
402	274	Only one position fix from tail mounted ARGOS transmitter.	0.01	0.03	0.1		Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. This damage should have no effect on the recovery procedures. Under ice shelf: Damage occurred when AUV is at the surface so this case is not applicable. Under sea ice: Damage occurred when AUV is at the surface so this case is not applicable. Coastal: The AUV is near the ship but P(loss) is assessed higher than the open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is near the ship hence the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		
		GPS antenna damaged on recovery.	0.01	0.03			Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. This damage should have no effect on the recovery procedures. Under ice shelf: Damage occurred when AUV is at the surface so this case is not applicable. Under sea ice: Damage occurred when AUV is at the surface so this case is not applicable. Coastal: The AUV is near the ship but P(loss) is assessed higher than the open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is near the ship hence the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3			

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.02	0.05			Assume that this incident occurs only at the end of a successful voyage hence the only effect is on the recovery process. Under ice shelf: Incident occurred when AUV is at the surface so this case is not applicable. Under sea ice: Incident occurred when AUV is at the surface so this case is not applicable. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4.
			4	3			
		Took over 1 hour to get GPS fix at final waypoint.	0.05	0.15			The issue here is potential damage to the AUV during 1-hour drifting on the surface at the final waypoint. Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. This fault should have no effect on the recovery procedures once they commence. Increase the P-values by a factor of five, use 0.15 and 0.05.
			4	3			

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.02	0.05	0.15	0.8	Assume that this measurement was made at the end of the mission after a successful recovery. Suppose that this fault was not detected prior to the start of the next mission. The issue then becomes how long will the propeller keep turning sufficiently to provide forward propulsion to "come home" once the fault has been detected by some self-diagnostic test which is routinely executed within the AUV. Under ice shelf: If the propeller keeps turning until (a) the AUV gets out beyond the shelf edge then recover as usual, P(loss) is 0.6 and confidence is 3; (b) the AUV gets to within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3; (c) if the propeller stops and the AUV drifts beyond the reach of an ROV, P(loss) is 1.0, confidence is 5. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV. P(loss) is 0.15, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4. Note: All scenarios equally likely.
			4	3	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0.01	0.03	0.1	0.8	Suppose that this fault was not detected prior to the start of the next mission. If the weight falls out during the mission, the AUV would tend to rise toward the undersurface of the ice shelf. Assume that the control surfaces have sufficient control authority so that with some low forward speed the AUV can maintain a constant depth trajectory. The success of the "come home" procedure while under the ice shelf will then depend on the ability of the altimeter, depth sensor, upward-looking sonar, forward-looking sonar and obstacle-avoidance software to work in conjunction with the control surfaces to "come home" along a constant depth trajectory. Increase the usual value of P(loss) due to increased complexity of the recovery process due to the need for some forward speed during recovery. Under ice shelf: If the AUV tries to "come home" but ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, and, how difficult it is to recover a slowly-moving AUV. P(loss) is 0.2, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.1; confidence is 3. Open water: The recovery procedure will be affected by the need to recover a slowly-moving AUV; additional complications will be due to waves, fog or strong tidal currents, hence P(loss) is 0.05; confidence is 4. Note: Failure spotted pre-launch.
			4	3	3	3	

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
		Pre-launch, potential short circuit in motor controller that could stop motor.	0.01	0.03	0.1	0.8	Suppose that this fault was not detected prior to the start of the next mission. Assume that the short circuit stops the motor, thus no attempt to "come home" will be possible. Under ice shelf: If this event occurs under the ice shelf, and the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: If this event occurs under sea ice, the AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV. P(loss) is 0.1, confidence is 3. Coastal: If this event occurs in coastal waters, P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: If this event occurs in open water, the recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4. Note: It was spotted pre-launch.
			4	3	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	Propeller speed showed same problem as on m402 and 403.	0.02	0.05	0.15	0.8	Suppose that this fault was not detected prior to the start of the next mission. The issue then becomes how long will the propeller keep turning sufficiently to provide forward propulsion to "come home" once the fault has been detected by some diagnostic test which is executed within the AUV on a regular basis. Under ice shelf: If the propeller keeps turning until (a) the AUV gets out beyond the shelf edge then recover as usual, P(loss) is 0.6 and confidence is 3; (b) the AUV gets to within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3; (c) if the propeller stops and the AUV drifts beyond the reach of an ROV, P(loss) is 1.0, confidence is 5. Under sea ice: If the propeller keeps turning until the AUV gets out beyond the shelf edge then recover as usual. The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV. P(loss) is 0.15, confidence is 3. Coastal: If the propeller keeps turning until the AUV gets out beyond the shelf edge into coastal waters, then recover as usual. P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If the propeller keeps turning until the AUV gets out beyond the shelf edge into open water then recover as usual. The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4. Note: All scenarios equally likely.
			4	3	3	3	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).					Suppose that this fault was not detected prior to the start of the next mission. Assuming that the AUV is equipped with an additional depth sensor which is used when operating in the constant-depth control mode, this fault has no effect on the behaviour of the AUV. When the fault is detected either (a) continue the mission to gather a reduced data-set, or, (b) "come home". Figure 6a of [1] shows that the probability of survival from a voyage of length 75 km without the occurrence of a high impact fault is about 0.79, thus P(loss) is 0.21 and confidence is 3. Note: Is not addressing the fault.

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**							
	Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	This incident occurred in open water, at the end of the mission, during recovery. What is P(loss) during recovery after this incident occurred? It is no different that a normal open-water recovery, hence P(loss) is 0.01, confidence is 4.				
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.					This incident occurred in open water, at the end of the mission, during recovery, after the lifting lines were attached. What is P(loss) during recovery after this incident occurred? Since the lifting lines are now attached, there is a high probability that the recovery will be completed successfully, hence P(loss) is 0.005, confidence is 5.
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0.01				This incident occurred in open water, at the end of the mission, during recovery. What is P(loss) during recovery after this incident occurred? It is no different that a normal open-water recovery, hence P(loss) is 0.01, confidence is 4. Ensure that the transducer is checked, and, repaired or replaced and tested prior to the next deployment.
			4				

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0.01	0.03	0.1	0.8	Is this the only range-to-ship measurement device, or, is there another independent range-to-ship measurement device? If it is the only such device, and, if this fault was not detected prior to the next deployment, then once the fault is detected, issue a "come home" command via the acoustic modem. Note that a fault with the acoustic tracking system may make it difficult to locate the AUV. Under ice shelf: If the AUV ends up far under the ice shelf, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The recovery should be straight-forward unless it is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4. Note: Not essential for vehicle control.
			4	3	3	3	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0.05	0.1	0.2	0.9	If this fault was not detected prior to starting the mission, then once the fault is detected, issue a "come home" command via the acoustic modem. Then the success of the "come home" procedure will depend on the ability of the altimeter, depth sensor, upward-looking sonar, forward-looking sonar and obstacle-avoidance software to work in conjunction with the six control surfaces to "come home" along a constant depth trajectory. Under ice shelf: If the AUV cannot extricate itself from under the ice shelf and ends up a long distance in from the edge, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.9; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV is not significantly impaired by an these two loose control surfaces. P(loss) is 0.2, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.1; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV is not significantly impaired by an these two loose control surfaces, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.05; confidence is 4.

							Note: Caught pre-launch.
			4	3	3	3	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.02	0.05	0.2	0.8	Assume that this measurement was made at the end of the mission after a successful recovery. Suppose that this fault was not detected prior to the start of the next mission. The issue then becomes how long will the propeller keep turning sufficiently to provide forward propulsion to "come home" once the fault has been detected by some diagnostic test which is executed within the AUV on a regular basis. Under ice shelf: If the propeller keeps turning until (a) the AUV gets out beyond the shelf edge then recover as usual, P(loss) is 0.6 and confidence is 3; (b) the AUV gets to within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8; confidence is 3; (c) if the propeller stops and the AUV drifts beyond the reach of an ROV, P(loss) is 1.0, confidence is 5. Under sea ice: If the propeller keeps turning until the AUV gets out beyond the shelf edge then recover as usual. The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV. P(loss) is 0.20, confidence is 3. Coastal: If the propeller keeps turning until the AUV gets out beyond the shelf edge and into coastal waters then recover as usual. P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If the propeller keeps turning until the AUV gets out beyond the shelf edge and into open water then recover as usual. The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4.

							Note: All scenarios equally likely.
			4	3	3	3	
		Current spikes of 3A and voltage drops in first part of mission.					Apparently this was not severe enough to abort a 104 km mission, or, it was detected after a voyage of 52 km and the "come home" command was issued then. Or, these irregularities were observed "in the first part of the mission" and disappeared later? Suppose that these irregularities were not detected (by some self-diagnostic test which is routinely executed within the AUV) until part way through a mission, then the appropriate action would be to halt the mission and issue the "come home" command. Figure 6a of [1] shows that the probability of survival from a voyage of length 100 km without the occurrence of a high impact fault is about 0.74, thus P(loss) is about 0.26 and confidence is probably 3. Given that the above fault was not severe enough to cause an abort of a 104 km mission, perhaps the values of P(loss) should be increased by 10% from those that would be predicted for any other length of voyage by Figure 6a.

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**

406	104	Propulsion motor failed 500V Megger on recovery on windings to case.	0.02	0.05	0.2	0.8	Assume that this measurement was made at the end of the mission after a successful recovery. Suppose that this fault was not detected prior to the next deployment. The issue then becomes how long will the propeller keep turning sufficiently to provide forward propulsion to "come home" once the fault has been detected by some self-diagnostic test which is routinely executed within the AUV. Under ice shelf: If the propeller keeps turning until (a) the AUV gets to within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8 and confidence is 3; otherwise (b) if the propeller stops and the AUV drifts beyond the reach of an ROV, P(loss) is 1.0, confidence is 5. Under sea ice: If the propeller keeps turning until the AUV gets out beyond the shelf edge then recover as usual. The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV. P(loss) is 0.20, confidence is 3. Coastal: If the propeller keeps turning until the AUV gets out beyond the shelf edge and into coastal waters then recover as usual. P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If the propeller keeps turning until the AUV gets out beyond the shelf edge and into open water then recover as usual. The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV, or unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4. Note: Failed test on recovery.
			4	3	3	3	

Table 4 ***Terschelling*** **July 2006 – Turbulence studies in the Irish Sea**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**

406	104	One battery pack out of four showed intermittent connection.	0.02	0.05	0.2	0.8	Given that the above fault was not severe enough to cause an abort of a 104 km mission, it is highly probable that the AUV can "limp home" using only three battery packs over that distance. However, if the voyage is too long, three battery packs will contain insufficient energy to enable the AUV to "limp home" even with all non-navigation and non-collision-avoidance sensors turned off; this is a straight-forward energy calculation that does not require any statistical assumptions. Under ice shelf: If the voyage length is such that the AUV can "limp" out to the edge of the ice shelf while using only three battery packs, then recover as usual. If while running on three battery packs the AUV gets to within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8 and confidence is 3. If the battery energy is completely consumed and the AUV comes to rest and then drifts beyond the reach of an ROV, P(loss) is 1.0, confidence is 5. Under sea ice: If while running on three battery packs the AUV gets out beyond the shelf edge, then recover as usual. The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV. P(loss) is 0.20, confidence is 3. Coastal: If while running on three battery packs the AUV gets out beyond the shelf edge and into coastal waters then recover as usual. P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If while running on three battery packs the AUV gets out beyond the shelf edge and into open water then recover as usual. The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a functioning propulsion system on the AUV, or unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4. Note:May have suffient energy.
			4	3	3	3	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
406	104	Acoustic telemetry unit gave no replies.	0.26				Again, the above fault was not severe enough to cause an abort of a 104 km mission, when the AUV operated in its completely-autonomous mode. Suppose that this fault is not detected prior to the next deployment. If this fault is detected before the AUV submerges, presumably a "come home" command can be issued via the RF link. If not, at some point the ship will discover that it cannot communicate with the AUV once it is submerged, so it will then be useless to issue a "come home" command; it will be therefore necessary to allow the AUV to complete its intended mission, autonomously. Using Figure 6a of [1] as a basis for prediction of successful completion during the completely-autonomous mode, a subsequent voyage of length 100 km without the occurrence of a high impact fault is about 0.74, thus P(loss) is about 0.26 and confidence is probably 3.
			3				

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**

406	104	On surfacing first GPS fix was 1.2km out.	0.02	0.06	0.2		Here the AUV completed the voyage but the GPS gave a position 1.2 km from where the ship found the AUV. Thus the main problem is to locate the AUV based on its most-recent ded-reckoning position. This GPS "glitch" should not affect the ability of the AUV to "come home" nor the ability of the ship's crew to recover the AUV once it has been located. Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. So P(loss) will be somewhat higher than usual if the usual method of location the AUV is to use the most-recent GPS fix. Under ice shelf: The AUV does not use the GPS unit to get itself out from under the ice shelf so this case is not applicable. Under sea ice: If the ship can locate the AUV and get near to it, recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.2, confidence is 3. Coastal: If the ship can locate the AUV and get near to it, P(loss) is assessed higher than for the open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.06; confidence is 3. Open water: If the ship can locate the AUV and get near to it, the recovery should be straight-forward unless it is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4.
			4	3	3		
		Spikes in indicated motor rpm	0.36				Again this was not a critical fault since the voyage was completed successfully. Suppose that these spikes were not detected (by some self-diagnostic test which is routinely executed within the AUV) until part way through a mission, then the appropriate action would be to halt the mission and issue the "come home" command. Figure 6a of [1] shows that the probability of survival from a voyage of length 100 km without the occurrence of a high impact fault is about 0.74, thus P(loss) is about 0.26 and confidence is probably 3. Given that the above fault was not severe enough to cause an abort of a 104 km mission, perhaps for this type of fault the values of P(loss) should be increased by say 10% from those that would be predicted for any other length of voyage by Figure 6a.
			3				

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.4 3				Here is another case where the above fault was not severe enough to cause an abort of a 204 km mission, when the AUV operated in its completely-autonomous mode. Suppose that this fault was not detected prior to the next deployment. If this fault is detected before the AUV submerges, presumably a "come home" command can be issued via the RF link. If not, at some point the ship will discover that it cannot communicate with the AUV once it is submerged, so it will then be useless to issue a "come home" command; it will be therefore necessary to allow the AUV to complete its intended mission, autonomously. Using Figure 6a of [1] as a basis for prediction of successful completion during the completely-autonomous mode, a subsequent voyage of length 200 km without the occurrence of a high impact fault is about 0.60, thus P(loss) is about 0.40 and confidence is probably 3.
		Noise spikes on both channels of turbulence probe data.	0.4 3				Although this fault will affect the scientific value of the mission, this fault should not affect the ability of the AUV to "come home" provided that the AUV can receive that acoustic command, or, that the eventual mission time-out invokes a "come home" action. Figure 6a of [1] shows that the probability of survival from a voyage of length 200 km without the occurrence of a high impact fault is about 0.60, thus P(loss) is about 0.40 and confidence is probably 3.

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0.02	0.05	0.2	0.8	Suppose that this fault was not detected prior to the next deployment. The issue then becomes how long will the propeller keep turning sufficiently to provide forward propulsion to "come home" once the fault has been detected by some self-diagnostic test which is routinely executed within the AUV. Under ice shelf: If the propeller keeps turning until (a) the AUV gets to within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.8 and confidence is 3; otherwise (b) if the propeller stops and the AUV drifts beyond the reach of an ROV, P(loss) is 1.0, confidence is 5. Under sea ice: If the propeller keeps turning until the AUV gets out beyond the shelf edge then recover as usual. The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV. P(loss) is 0.20, confidence is 3. Coastal: If the propeller keeps turning until the AUV gets out beyond the shelf edge and into coastal waters then recover as usual. P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.05; confidence is 3. Open water: If the propeller keeps turning until the AUV gets out beyond the shelf edge and into open water then recover as usual. The recovery should be straight-forward, as long as the procedure to recover the AUV does not require a fully-functioning propulsion system on the AUV, or unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.02; confidence is 4. Note: Motor was not siezed.
			4	3	3	3	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem, this would show itself immediately on first dive.	0.01				Suppose that this fault was not detected prior to the next deployment. As long as the AUV does a dive check-out manoeuvre prior to the start of the mission, it is highly probable that this fault will be detected in open water and near the ship. Provided the AUV returns to the surface in open water, and is located, and that the ship can get to the AUV, the normal probability of loss in open water will apply, thus P(loss) is 0.01 and confidence is 4.
			4				

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
408	302.5	No telemetry from Acoustic telemetry unit.					Again, the above fault was not severe enough to cause an abort of a 300 km mission, when the AUV operated in its completely-autonomous mode. Suppose that this fault is not detected prior to the next deployment. If this fault is detected before the AUV submerges, presumably a "come home" command can be issued via the RF link. If not, at some point the ship will discover that it cannot communicate with the AUV once it is submerged, so it will then be useless to issue a "come home" command; it will be therefore necessary to allow the AUV to complete its intended mission, autonomously. Using Figure 6a of [1] as a basis for prediction of successful completion during the completely-autonomous mode, a subsequent voyage of length 300 km without the occurrence of a high impact fault is about 0.50, thus P(loss) is about 0.50 and confidence is probably 3. Note: Did not answer the question.
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.015				These problems could present difficulties during recovery; it is not stated whether or not in this situation the AUV would accept a "halt" command via the acoustic modem link. Supposing that the AUV could eventually be stopped in open water, and located, and that the ship can get to the AUV, then the usual probability for loss during recovery in open water could be increased by say 50% for this situation, thus P(loss) is 0.015 and confidence is 3.
			3				
		Still spikes on motor rpm that need investigating.					Again this was not a critical fault since a 300 km voyage was completed successfully. Suppose that these spikes were not detected (by some self-diagnostic test which is routinely executed within the AUV) until part way through a mission, then the appropriate action would be to halt the mission and issue the "come home" command. Figure 6a of [1] shows that the probability of survival from a voyage of length 300 km without the occurrence of a high impact fault is about 0.50, thus P(loss) is about 0.50 and confidence is probably 3. Given that the above fault was not severe enough to cause an abort of a 300 km mission, perhaps for this type of fault the values of P(loss) should be increased by say 10% from those that would be predicted for any other length of voyage by Figure 6a. Note: Question not answered.

Table 5 ***Terschelling*** **March 2007 – Deep water AUV reliability proving trials in Norway.**

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	Here is another case where the above fault was not severe enough to interfere with a "come home" command which was presumably issued via the RF link, and, the safe return of the AUV to near the ship when the AUV operated in its completely-autonomous mode. Suppose that this fault was not detected prior to the next deployment. If this fault is detected before the AUV submerges, presumably a "come home" command can be issued via the RF link. If not, at some point the ship will discover that it cannot communicate with the AUV once it is submerged, so it will then be useless to issue a "come home" command; it will be therefore necessary to allow the AUV to complete its intended mission, autonomously. Figure 6a of [1] can then be used as a basis for prediction of successful completion of any mission which operates using the completely-autonomous mode. For example, for any voyages of length 10 km or less, the probability of success without the occurrence of a high impact fault is at least 0.95, thus P(loss) is less than 0.05 and confidence is probably 3. Note: Question not answered.				
410	9	No acoustic telemetry or transponding.					Essentially the same as situations #44, 47, 51 and 54.
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	0.01	0.03	0.1		Assume that the alternate devices (acoustic pinger, strobe light, ARGOS transmitter) function correctly, or, that the AUV can be located visually. Under ice shelf: The mission was completed so this case is not applicable. Under sea ice: The AUV is near the ship but GPS antenna was damaged. Recovery through sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind. P(loss) is 0.1, confidence is 3. Coastal: The AUV is near the ship but P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.03; confidence is 3. Open water: The AUV is near the ship hence the recovery should be straight-forward unless complicated by waves, fog or strong tidal currents, hence P(loss) is 0.01; confidence is 4.
			4	3	3		

Table 5 ***Terschelling*** **March 2007 – Deep water AUV reliability proving trials in Norway.**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	0.01	0.03	0.1		Essentially the same as situation #56 (this is 57).
			4	3	3		
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	0.01				Supposing that the AUV could eventually be stopped in open water, and located, and that the ship can get to the AUV, then the usual probability for loss during recovery in open water should apply, thus P(loss) is about 0.01 and confidence is probably 4.
			4				

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	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.	0.05	0.1	0.2	0.9	If this fault was not detected prior to starting the mission, then once the fault is detected, issue a "come home" command via the acoustic modem. Then the success of the "come home" procedure will depend on the ability of the altimeter, depth sensor, upward-looking sonar, forward-looking sonar and obstacle-avoidance software to work in conjunction with the five remaining control surfaces to "come home" along a constant depth trajectory. Under ice shelf: If the AUV cannot extricate itself from under the ice shelf and ends up a long distance in from the edge, no recovery is possible, hence P(loss) is 1.0; confidence is 4 or 5. If the AUV ends up within say 300 m of the edge of the ice shelf, recovery using an ROV may be possible, hence P(loss) is 0.9; confidence is 3. Under sea ice: The AUV location may be known and recovery through the sea ice may be possible depending on how drastically the ice floes are pressed together by tide, water currents or wind, as long as the procedure to recover the AUV is not significantly impaired by the rudder actuator fault. P(loss) is 0.2, confidence is 3. Coastal: P(loss) is assessed higher than open water case as extra time on the surface exposes the AUV to additional hazards, hence P(loss) is 0.1; confidence is 3. Open water: The recovery should be straight-forward, as long as the procedure to recover the AUV is not significantly impaired by the rudder actuator fault, unless the recovery is complicated by waves, fog or strong tidal currents, hence P(loss) is 0.05; confidence is 4. Note: Serious fault in actuator.
			4	3	3	3	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system					One would expect that the simultaneous (or consecutive) failures of three harness connectors within the same mission would be a highly unlikely event. If the release of the emergency drop weight is in fact the issue, then the AUV may have difficulty coming to the surface. Assume that the control surfaces have sufficient control authority so that with some low forward speed the AUV can come to the surface, then the usual recovery procedures can be used. The success of the "come home" procedure while under the ice shelf will depend on the ability of the altimeter, depth sensor, upward-looking sonar, forward-looking sonar and obstacle-avoidance software to work in conjunction with the control surfaces in order to "come home" along a constant depth trajectory. Increase the usual value of P(loss) due to increased complexity of the recovery process due to the need for some forward speed during recovery. See the details in situations #24 and 31.
		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.					Here is another case where the above fault was not severe enough to interfere with a "come home" command which was presumably issued via the RF link, and, the safe return of the AUV to near the ship. Suppose that this fault was not detected prior to the next deployment; see the details in situation #54.
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.					Here the positive outcome was dependent on the fact that a timeout situation occurred and the "come to the surface" behaviour executed correctly. Otherwise one would have to wait for some other timeout to occur, or, battery depletion condition; for the details see situation #3.

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a "stay here" mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	0.5				Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools. Distance travelled was 15 km. Here P(loss) in open water and coastal waters is increased due to possibility of collision with the shore, submerged obstacles etc. if the obstacle detection and avoidance system does not function perfectly in shallow waters. It may be necessary to retrieve the AUV with the ROV if the ship and usual recovery equipment cannot operate near shore. This fault was, fortunately, not fatal to the mission. Perhaps P(loss) is as high as 0.5 for this situation and confidence is probably 2 out of 5.
			2				

Thomas Curtin

Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.001	0.001	0.01	0.7	At the surface, at a range of 1.5 km, the vehicle is likely to be located and recovered. Recovery under shelf ice is formidable, but at 1.5 km is within range of an ROV.
			4	4	4	4	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.001	0.001	0.01	0.7	Assuming the vehicle was ballasted positive at zero thrust, if the propeller was fouled it would come to the surface. At 1.5 km, it is likely to be located and recovered. Recovery under shelf ice is formidable, but at 1.5 km is within range of an ROV
			4	4	4	4	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.8	0.7	0.8	0.95	If it's out of control 15 km out, the chances of loss are pretty high unless it is still being tracked somehow. If the vehicle remains water tight (no seal leaks, collisions, …), the chances of ultimate recovery are slightly higher in coastal regions due to the likelihood of its being found on a beach .
			2	2	2	2	
386	26	GPS antenna failed at end of mission.	0.001	0.001	0.001	0.001	Assuming other locating devices (pinger, RF, strobe) were operational, and the mission was executed close to its programmed waypoints.
			4	4	4	4	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message (“homing lost”) being lost on the network.	0.01	0.01	0.01	0.8	Since vehicle was within range of acoustic communication and the mission was stopped, vehicle recovery is likely if locating devices (e.g., pinger) are working.
			2	2	2	2	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.0001	0.0001	0.0001	0.01	Assuming abort default is to surface.
			4	4	4	4	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0.0001	0.0001	0.001	0.01	This amplitude oscillation is low risk for loss unless operating near the surface, especially if the surface is ice covered.
			4	4	4	4	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.001	0.001	0.05	0.05	Not clear what is happening here. "Mission stopped" implies some default behavior which is known. At 3 km before diving , plotting an intercept should be straight forward.
			4	4	3	3	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.001	0.001	0.5	0.7	See note above. If vehicle is at depth (not clear from description) then the risk of loss in ice covered conditions is high as indicated. If the vehcile is at the surface then these probablilities should be reduced by at least an order of magnitude.
			3	3	2	2	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.0001	0.0001	0.001	0.001	Assuming RF systems working. 3 km is line of sight.
			4	4	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.01	0.01	0.02	0.03	By itself and within limits, this should not be a problem. Risk goes up, however, if combined with the next fault.
			3	3	3	3	
		GPS antenna flooded. No fix at end point of mission.	0.001	0.001	0.01	0.02	
			3	3	3	3	
		EM2000 swath sonar stopped logging during mission.	0	0	0	0	Unless there is adaptive control slaved to this sensor, this should not affect risk of loss.
			4	4	4	4	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.001	0.001	0.005	0.01	Pinger should still be audible, and wireless should connect at these ranges.
			4	4	4	4	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.001	0.001	0.005	0.005	Assuming pre-programmed mission is being executed as planned, and acoustic telemetry not being used to contol the vehicle in real time.
			4	4	3	3	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.005	0.005	0.4	0.8	Probabilities of loss go up with sea state. These estimates are for sea state 2 and below. For ice covered conditions, the assumption is that the mission abort resulted in the vehicle surfacing under the ice.
			3	3	4	4	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.01	0.01	0.8	1	Same as above, only at greater range.
			3	3	4	4	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.002	0.003	0.001	0.001	Probabilities of loss go up with the magnitude of the currents, of course. Therefore, coastal slightly higher, under-ice slightly lower.
			4	4	4	4	
397	4	Main lifting lines became loose, could have jammed motor.	0.001	0.001	0.001	0.001	
			4	4	4	4	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.0001	0.0001	0.0002	0.0005	Probabilities of loss go up with the magnitude of the error in incorrect positions. Description implies that the errors were not egregious.
			4	4	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.001	0.001	0.0001	0.0001	If recovery transmissions working properly, the increased risk here lies mostly in the chance of "grounding" on the bottom or under the ice due to inaccurate navigation. Under the ice, the ADCP up should work well (not be noisy) even though mis-configured.
			3	3	4	4	
		Damaged on recovery, “moderately serious” to sternplane, shaft bent.	0.01	0.01	0.01	0.01	There is always a risk of loss on recovery. This incident is not unusual.
			4	4	4	4	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.05	0.05	0.9	1	Assuming vehicle stuck on surface with locating devices working.
			3	3	4	4	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.05	0.05	0.9	1	Same as above.
			3	3	4	4	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.01	0.01	0.1	0.3	Indication is motor seal compromised under pressure.
			2	2	2	2	
		Only one position fix from tail mounted ARGOS transmitter.	0.01	0.01	0.01	0.01	Risk depends on the distance between the position fix and the recovery vessel at the time of the fix. Also the operational status of other locating devices (GPS, pinger, …)
			2	2	2	2	
		GPS antenna damaged on recovery.	0	0	0	0	
			5	5	5	5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.01	0.01	0.01	0.01	Assuming "on surface" does not mean on surface under ice. Sea state comments above apply.
			4	4	4	4	
		Took over 1 hour to get GPS fix at final waypoint.	0	0.001	0	0	
			4	4	4	4	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.01	0.01	0.1	0.3	
			2	2	2	2	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	0.001	0.001	0.1	0.1	Risk here is that vehicle surfaces pre-maturely. Problem under ice.
			3	3	3	3	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0.001	0.001	0.01	0.01	"Potential" = ?
			2	2	2	2	
		Propeller speed showed same problem as on m402 and 403.	0.01	0.01	0.1	0.3	
			2	2	2	2	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	0	0	0	0	
			4	4	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	0.04	0.04	0.04	0.04	
			3	3	3	3	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0	0	0	0	
			4	4	4	4	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0	0	0	0	
			4	4	4	4	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0	0	0	0	Since fault found pre-launch and fixed, risk is negligible. If fault not found or repair unreliable, the risk is higher.
			5	5	5	5	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0	0	0	0	Since fault found pre-launch and fixed, risk is negligible. If fault not found or repair unreliable, the risk is higher.
			5	5	5	5	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.01	0.01	0.1	0.3	
			2	2	2	2	
		Current spikes of 3A and voltage drops in first part of mission.	0.01	0.01	0.1	0.3	
			2	2	2	2	
		Propulsion motor failed 500V Megger on recovery on windings to case.	0.01	0.01	0.1	0.3	
			2	2	2	2	
		One battery pack out of four showed intermittent connection.	0.05	0.05	0.1	0.3	
			2	2	2	2	
		Acosutci telemetry unit gave no replies.	0.005	0.005	0.01	0.01	
			2	2	2	2	
		On surfacing first GPS fix was 1.2km out.	0	0	0	0	
			5	5	5	5	
		Spikes in indicated motor rpm	0.01	0.01	0.1	0.3	
			2	2	2	2	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.005	0.005	0.01	0.01	
			2	2	2	2	
		Noise spikes on both channels of turbulence probe data.	0	0	0	0	
			5	5	5	5	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0	0	0	0	Since fault found pre-launch and fixed, risk is negligible. If fault not found or repair unreliable, the risk is higher.
			5	5	5	5	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem, this would show itself immediately on first dive.					Not sure how to interpret this.
		No telemetry from Acoustic telemetry unit.	0.005	0.005	0.01	0.01	
			2	2	2	2	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0	0.001	0	0	
			5	5	5	5	
		Still spikes on motor rpm that need investigating.	0.01	0.01	0.1	0.3	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	0.005	0.005	0.01	0.01	
			2	2	2	2	
410	9	No acoustic telemetry or transponding.	0.005	0.005	0.01	0.01	
			2	2	2	2	
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	0.001	0.001	0.01	0.02	
			3	3	3	3	
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	0.001	0.001	0.01	0.02	
			3	3	3	3	
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	0	0	0	0	
			4	4	4	4	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	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.	0.1	0.1	0.5	0.9	
			3	3	3	3	
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system	0.05	0.05	0.1	0.2	
			3	3	3	3	
		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.	0.005	0.005	0.01	0.01	
			2	2	2	2	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.	0.01	0.01	0.8	0.9	
			3	3	3	3	
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a “stay here” mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	0.01	0.1	0.01	0.01	
			2	2	2	2	

Dana Yoerger

Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	0.1	0.2	0.5	1	I have least confidence in my estimates for sea ice, as that type of environment can vary significantly. for example, leads might be more or less prevalent. Likewise underice currents can tend to push a floating vehicle along the underside of the ice until a lead is reached. This explains several "miraculous" recoveries with Singh and Bellingham's vehicles in the ice 0.1 The response to this type of problem is pretty routine, proper surface localization aids are critical, however. Strobes, RF beacons, GPS/Iridium systems help avoid loss 0.2 similar to the open case, but coastal setting could have higher surface currents and more difficult destinations for a drifting vehicle. Timely recovery could be necessary. 0.5 This could be big trouble, but open areas could provide access, and drifting vehicle often find such openings 1.0 big trouble, abort to the surface probably means the vehicle will not be recoverable.
			5	5	3	5	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	0.1	0.2	0.5	1	0.1 provided the vehicle is positively buoyant (drop weight?), then in open water this problem should not prevent recovery 0.2 same analysis as for the previous problem 0.5 the tangled propellor does not make any more problems than for the previous abort scenario 1.0 same as above
			5	5	3	1	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	0.3	0.4	0.5	0.8	0.3 If this problem cannot be diagnosed by the autonomous system or from topside monitoring, the vehicle could travel a very long distance in an unknown direction. Long range surface location aids (gps/iridium or similar) would be critical 0.4 more potential problem scenarios near the coast, the vehicle could end up running aground which could make the vehicle harder to find and complicate the recovery considerable 0.5 Sea ice would complicate localizing the vehicle provided it ascended due to positive buoyancy 0.8 Murphy's law would say the uncontrolled motion would take the vehicle to a place where it could not be recovered.
			5	5	3	5	

Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
386	26	GPS antenna failed at end of mission.	0.1	0.2	0.2	0.2	usually, GPS failure at the end will not increase probability of loss as the vehicle will home and be recovered normally. This failure creates problems only when the vehicle can't home. 0.1 this means short range RF beacon and strobe are the only recovery aids, they have a max range of a few km 0.2 again loss of GPS to satellite comms system means only local recovery aids are available 0.2 Reliance on local surface localization aids is more difficult here
			4	4	4	4	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message (“homing lost”) being lost on the network.	0.1	0.1	0.5	0.5	0.1 vehicle is already near the vessel, simple localization aids (rf beacon, strobe) are sufficient 0.1 My logic is the same as for the open water case 0.5 An uncontrolled ascent in sea ice means that recovery requires some good fortune. 0.5 I assume the vehicle is out from under the shelf, so the probablity is similar to the open ice scenario
			5	5	4	4	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	0.1	0.2	0.5	1	I am assuming that the surface localization aids are independent of the logger, so this failure has the same implication as 384, first failure. 0.1 I rate this the same as the previous example (387, first failure) 0.2 (see 384, first failure) 0.5 (see 384, first failure) 1.0 (see 384, first failure)
			5	5	4	4	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	0.1	0.3	0.5	1	same as above, depth instability would not effect the function of the surface localization aids 0.1 (see previous) 0.3 (see previous) 0.5 (see previous) 1.0 (see previous)
			5	5	4	4	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	0.3	0.5	0.7	1	The prospect of the vehicle driving at high speed in an improper direction can significantly increase the likelihood of loss, depending on the type of surface localization aids available. Strobes and RF beacons have a range on he order of a few km, depending on weather. A gps/iridium combination significantly reduces the likelihood of loss in this circumstances. Likewise, a timeout in the homing process would also reduce the likelihood of loss in this scenario. 0.3 (see comment about timeout)
			5	5	4	4	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	0.3	0.5	0.7	1	Again, a high-speed drive-off is very scary for a vehicle with the speed and endurance of Autosub. Does the homing mode have a timeout? If so, the consequences of this failure would be less severe. 0.3 (see comment about timeout)
			3	3	4	4	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	0.2	0.2	0.2	0.2	A high-speed driveoff coupled with a loss of acoustic comms could result in high likelihood of loss, depending on any other failures. For this evaluation, I have assumed no other failures.
			3	3	3	3	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	0.1	0.1	0.2	0.3	reduced navigational accuracy increases the possibility that the vehicle will not be able to home at the end of the mission, but this is not very likely
			3	3	3	3	
		GPS antenna flooded. No fix at end point of mission.	0.05	0.1	0.2	0.2	I am assuming the vehicle has a gps/RF or satellite combination. The loss of GPS increases the likelihood that the vehicle will not be located on the surface, which is more serious for the under ice missions.
			3	3	3	3	
		EM2000 swath sonar stopped logging during mission.	0	0	0	0	EM2000 is not used in real-time (I think), so its loss would not increase likelihood of loss
			4	4	4	4	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	0.1	0.2	0.3	0	same as 391, failure 2 a
			3	3	3		
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	0.2	0.2	0.2	0.2	same as 389, failure 3
			3	3	3	3	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	0.1	0.2	0.4	0.8	such a failure could cause the vehicle to stop whenever the float came out (i.e. some random point in the mission). If the vehicle is not under ice, then this failure simply causes a random abort, in which case the reliability of the long-range surface localization aids determines the risk. Under ice (sea or shelf), this results in very significant likelihood of loss.
			4	4	4	4	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	0.1	0.2	0.4	0.8	same as 394
			4	4	4		

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	0.1	0.1	0.2	0.3	reduced navigational accuracy, similar to ADCP problem, 391 #1
			3	3	3	3	
397	4	Main lifting lines became loose, could have jammed motor.	0.1	0.2	0.3	0.5	I am assuming the motor that could jam is the main propulsion motor. The likelihood of loss is the same as for any other random abort. 0.5. Probability of loss is the same as the probability of jamming the motor (propulsion motor?)
			4	4	4	4	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	0.05	0.05	0.05	0.05	the real risk is not very big, the problem was more in the operator's perception than in the actual vehicle function.
			4	4	4	4	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	0.1	0.1	0.3	0.5	inaccurate vehicle localization does not create large likelihood of loss in open or coast cases, provided the long range surface localization aids work properly. Under sea or shelf ice, bad nav could mean that the vehicle does not home properly, at great risk to the vehicle.
			4	4	4	4	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	0	0	0	0	not increase in probability of loss, although possibly no more dives for the cruise
			5	5	5	5	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	0.1	0.1	0.5	0.9	This is equivalent to a random stop in the mission. In open or coast scenarios, this does not create great risk if the surface localization aids work. Under sea or shelf ice, this creates much larger risk, as the vehicle will not home to the ship.
			4	4	4	4	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	0.1	0.1	0.5	0.9	same as 402, failure 1
			5	5	5	5	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	0.1	0.1	0.5	0.9	another failure at a random time during the mission.
			5	5	5	5	
		Only one position fix from tail mounted ARGOS transmitter.	0.1	0.1	0.2	0.2	reduced reliability of the long range surface localization increases risk for all missions, especially in ice when other surface localization methods may not work.
			4	4	4	4	
		GPS antenna damaged on recovery.	0	0	0	0	no increased risk for the dive in question, some increased risk for the next dive as the GPS antenna will be replaced and won't be as thoroughly tested.
			5	5	5	5	

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	0.05	0.05	0.05	0.05	any departure from normal recovery procedure increases likelihood of loss, especially if the weather is bad.
			3	3	3	3	
		Took over 1 hour to get GPS fix at final waypoint.					
			4	4	4	4	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	0.1	0.1	0.5	0.9	failure at a random time in the mission (see 402, first failure)
			4	4	4	4	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. “If not spotted, could have dropped out during mission”, considered low probability of distortion ***and*** not checked.	0.1	0.1	0.5	0.9	if not found and if the abort weight was actually lost, this is equivalent to a mission failure at a random time (see 403, first failure)
			4	4	4	4	
		Pre-launch, potential short circuit in motor controller that could stop motor.	0.1	0.1	0.5	0.9	If this happened during the mission, it would constitute a random mission failure, I've assumed it happened subsea
			4	4	4	4	
		Propeller speed showed same problem as on m402 and 403.	0.1	0.1	0.5	0.9	failure at a random time in the mission (see 402, first failure)
			4	4	4		
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	0	0	0	0	does not threaten vehicle, but could have serious consequences for the science program
			5	5	5	5	
		M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	0.05	0.05	0.05	0.05	same as 403, failure 1
			3	3	3	3	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	0.05	0.05	0.05	0.05	the loss of the sternplane doesn't increase the risk of losing the vehicle, but the trapped lift line counts as a departure from the nominal recovery procedure, see 403, failure 1
			3	3	3	3	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	0	0	0	0	does not threaten vehicle, but could have serious consequences for the next dive if proper repairs not made.
			4	4	4	4	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	0	0	0	0	problem found before launch, so vehicle safety not effected.
			5	5	5	5	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	0	0	0	0	problem found before launch, so vehicle safety not effected.
			5	5	5	5	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	0.05	0.05	0.4	0.6	this could result in a random failure at some point during the mission.
			3	3	3	3	
		Current spikes of 3A and voltage drops in first part of mission.					sorry, I can't judge how this could put the vehicle in jeopardy
			1	1	1	1	
		Propulsion motor failed 500V Megger on recovery on windings to case.	0.1	0.1	0.3	0.6	this condition could result in a random mission failure, much more significant under ice.
			4	4	4	4	
		One battery pack out of four showed intermittent connection.	0.1	0.1	0.5	0.9	this could result in a mission being aborted early, nearly the same as a random mission failure
			4	4	4	4	
		Acosutci telemetry unit gave no replies.	0	0	0	0	I'm not sure how the loss of the acoustic telemetry uplink could put the vehicle at risk
			1	1	1	1	
		On surfacing first GPS fix was 1.2km out.	0.01	0.01	0.01	0.01	at worst, this could result in the vehicle reporting its position improperly, but other surface localization aids should allow vehicle to be located.
			4	4	4	4	
		Spikes in indicated motor rpm	0.01	0.01	0.01	0.01	I don't understand how the vehicle would handle spikes in rpm

			3	3	3	3	

Table 4 ***Terschelling*** **July 2006 – Turbulence studies in the Irish Sea**							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	0.05	0.05	0.05	0.05	I'm not sure how the loss of the acoustic telemetry uplink could put the vehicle at risk, if the vehicle can't be tracked, many other failures could be more significant.
			1	1	1	1	
		Noise spikes on both channels of turbulence probe data.	0	0	0	0	no impact on probability of vehicle loss. Loss of science data significant in terms of mission goals, but not safety.
			4	4	4	4	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	0	0	0	0	This problem was diagnosed so it did not put the vehicle at risk. However, this could mean that the bearing could wear prematurely, which could result in a problem during a long mission.
			3	3	3	3	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	0.01	0.01	0.01	0.01	this problem will not put the vehicle at risk because the dive would abort soon after launch
		this would show itself immediately on first dive.	3	3	3	3	
		No telemetry from Acoustic telemetry unit.	0	0	0	0	same as 406 error 5
			1	1	1	1	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	0.01	0.01	0.01	0.01	loss of control on the surface could make vehicle recovery more risky. Damage more likely than loss, however
			3	3	3	3	
		Still spikes on motor rpm that need investigating.	0	0	0	0	same as 407, error 2
			4	4	4	4	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.

			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	0.05	0.05	0.05	0.05	same as 407, error 1
			1	1	1	1	
410	9	No acoustic telemetry or transponding.	0.05	0.05	0.05	0.05	same as 407, error 1
			1	1	1	1	
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	0.05	0.1	0.2	0.2	same as 391, error 2
			3	3	3	3	
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	0.05	0.1	0.2	0.2	same as 391, error 2
			3	3	3	3	
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	0.01	0.01	0.01	0.01	same as 408, error 2
			3	3	3	3	
415	6	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.	0.1	0.1	0.5	0.9	the consequences of this failure depend on how long into the mission it occurs. If it happened immediately, then its an early failure like 408 #2. If it could happen at any time (I've assumed that here), then it's a random failure like
			4	4	4	4	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Estimated probability of leading to loss (on scale of 0 to 1), with confidence level 1 (lo) to 5 (hi) for each estimate in the grey boxes.				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system	0.1	0.1	0.5	0.9	I'm uncertain about the consequences of losing the power connector to the abort system. Does it have a redundant battery? Would the abort system work without external power? I have considered this to be a random failure
			4	4	4	4	
		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.	0.05	0.05	0.2	0.4	if the mission went as planned with no need to abort, then this problem would have no effect. But if an abort was required beyond 1200m, this would be a big problem. I rate this as 1/2 as likely to result in vehicle loss as a random failure.
			3	3	3	3	
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.	0.05	0.05	0.2	0.4	similar to problem in 415
			3	3	3	3	
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a “stay here” mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	0.05	0.05	0.05	0.05	this failure could make the vehicle recovery depart from the expected process, which would increase the likelihood of vehicle loss equally for all cases. I'm assuming an acoustic abort would work normally.
			3	3	3	3	

--- ANNEX B – EXPERTS RESPONSES ---

Robert Bogucki

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	S	S	S	L	Shelf ice: relatively quick occurrence of the failure increases chance of recovery. What's the default behavior after aborting mission when under ice cover? Any attempts to return?
			0.95	0.95	0.6	0.6	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	S	S	L	L	How likely is the entanglement given the sub's geometry and range of manouevres? Once immobilized under ice, very slim chances of recovery. In other environments, much depends on how the software handles stuckness.
			0.75	0.75	0.55	0.95	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	S	S	L	L	Insufficient information to make prognoses: what sort of side-effect? Are the failsafe mechanisms (abort radius, timeouts) still in operation? Assuming abort by acoustic command is possible.
			0.85	0.9	0.75	0.99	
386	26	GPS antenna failed at end of mission.	S	S	S	S	Assuming it's a problem of tracking and recovery of the sub which already surfaced after the mission, and acoustic tracking is available.
			0.95	0.85	0.8	0.7	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	S	S	L	L	Timely abort of mission increases chance of recovery, even from under ice.
			0.95	0.95	0.5	0.75	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	S	S	S	L	Assumed comms reestablished after the abort. Coastal area more dangerous for retrieval than open sea.
			0.99	0.95	0.65	0.75	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	S	S	S	S	Attitude and inclination variations may affect dead reckoning quality. Is an undersea tracking system utilized (reduced confidence)? In case of a close-to-bottom tracking mission segment increased risk of getting stuck or collision.
			0.9	0.75	0.9	0.6	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	S	S	S	L	Shelf ice – loss near certain if AUV gets trapped under ice.
			0.9	0.9	0.6	0.85	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	S	S	L	L	The homing mode is surface or underwater? The surface behavior will most likely continue until battery reserves are depleted or an obstacle is encountered. Shore acts as safety net to some degree. Successful recovery greatly depends on rapid pursuit and radio communication range and robustness. In Sea Ice environ increased potential for damage.
			0.9	0.6	0.55	0.95	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	S	S	S	L	Provided positive buoyancy and mission abort function are present,
			0.85	0.85	0.5	0.95	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?

Mark how confident you are in each grey box (on a scale 0.5 to 1).

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	S	S	S	S	
			0.98	0.98	0.8	0.65	
		GPS antenna flooded. No fix at end point of mission.	S	S	S	S	Assuming all else went well and sub is on surface.
			0.95	0.99	0.85	0.8	
		EM2000 swath sonar stopped logging during mission.	S	S	S	S	Unless the sonar output is integrated into the navigational solution, or used for an adaptive explicitly used for those purposes, sowill not affect navigation/recovery, unless sonar malfunction triggers an undetected software bug (memory leak, unhandled timeout) leading to a crash.
			1	1	0.98	0.98	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	S	S	S	L	Not a showstopper in all environments except shelf ice.
			1	1	0.85	0.55	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	S	S	S	L	Icy cover may cut out radio.
			0.85	0.8	0.5	0.7	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	S	S	L	L	Immobilized and damaged sub, much harder recovery. Insufficient information about exception handling: would a chain of software failures occur resulting in loss of command/telemetry also?
			0.85	0.85	0.75	1	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	S	S	L	L	Immobilized sub.
			0.75	0.75	0.75	0.99	
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	S	S	S	S	Shouldn't be a showstopper if the failure was noticed and corrected.
			0.99	0.99	0.98	0.97	
397	4	Main lifting lines became loose, could have jammed motor.	S	S	L	L	Likelihood of jamming motor the deciding factor (manouevres, currents and wave action)
			0.85	0.85	0.55	0.6	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	S	S	S	S	Assuming operators aborted in a location allowing for easy retrieval
			0.99	0.99	0.95	0.9	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	S	S	S	L	
			0.999	0.999	0.99	0.55	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	S	S	S	S	
			0.99	0.99	0.95	0.95	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	S	S	S	L	
			0.96	0.96	0.7	0.7	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems. `	S	S	S	L	
			0.97	0.97	0.8	0.55	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	S	S	S	S	
			0.97	0.97	0.85	0.65	
		Only one position fix from tail mounted ARGOS transmitter.	S	S	S	S	
			0.99	0.99	0.89	0.85	
		GPS antenna damaged on recovery.	S	S	S	S	
			0.999	0.999	0.95	0.95	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	S	S	S	S	
			0.99	0.99	0.98	0.98	
		Took over 1 hour to get GPS fix at final waypoint.	S	S	S	S	
			0.9	0.8	0.8	0.9	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	S	S	S	S	
			0.9	0.9	0.75	0.5	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. “If not spotted, could have dropped out during mission”, considered low probability of distortion ***and*** not checked.	S	S	S	L	
			0.97	0.97	0.65	0.7	
		Pre-launch, potential short circuit in motor controller that could stop motor.	S	S	S	S	
			0.95	0.95	0.9	0.85	
		Propeller speed showed same problem as on m402 and 403.	S	S	S	S	
			0.9	0.9	0.75	0.5	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	S	S	S	S	
			0.99	0.99	0.99	0.99	

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**

Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?

Mark how confident you are in each grey box (on a scale 0.5 to 1).

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
404	75	M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	S	S	S	S	
			0.95	0.95	0.92	0.92	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	S	S	S	S	
			0.93	0.93	0.9	0.9	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	S	S	S	S	
			0.99	0.99	0.98	0.98	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	S	S	S	S	
			0.999	0.999	0.99	0.98	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	S	S	S	S	
			0.98	0.98	0.97	0.96	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	S	S	S	S	
			0.98	0.98	0.92	0.85	
		Current spikes of 3A and voltage drops in first part of mission.	S	S	S	S	
			0.97	0.97	0.97	0.97	
		Propulsion motor failed 500V Megger on recovery on windings to case.	S	S	S	S	
			0.95	0.95	0.93	0.92	
		One battery pack out of four showed intermittent connection.	S	S	S	S	
			0.97	0.97	0.97	0.97	
		Acosutci telemetry unit gave no replies.	S	S	S	S	
			0.8	0.8	0.8	0.65	
		On surfacing first GPS fix was 1.2km out.	S	S	S	S	
			0.99	0.99	0.95	0.9	
		Spikes in indicated motor rpm	S	S	S	S	
			0.98	0.98	0.98	0.98	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	S	S	S	S	
			0.8	0.8	0.8	0.65	
		Noise spikes on both channels of turbulence probe data.	S	S	S	S	
			0.999	0.999	0.999	0.999	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	S	S	S	S	
			0.99	0.99	0.95	0.85	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	S	S	S	L	
		this would show itself immediately on first dive.	0.95	0.95	0.75	0.65	
		No telemetry from Acoustic telemetry unit.	S	S	S	L	
			0.8	0.8	0.8	0.65	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	S	S	S	S	
			0.9	0.9	0.85	0.55	
		Still spikes on motor rpm that need investigating.	S	S	S	S	
			0.98	0.98	0.98	0.9	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?				
			Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.					
410	9	No acoustic telemetry or transponding.					
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.					
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.					
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.					

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	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.					
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system					

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.

Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?

Mark how confident you are in each grey box (on a scale 0.5 to 1).

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
415	6	Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.					
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.					
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a "stay here" mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.					

Neil Bose

Table 1 ***Discovery*** **295T July 2005 – AUV and other trials in the SW Approaches.**

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	S	S	L	L	Surface abort normal for open water missions so survival expected. Under shelf ice would result in loss. Under sea ice vehicle may have a chance of recovery.
			1	1	0.75	1	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	S	S	L	L	As above
			1	1	0.75	1	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	S	S	L	L	Survival or loss depends on "what happens next" in mission plan, so loss or survival would not be 100% sure.
			0.9	0.9	0.5	0.9	
386	26	GPS antenna failed at end of mission.	S	S	S	S	Vehicle should be where it is expected at the end of the mission. Surface homing can be used to locate it.
			0.999	0.999	0.999	0.9	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	S	S	L	S	Homing assumes an "end of mission" in open water or under sea ice, but not under shelf ice. Under sea ice, homing failure may cause an abort under the ice and survival is doubtful. Under shelf ice, vehicle would be in open water at the end of the mission and survival is likely.
			0.9	0.9	0.7	0.9	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**			Note I have answered this and others as though there could be shelf ice here; not possible in this era at this location!!				
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?				
			Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	S	S	S	S	Survival expected since within 4 minutes of dive vehicle is likely to surface in open water and be recovered. In sea ice, if the vehicle dives from a lead it may be under ice. However mission length is only 500m so loss may occur if vehicle starts mission very close to the ice edge.
			1	1	0.5	0.5	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	S	S	S	S	The level of instability, +/- 1m is unlikely to affect survival or loss of vehicle since vehicle is unlikely to operate within this depth range of an obstacle. Faults should be set to abort mission if proximity to bottom or ice falls below a certain value.
			1	1	1	1	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	S	S	L	L	Survival expected in open water or coastal (recovery might be difficult in some coastal loactions). Loss is likely in under ice operation since it may be difficult in sea ice and impossible under shelf ice for the ship to follow. Some element of survival is likely depending on which direction the vehicle homes in to - if towards open water survival may be possible.
			1	0.9	0.75	0.9	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	L	L	L	L	Loss expected, but in open water or coastal the mission might be aborted by acoustic command if within range (mission length is 3km only so eroor may be noticed while vehicle is nearby). Same may result under sea ice, but vehicle is unlikely to be recovered under shelf ice.
			0.75	0.5	0.85	0.999	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	S	S	S	S	Not sure I understand this one, but if problem is with ship side of the acoustic telemetry receiver then vehicle mission should proceed as planned and recovery be made even if it cannot be monitored acoustically during the mision - at least unless something else goes wrong.
			0.95	0.95	0.95	0.95	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**			Note I have answered this and others as though there could be shelf ice here; not possible in this era at this location!!				
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?				
			Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	S	S	S	S	ADCP range of 360m is maximum expected in any case? Result depends on depth of water of mission. In open water AUV should end mission, get a GPS fix and report position by radio telemetry, so survival likely. In a coastal area reduced accuracy of navigation may mean the vehicle aborts its mission prematurely and it may be in a difficult to recover position. Under ice or under shelf ice there is reduced likelihood that vehicle will suvive over this length of mission.
			0.9	0.75	0.6	0.5	
		GPS antenna flooded. No fix at end point of mission.	S	S	S	S	Survival likely, but it may be difficult to find the vehicle. After a 31 km mission the vehicle may be some distance from where it is expected. Survival depends on effectiveness of radio direction finding survival beacon system.
			0.99	0.99	0.9	0.9	
		EM2000 swath sonar stopped logging during mission.	S	S	S	S	Should not affect survival of vehicle. The mission will produce no data, but it should complete its mission and be recovered.
			1	1	1	1	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	S	S	S	S	After a mission of this length mission should be designed to end in a region of open water that is at least of this extent, although the navigable waters may be limited in coastal regions and leads may move in sea ice area - hence the choice of probabilities. Vehicle should be located by RDF beacon system.
			0.99	0.9	0.75	0.9	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	S	S	S	S	This affects monitoring of vehicle position during the mission and the ability to acoustically abort or change the mission, but if mission executes according to plan, survival is likely.
			0.99	0.99	0.99	0.99	

Table 2 ***Terschelling*** **May 2006 – AUV trials in the SW Approaches.**			Note I have answered this and others as though there could be shelf ice here; not possible in this era at this location!!				
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	S	S	L	L	Loss is likely under shelf ice and may occur under sea ice as vehicle may abort its mission in an area where it cannot be recovered. The vehicle is likely to be recovered in open water or coastal although there is an element of risk depending on where the vehicle is (say relative to the coast). The mission length of 3km means that it should be nearby to the recovery vessel.
			0.95	0.95	0.9	1	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	S	S	L	L	Similar to above but mission length longer affecting probabilities.
			0.9	0.9	0.99	1	
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	S	S	L	L	In open water vehicle can surface and be reprogrammed. In coastal areas significant unexpected drift may result in the vehicle being in a position that makes recovery difficult. In sea ice it may not be possible to stop the mission in a location wher there is an open water lead; same under shelf ice, but more severe.
			1	0.9	0.5	0.8	
397	4	Main lifting lines became loose, could have jammed motor.	S	S	L	L	Survival likely in open water although vehicle may be disabled; in coastal areas again this may occur in a location where recovery is difficult. Under sea ice the vehicle could end up under a pressure ridge where recovery is unlikely; under shelf ice the vehicle is most likely to be lost unless by a chance the rope does not snag the prop.
			1	0.95	0.99	0.999	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	S	S	L	L	Difficult! Operators are unlikely to abort the mission unless recovery is likely. However, if vehicle is under ice in a location where it was not expected to be then the mission may be aborted in a location where recovery is impossible - more likely operators would "give the mission the benefit of the doubt" and there is a chance that the later waypoints are correct and that the vehicle is able to make its way to the correct final location without coming to grief on the way.
			1	0.99	0.5	0.5	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	S	S	S	S	Survival in open water or coastal depends on whether the RDF beacon system can work over the range at the end of the mission (7.5km x 1.5 error). Under ice the upward looking ADCP might track drift relatively accurately, but perhaps less so for the sea ice.
			0.5	0.5	0.8	0.9	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	S	S	S	S	Vehicle survives but has to be repaired. Could be a serious repair.
			1	1	1	1	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.	L	L	L	L	This is a very long mission and fault occurs well into the mission. On such a long mission, an Iridium type interogation system may be required to ensure that the vehicle can be found and can report its lat/long to the operators after an abort. Survival then would be likely in open water or even coastal. If reliance is on RDF beacons location may be difficult. Loss would be expected under shelf ice, but no one has dared a mission of this length under shelf ice yet; this would be an extremely risky mission also under sea ice.
			0.8	0.9	0.95	1	
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	L	L	L	L	As above. Again survival possible if satellite communications are fitted. In coastal areas a complicated coastal mission is likely to lead to increased chance of loss.
			0.8	0.9	0.95	1	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	L	L	L	L	As above. Perhaps slightly lower probability of loss, but it depends what abort/fault sequence might be programmed following this event.
			0.75	0.85	0.9	0.99	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?

Mark how confident you are in each grey box (on a scale 0.5 to 1).

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
402	274	Only one position fix from tail mounted ARGOS transmitter.	S	S	S	S	This depends on context and I am unsure of result. I have been assuming the vehicle has no satellite positioning system, but of course this shows it has Argos so the vehicle can be found from a distance. If the mission completes as planned and the vehicle is where it is expected to be then it will found say using RDF beacons. But for a mission of this length satellite positioning is likely to be necessary due to the error in positioning at the end of the mission. Effectively since the ARGOS is not working, then the vehicle is operating as if it doesn't have satellite positioning.
			0.8	0.8	0.8	0.8	
		GPS antenna damaged on recovery.	S	S	S	S	Survival likely since damage occurs on recovery. Antenna can be replaced prior to next mission.
			1	1	1	1	
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	S	S	L	L	Under shelf ice this would lead to loss. In open water it is most likely the vehicle would be recovered since it could be located using ARGOS. In a coastal area if a mission of this length could be done then again survival is likely. Under sea ice it depends if the vehicle surfaces under ice or in a lead.
			0.95	0.8	0.95	1	
		Took over 1 hour to get GPS fix at final waypoint.	S	S	S	S	The vehicle should be positioned using the ARGOS even if it is unable to report its GPS coordinates.
			0.95	0.95	0.95	0.95	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	S	S	S	S	Results would be the same as in 402 if the fault had not been noticed. Here the vehicle is being tested so it is onboard and "safe".
			1	1	1	1	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	S	S	L	L	Survival likely in open water and coastal. Under ice there is a high chance of loss with premature surfacing of vehicle.
			0.99	0.95	0.95	1	
		Pre-launch, potential short circuit in motor controller that could stop motor.	L	L	L	L	Results would be the same as in 402. I have left the same probabilities, but they might be less as mission length is shorter.
			0.75	0.85	0.9	0.99	
		Propeller speed showed same problem as on m402 and 403.	L	L	L	L	Results would be the same as in 402.
			0.75	0.85	0.9	0.99	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	S	S	S	S	Does not affect vehicle survival/loss. Data will be lost.
			1	1	1	1	
		M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	S	S	S	S	Survival likely and the same in all cases since vehicle is located and close to ship. But loss is possible should the situation cause damage to occur to the vehicle from collision with the ship and/or its propellers.
			0.9	0.9	0.9	0.9	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.	S	S	S	S	As above.
			0.9	0.9	0.9	0.9	
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	S	S	S	S	Assumed occurred on recovery. Does not significantly affect survival but has to be replaced prior to redeployment.
			1	1	1	1	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.	S	S	S	S	As fault found pre launch, survival would result. Survival also likely if deployed since the transducer is a tracking device and if no response is found after launch, mission could have been aborted. In this case with a mission of only 2.5km, mission could be completed without incident even if the transducer was not operable.
			1	1	1	1	
		Fault found pre-launch, starboard lower rudder and sternplane loose.	S	S	S	S	Again fault found prelaunch and fixed. If this occurred after launch, erratic course and depth keeping could result. Under ice this might result in loss so in that case the response would be modified.
			1	1	1	1	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	S	S	L	L	Survival expected in open water and coastal, but loss is likely under ice since on a mission of this length, the vehicle may not be able to complete its mission and may have to abort prematurely; under ice that could/would result in loss.
			0.999	0.999	0.9	0.95	
		Current spikes of 3A and voltage drops in first part of mission.	S	S	L	L	Survival expected in open water and coastal, but loss expecetd under shelf ice and possible loss under sea ice.
			0.999	0.999	0.9	0.99	
		Propulsion motor failed 500V Megger on recovery on windings to case.	S	S	L	L	If occurring during the mission this would likely lead to loss under shelf ice and possible loss under sea ice.
			0.999	0.999	0.9	0.99	
		One battery pack out of four showed intermittent connection.	S	S	S	S	Vehicle can still operate but if insufficient energy for mission, this may cause loss under ice.
			0.999	0.999	0.5	0.5	
		Acoustic telemetry unit gave no replies.	S	S	S	S	Depends on need to communicate during mission. If mission exceutes correctly, the vehicle should complete its mission correctly. If something goes wrong, or a modification is needed, survival may be affected.
			0.999	0.999	0.9	0.7	
		On surfacing first GPS fix was 1.2km out.	S	S	S	S	Even if GPS is out, vehicle should be located using RDF beacons and ARGOS. Problems may occur in sea ice due to size of the lead in which vehicle surfaces.
			0.999	0.999	0.9	0.99	
		Spikes in indicated motor rpm	S	S	L	L	Vehicle may be lost under ice on a mission of this length depending on the reasons for this and its effect on continued operation.
			0.999	0.999	0.8	0.9	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	S	S	S	S	Depends on need to communicate during mission. If mission exceutes correctly, the vehicle should complete its mission correctly. If something goes wrong, or a modification is needed, survival may be affected.
			0.999	0.999	0.9	0.7	
		Noise spikes on both channels of turbulence probe data.	S	S	S	S	Mission collects poor data, but survival of vehicle expected.
			1	1	1	1	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	S	S	S	S	Found as expected during prelaunch inspection. This is a long mission and if not found problems and even loss might result, but attention to pre launch checks should catch this.
			1	1	1	1	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	S	S	S	S	As explained this would be expected to show on first dive before mission got fully underway and so survival is likley. Lower probabilities given under ice as vehicle may already be under sea ice if lead is small when fault is found. Under shelf ice, compounded with another problem loss may occur.
		this would show itself immediately on first dive.	0.99	0.99	0.8	0.6	
		No telemetry from Acoustic telemetry unit.	S	S	S	S	Depends on need to communicate during mission. If mission exceutes correctly, the vehicle should complete its mission correctly. If something goes wrong, or a modification is needed, survival may be affected.
			0.999	0.999	0.9	0.7	
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	S	S	L	S	On surface implies not under ice. Suvival in one piece may be affected since it may be necessary to chase the vehicle with RIB and abort mission say by imparting extreme motion (e.g. roll) - doing this may result in damage.
			0.6	0.6	0.9	0.6	
		Still spikes on motor rpm that need investigating.	S	S	L	L	Vehicle may be lost under ice on a mission of this length depending on the reasons for this and its effect on continued operation.
			0.999	0.999	0.8	0.9	

Table 5 ***Terschelling*** **March 2007 – Deep water AUV reliability proving trials in Norway.**							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? **Mark how confident you are in each grey box (on a scale 0.5 to 1).**				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
409	1.5	No acoustic telemetry or transponding. LXT ship side USBL receiver had leaked during mission giving poor bearings to sub, replaced with spare.	S	S	S	S	Depends on need to communicate during mission. If mission exceutes correctly, the vehicle should complete its mission correctly. If something goes wrong, or a modification is needed, survival may be affected. But mission is v short.
			0.999	0.999	0.9	0.9	
410	9	No acoustic telemetry or transponding.	S	S	S	S	Depends on need to communicate during mission. If mission exceutes correctly, the vehicle should complete its mission correctly. If something goes wrong, or a modification is needed, survival may be affected.
			0.999	0.999	0.9	0.7	
411	128	No GPS fix at the end of the mission. GPS antenna bulkhead had water inside and had flooded.	S	S	S	S	Even if GPS is not working, vehicle should be located using ARGOS. Problems may occur in sea ice due to size of the lead in which vehicle surfaces. The mission is long so the vehicle may be some distance from where expected.
			0.9	0.9	0.6	0.75	
412	270	No GPS fix at end of mission. After next mission, GPS fixes started coming in after vehicle power up/power down; perhaps problem was due to initialisation with receiver – and not this time the antenna.	S	S	S	S	Even if GPS is not working, vehicle should be located using ARGOS. Problems may occur in sea ice due to size of the lead in which vehicle surfaces. The mission is long so the vehicle may be some distance from where expected.
			0.9	0.9	0.6	0.75	
		Problem at start for holding pattern. Holding pattern timed out due to programming mistake.	S	S	S	S	Occurs at start of mission and so survival likely.
			0.99	0.99	0.99	0.99	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
415	6	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.	S	S	L	L	Survival expected in open water and coatsal, but loss likely if this occurs into an under ice mission.
			0.99	0.99	0.95	0.99	
415	6	Three harness connectors failed due to leakage, affecting payload systems: EM2000 tube, ADCP_down, and Seabird CTD. Despite connector problems the system worked without glitches and failed only when the power pins had burned completely through on the connector feeding power to the abort system	S	S	S	S	ADCP down may affect navigation and could affect survival on an under ice mission. In open water of coastal reduced nav accuracy should still not affect survival.
			0.99	0.99	0.9	0.8	
		Although it worked properly at the start of the mission at a range of 1200m, the acoustic telemetry stopped working at the end of mission. Hence could not stop the mission acoustically when needed.	S	S	S	S	Depends on need to communicate during mission. If mission exceutes correctly, the vehicle should complete its mission correctly. If something goes wrong, or a modification is needed, survival may be affected.
			0.999	0.999	0.9	0.7	

Table 5 *Terschelling* March 2007 – Deep water AUV reliability proving trials in Norway.							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
416	18	Not possible to communicate with vehicle at 1180m depth; holding pattern caused a timeout, and AUV surfaced. Acoustic telemetry max range was 500m for digital data.	S	S	L	L	Loss expected if occurs under shelf ice; loss likely under sea ice. Survival likely in non-iced water, although mission would abort.
			0.99	0.99	0.95	1	
418	15	When homing was stopped deliberately after 10 min, the AUV did not go into a "stay here" mode. Rather it continued on the same heading; stopped by acoustic command 500m from shore. Cause was incorrect configuration of mission exception for homing. Default in campaign configuration script was not set due to inexperience with new configuration tools.	S	S	L	S	Survival expeceted at the end of the mission when vehicle would be in relatively open water. But in sea ice vehicle may collide with ice, or run under the ice. Near to shore the vehicle may collide with the shore; total loss not expected, but damage could occur.
			0.99	0.8	0.8	0.99	

ANNEX B – EXPERTS RESPONSES

Adam Skarke

Table 1 *Discovery* 295T July 2005 – AUV and other trials in the SW Approaches.							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
384	1.5	Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).	S	S	S	L	Unplanned surfacing introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.9	0.85	0.6	0.7	
		Loop of recovery line came out from storage slot, long enough to tangle propeller.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.9	
385	15.2	Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.	S	S	S	S	Lack of directional control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	
386	26	GPS antenna failed at end of mission.	S	S	S	S	Loss of GPS within visual range of the support vehicle would introduce very little threat of loss.
			1	0.9	0.8	0.8	
387	27.2	Homing failed, and the vehicle headed off in an uncontrolled direction. Mission was stopped by acoustic command. Problem was due to (a) the uncalibrated receiver array, and (b) a network message ("homing lost") being lost on the network.	S	S	S	S	Lack of directional control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
388	0.5	Aborted after 4 minutes post dive, due to network failure. Logger data showed long gaps, up to 60s, across all data from all nodes, suggesting logger problem.	S	S	S	L	Unplanned surfacing introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.9	0.85	0.6	0.7	
		Depth control showed instability. +/- 1m oscillation due to incorrect configuration gain setting.	S	S	S	S	There is no risk of loss unless hazards lie within the amplitude of depth oscillation.
			1	0.95	0.95	0.9	
389	3	Vehicle went into homing mode, just before dive and headed north. Vehicle mission stopped by acoustic command. It was fortunate that the ship-side acoustics configuration allowed the ship to steam at 9kt (faster rather than 6kt with the towfish) and catch the AUV.	S	S	S	S	Lack of directional control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	
		Separately, homing mode not exited after 2 minutes, as expected. It will continue on last-determined heading indefinitely – a Mission Control configuration error.	S	S	S	S	Lack of directional control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	
		Problem with deck side of acoustic telemetry receiver front end, unrelated to vehicle systems.	S	S	S	S	The only risk introduced is the inability to communicate with the vehicle given a second fault. Probability of a double fault that can only be rectified by acoustic communication is low
			1	0.99	0.99	0.9	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?				
			Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
391	31	ADCP down range limited to 360m, reduced accuracy of navigation.	S	S	S	S	Reduced navigational accuracy introduced the potential for unanticipated collision with ice, vessel traffic, or the shoreline.
			0.95	0.9	0.8	0.7	
		GPS antenna flooded. No fix at end point of mission.	S	S	S	S	Loss of GPS within visual range of the support vehicle would introduce very little threat of loss.
			1	0.9	0.8	0.8	
		EM2000 swath sonar stopped logging during mission.	S	S	S	S	Loss of payload should not impact vessel safety unless swath is employed in obstacle avoidance or adaptive mission planning.
			1	1	1	1	
392	32	As consequence of GPS failure on M391, AUV ended up 700m N and 250m E of expected end position.	S	S	S	S	Lack of navigational control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	
393	5	Acoustic telemetry giving poor ranges and no acoustic telemetry.	S	S	S	S	The only risk introduced is the inability to communicate with the vehicle given a second fault. Probability of a double fault that can only be rectified by acoustic communication is low
			1	0.99	0.99	0.9	
394	3	Jack-in-the-box recovery *float* came out, wrapping its line around the propeller, jamming it, and stopping the mission. Caused severe problems in recovery, some damage to upper rudder frame, sub-frame and GPS antenna. Required boat to be launched.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline. Potential loss of GPS and associated location information increases lost risk as it may not be possible to locate AUV. Finally, launch of rescue boat introduces risk for collision
			0.9	0.8	0.7	0.9	
395	8	Jack-in-the-box *line* came out, wrapped around the propulsion motor and jammed.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.9	

Table 2 *Terschelling* May 2006 – AUV trials in the SW Approaches.							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?				
			Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
396	4	Current estimation did not work, because minimum time between fixes for current to be estimated had been set to 15min; leg time was only 10min. Mission stopped and restarted with configurable time set to 5min.	S	S	S	S	Risk arises from lack of current information in navigation algorithm. If unable to correct for currents, navigation is compromised and vehicle risk collision with ice, vessel traffic, or the shoreline.
			0.99	0.9	0.8	0.5	
397	4	Main lifting lines became loose, could have jammed motor.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.9	
398	8	Operators ended mission prematurely, they believed the AUV was missing waypoints. In fact, a couple of waypoints had been positioned incorrectly.	S	S	S	S	Unplanned surfacing introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline. However, operators in control of mission could have foreseen and mitigated any hazards.
			1	0.9	0.8	0.7	

Table 3 ***Discovery*** **June-July 2006 – Biological measurements in the NE Atlantic**

			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?				
			Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
401	7.5	Configuration mistake; ADCP up configured as down- looking ADCP causing navigation problems through tracking sea surface as reference. This data was very noisy and put vehicle navigation out by a factor of 1.5.	S	S	S	S	Lack of navigational control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	
		Damaged on recovery, "moderately serious" to sternplane, shaft bent.	S	S	S	S	If damage occurred after AUV was positively attached to the ship there is no risk of loss unless line breaks. If occurs before connection, rish high because of compromised propulsion and possibly compromised watertight housing
			0.9	0.9	0.9	0.9	
402	274	Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.					Not enough information to determine risk.
		Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.	S	S	S	S	Unplanned surfacing introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline. Inability to communicate with depth control introduces potential risk for sea floor collision
			1	0.7	0.8	0.7	
		Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive	S	S	S	S	Compromised propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.7	
		Only one position fix from tail mounted ARGOS transmitter.					Not enough information to determine risk
		GPS antenna damaged on recovery.	S	S	S	S	If damage occurred after AUV was positively attached to the ship there is no risk of loss unless line breaks. If occurs before connection risk is low since AUV is in visual range
			0.9	0.9	0.9	0.9	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
403	140	Recovery light line was wrapped around the propeller on surface. Flaps covering the main recovery lines (and where the light line was towed) were open.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.9	
		Took over 1 hour to get GPS fix at final waypoint.	S	S	S	S	Lack of navigational control introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline.
			0.99	0.85	0.7	0.6	
		Propeller speed showed same problem as m402. Subsequent testing of motor with Megger showed resistance of a few kohm between windings.	S	S	S	S	Compromised propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.7	
404	75	Pre-launch, abort weight could not be loaded successfully due to distorted keeper. "If not spotted, could have dropped out during mission", considered low probability of distortion ***and*** not checked.	S	S	S	S	Unplanned surfacing introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline. Inability to communicate with depth control introduces potential risk for sea floor collision
			1	0.7	0.8	0.7	
		Pre-launch, potential short circuit in motor controller that could stop motor.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.9	
		Propeller speed showed same problem as on m402 and 403.	S	S	S	S	Compromised propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.7	
		CTD drop-out of 1 hour (shorter drop-outs noted in previous missions).	S	S	S	S	Loss of payload instrument should not impact vessel safety unless CTD is employed in adaptive mission planning.
			1	1	1	1	

Table 3 *Discovery* June-July 2006 – Biological measurements in the NE Atlantic

Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?

Mark how confident you are in each grey box (on a scale 0.5 to 1).

No.	Distance (km)	Fault/incident description	Open	Coast	Sea Ice	Shelf Ice	Reasons
404	75	M404 recovery was complicated when lifting lines and streaming line became trapped on the rudder (probably stuck on the Bolen where the two were attached). Recovery from the situation required the trapped lifting lines grappled astern of the ship, attached to the gantry lines, and the caught end cut.	S	S	S	S	No risk of loss unless line failure is compounded by a secondary failure
			1	1	1	1	
		The forward sternplane was lost due to lifting line trapping between the fin and its flap on recovery.					Not enough information to determine risk
		The acoustic telemetry nose transducer was damaged due to collision with the ship.	S	S	S	S	As long as pressure vessel is sound and AUV is within visual range of ship, there is no risk
			1	1	1	1	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
			Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment? Mark how confident you are in each grey box (on a scale 0.5 to 1).				
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
405	2.5	Fault found pre-launch, LXT tracking transducer had leaked water – replaced.					Not enough information to determine risk
		Fault found pre-launch, starboard lower rudder and sternplane loose.	S	S	S	S	If fault was found prior to launch there is no risk of loss
			1	1	1	1	
406	104	AUV ran slower than expected and speed dropped off during mission, due to motor problem.	S	S	S	S	As long as velocity is sufficient to remain submerged and motor does not stop, the risk of loss is very low
			0.9	0.9	0.9	0.9	
		Current spikes of 3A and voltage drops in first part of mission.					Not enough information to determine risk
		Propulsion motor failed 500V Megger on recovery on windings to case.	S	S	S	L	Lack of viable propulsion introduces potential for entrapment under shelf ice (which can not be corrected remotely) as well as inability to avoid hazards such as sea ice, vessel traffic, and the shoreline.
			0.99	0.9	0.8	0.9	
		One battery pack out of four showed intermittent connection.	S	S	S	L	Unexpected loss of power could result in unexpected surfacing which introduces risk of entrapment under ice or collision with ice, vessel traffic, or the shoreline
			0.99	0.9	0.8	0.6	
		Acoustic telemetry unit gave no replies.					Not enough information to determine risk
		On surfacing first GPS fix was 1.2km out.	S	S	S	S	Reduced navigational accuracy introduced the potential for unanticipated collision with ice, vessel traffic, or the shoreline.
			1	0.9	0.8	0.8	
		Spikes in indicated motor rpm	S	S	S	S	As long as motor does not fail, spike in velocity should not compromise DVL or inertial navigation, resulting in low risk of loss
			0.99	0.9	0.9	0.9	

Table 4 *Terschelling* July 2006 – Turbulence studies in the Irish Sea							
	Is Survival (S) or Loss (L) the most likely outcome after each fault or incident in each environment?						
	Mark how confident you are in each grey box (on a scale 0.5 to 1).						
No.	**Distance (km)**	**Fault/incident description**	**Open**	**Coast**	**Sea Ice**	**Shelf Ice**	**Reasons**
407	204	Acoustic telemetry unit gave no replies at all – no tracking or telemetry.	S	S	S	S	Inability to track vehicle is not a risk of loss in itself but could be if combined with a secondary failure
			0.9	0.9	0.9	0.8	
		Noise spikes on both channels of turbulence probe data.	S	S	S	S	No risk unless turbulence sensor is incorporated into navigation solution or adaptive mission planning
			1	1	1	1	
408	302.5	Propulsion motor felt rough when turned by hand – bearings replaced before deployment.	S	S	S	S	Problem addressed before deployment so there is no risk of loss
			1	1	1	1	
		Aborted at 50m due to overdepth as no depth mode commanded. Unless compounded by another problem,	S	S	S	S	Unplanned surfacing introduces potential for entrapment under shelf ice as well as collision with sea ice, vessel traffic, or the shoreline. Inability to communicate with depth control introduces potential risk for sea floor collision
		this would show itself immediately on first dive.	1	0.7	0.8	0.7	
		No telemetry from Acoustic telemetry unit.					Not enough information to determine risk
		Difficulty stopping Autosub on surface via radio command. Separate problems with the two WiFi access points.	S	S	S	S	Inability to manually control AUV on surface may prevent obstacle avoidance. If on surface loss under shelf ice is not an issue
			1	0.9	0.9	1	
		Still spikes on motor rpm that need investigating.	S	S	S	S	As long as motor does not fail, spike in velocity should not compromise DVL or inertial navigation, resulting in low risk of loss
			0.99	0.9	0.9	0.9	

ANNEX C - BRIEF BIOGRAPHIES OF THE EXPERTS

Robert Bogucki

Robert Bogucki is a graduate student. He received an MS degree in Telecommunications from Gdansk University of Technology in 2002. After working in the IT sector for some time, he continued his education at the University of New Hampshire, obtaining a Master's Degree in Electrical Engineering in 2006. His thesis project, conducted under the auspices of the Synthetic Vision and Pattern Recognition Laboratory, involved designing and implementing a prototype Augmented Reality device for first responders.

He is currently pursuing a PhD in Ocean Engineering with focus on adaptive navigation and mapping for Autonomous Underwater Vehicles. In the summer of 2007 he participated in Byzantium 2007 underwater archaeology expedition on the Black Sea.

Source: http://ccom.unh.edu/index.php?page=people/people.php

Neil Bose

Neil Bose graduated in Naval Architecture and Ocean Engineering from Glasgow University in 1978 and obtained a PhD in hydrofoil design in 1982, also from Glasgow University. He taught at Glasgow University from 1983 to 1987 and joined Memorial University of Newfoundland, Canada in 1987. He was Director of the Ocean Engineering Research Centre from 1994 to 2000, and Chair of Ocean and Naval Architectural Engineering from 1998 to 2003.

He has been involved in research in the fields of ocean engineering, marine propulsion, and marine hydrodynamics performance evaluation. As a Tier I Canada Research Chair in Offshore and Underwater Vehicle Design, he built strongly interrelated research teams in both underwater vehicle and marine vehicle design involving industry partners and researchers from other universities and laboratories in Canada and elsewhere. He is currently Professor of Maritime Hydrodynamics and Manager, Australian Maritime Hydrodynamics Research Centre, National Centre for Maritime Engineering and Hydrodynamics, Tasmania.

Source: http://www.engr.mun.ca/people/nbose.php

Tom Curtin

Tom Curtin is currently Chief Knowledge Officer for the Association for Unmanned Vehicle Systems International, Arlington, Virginia. He has more than 37 years of experience in science and technology management and physical oceanographic research, most recently with the U.S. Office of Naval Research where he pioneered the concept of the Autonomous Ocean Sampling Network. A long-time advocate of unmanned systems, Curtin established an annual autonomous underwater vehicle student competition in 1998 and initiated the biennial AUVFest to stimulate interaction between researchers and users of unmanned underwater systems. He has authored over 35 peer-reviewed papers, 21 technical reports and one patent, and has been guest editor of several journals.

Source: Profile at http://www.zoominfo.com

Barbara Fletcher

Barbara Fletcher is an engineer and project manager at the Space and Naval Warfare Systems Centre in San Diego, California, specializing in unmanned undersea vehicle applications. A co-author of the US Navy UUV Master Plan, she has been involved in plume studies and mine countermeasure studies for the Office of Naval Intelligence and recently in the HROV project – a full ocean depth hybrid AUV-ROV. From 1993-1998, she was a founding member and systems engineer at Imetrix, a small marine sciences company. During her previous 10 years at the Naval Ocean Systems Centre, she worked in underwater security, mine countermeasures, deep submergence, and ocean surveillance. She has a BS and MS in Mechanical Engineering from Stanford University.

Source: Profile at http://www.zoominfo.com

Clayton Jones

Clayton Jones has been involved in design and development of buoyancy driven oceanographic instruments including ALACE and APEX floats and Slocum gliders, specialising in systems integration, control algorithms, antenna design and fieldwork. He has 11 years experience with underwater vehicles and is currently Vice President of Webb Research Corporation.

Source:

Rob McEwen

Rob McEwen is a control systems engineer at the Monterey Bay Aquarium Research Institute where is currently working on the control system for the Dorado AUV. He has nine years experience of AUV technology. He came to MBARI from an aerospace background, including work on attitude control of the Miniature Sensor Technology Integration (MSTI) spacecraft. He has a BSEE from Purdue University, an MSEE from the University of Illinois and an MSME from Stanford University.

Source: http://www.mbari.org/staff/rob/

Mark Moline

Mark Moline is an Associate Professor in the Biological Sciences Department, California Polytechnic University at San Luis Obispo. His research interests centre on Biological Oceanography, Phytoplankton Ecology, Phytoplankton Physiology, Phytobiology, Bio-optics, Remote Sensing, and Biogeochemistry, and Autonomous Underwater Vehicles. He has six years experience of using AUVs for scientific research.

Source: http://www.marine.calpoly.edu/community/faculty/markmoline.php

Adam Skarke

Adam Skarke is a graduate student at the Department of Geology, University of Delaware, where he has used the Fetch AUV in coastal environments and the Black Sea.

Christopher Williams

Chris Williams is a researcher with ten years experince of AUV hydrodynamics and design at the National Research Council's Institute for Ocean Technology in St John's, Newfoundland, Canada.

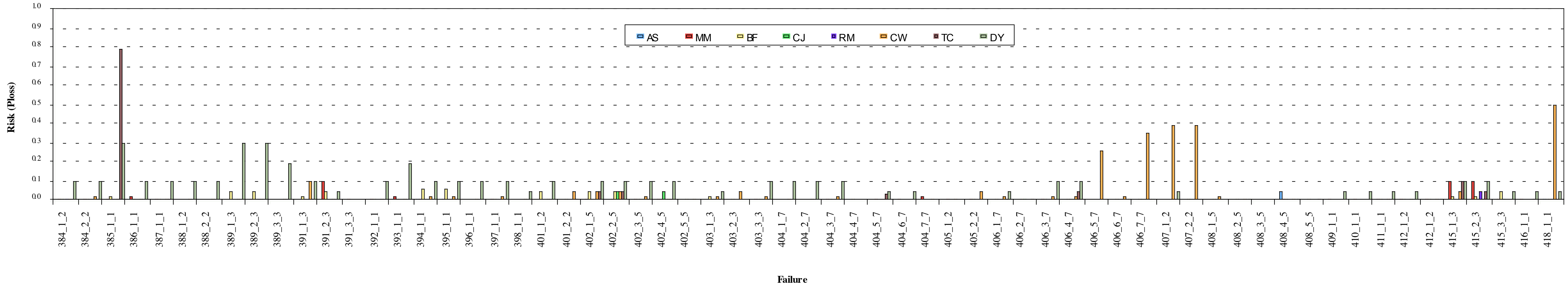
Dana Yoerger

Dana Yoerger has 15 years experience with AUVs. His research interests span robotics; applying principals of automation to remotely operated and autonomous underwater vehicles to add capability and ease of use; design of vehicles including the Medea/Jason remotely operated vehicle system and the Autonomous Benthic Explorer AUV; precise control, navigation and positioning and deep sea observatories. He has SB, SM and PhD degrees in mechanical engineering from MIT.

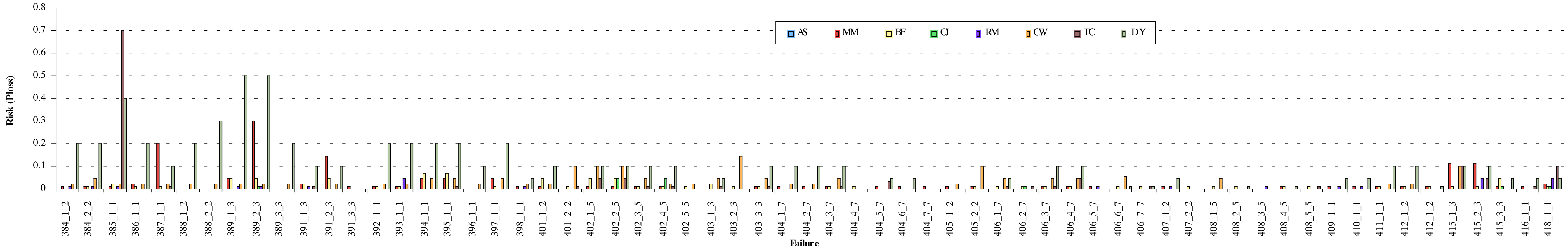
Source: http://www.whoi.edu/dept/profile.go?id=633

ANNEX D - FAILURE PROBABILITY JUDGMENT DISTRIBUTION FOR ANNEX A

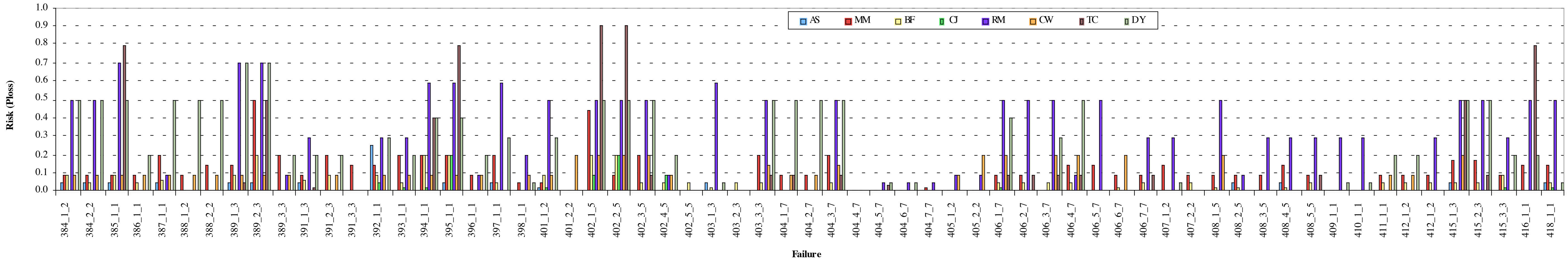
OPEN WATER

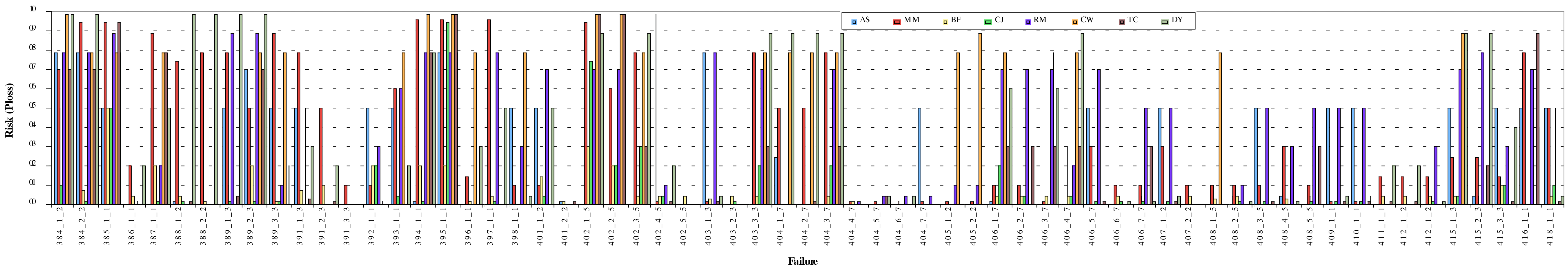


SEA ICE



ICE SHELF





ANNEX E - AGGREGATED JUDGMENTS

Failure	Open water			Coastal			Sea ice			Ice shelf		
	Mean	Linear	Log	Mean	Linear	Log	Mean	Linear	Log	Mean	Linear	Log
384_1_2	0.0178	0.02069	0.0060	0.03325	0.03797	0.0077	0.17125	0.15731	0.0619	0.7000	0.70385	0.57645
384_2_2	0.0185	0.02163	0.0063	0.03575	0.04016	0.0086	0.16500	0.15154	0.0571	0.6425	0.59542	0.32407
385_1_1	0.1446	0.11093	0.0141	0.14887	0.12417	0.0216	0.29500	0.26042	0.1083	0.7375	0.75200	0.72748
386_1_1	0.0192	0.01953	0.0052	0.03450	0.03381	0.0064	0.05788	0.05893	0.0121	0.0661	0.06318	0.00990
387_1_1	0.0178	0.02097	0.0064	0.04525	0.05193	0.0156	0.13000	0.14696	0.0645	0.4887	0.47810	0.24245
388_1_2	0.0147	0.01732	0.0000	0.03014	0.03438	0.0000	0.09039	0.10605	0.0100	0.2631	0.32660	0.06477
388_2_2	0.0140	0.01772	0.0000	0.04151	0.05159	0.0000	0.09525	0.11304	0.0000	0.2615	0.30976	0.00000
389_1_3	0.0461	0.05516	0.0000	0.08150	0.09716	0.0168	0.23250	0.21923	0.0937	0.4800	0.43810	0.14540
389_2_3	0.0480	0.04252	0.0086	0.12013	0.11761	0.0370	0.34500	0.38042	0.2064	0.6012	0.62409	0.36470
389_3_3	0.0268	0.02517	0.0000	0.03064	0.02855	0.0000	0.07888	0.08622	0.0304	0.3151	0.30776	0.05891
391_1_3	0.0303	0.02624	0.0000	0.03300	0.03308	0.0171	0.10586	0.09495	0.0329	0.3144	0.27967	0.06277
391_2_3	0.0267	0.03114	0.0078	0.04175	0.04300	0.0084	0.07329	0.07905	0.0138	0.1205	0.14822	0.01585
391_3_3	0.0017	0.00148	0.0000	0.00171	0.00148	0.0000	0.02171	0.01828	0.0000	0.0145	0.01228	0.00000
392_1_1	0.0172	0.01460	0.0043	0.06313	0.05937	0.0098	0.15688	0.13280	0.0758	0.2183	0.16706	0.09681
393_1_1	0.0306	0.02614	0.0047	0.04025	0.03474	0.0096	0.11063	0.10659	0.0525	0.3506	0.32452	0.13143
394_1_1	0.0273	0.02747	0.0108	0.04900	0.05026	0.0176	0.24125	0.23643	0.1194	0.5737	0.60533	0.26443
395_1_1	0.0266	0.02745	0.0083	0.04850	0.04968	0.0156	0.31875	0.34615	0.2594	0.8157	0.87682	0.81767
396_1_1	0.0150	0.01223	0.0000	0.01763	0.01443	0.0000	0.06413	0.05511	0.0099	0.1828	0.15530	0.01322
397_1_1	0.0180	0.01828	0.0049	0.03988	0.03981	0.0090	0.17300	0.17058	0.0461	0.4458	0.40148	0.07735
398_1_1	0.0090	0.00845	0.0000	0.01459	0.01312	0.0033	0.05746	0.03503	0.0054	0.1789	0.12738	0.00897
401_1_2	0.0205	0.02177	0.0000	0.02713	0.02807	0.0112	0.13626	0.12402	0.0291	0.2857	0.23335	0.04546
401_2_2	0.0091	0.00859	0.0000	0.01538	0.01188	0.0000	0.02788	0.02163	0.0000	0.0045	0.00441	0.00000
402_1_5	0.0328	0.03261	0.0105	0.03938	0.03723	0.0119	0.35637	0.36681	0.1459	0.7001	0.72255	0.31559
402_2_5	0.0444	0.04654	0.0279	0.05186	0.05219	0.0333	0.37143	0.40455	0.3102	0.6571	0.75417	0.66694
402_3_5	0.0217	0.02642	0.0093	0.02629	0.03052	0.0115	0.22286	0.23818	0.1285	0.5500	0.62381	0.49391
402_4_5	0.0240	0.02523	0.0098	0.02675	0.02803	0.0123	0.07138	0.07362	0.0297	0.2028	0.23522	0.07478
402_5_5	0.0028	0.00263	0.0000	0.00537	0.00418	0.0000	0.00757	0.00559	0.0000	0.0075	0.00559	0.00000
403_1_3	0.0141	0.01294	0.0000	0.01850	0.01581	0.0000	0.10729	0.09670	0.0187	0.2430	0.16018	0.02111
403_2_3	0.0088	0.00882	0.0000	0.02329	0.01856	0.0000	0.01183	0.01105	0.0000	0.0118	0.01105	0.00000
403_3_3	0.0217	0.02348	0.0084	0.02629	0.02763	0.0105	0.21571	0.21857	0.1156	0.5357	0.59500	0.45103
404_1_7	0.0142	0.01621	0.0000	0.01913	0.02111	0.0000	0.10150	0.12613	0.0000	0.3190	0.37204	0.00000
404_2_7	0.0142	0.01621	0.0000	0.01800	0.02052	0.0000	0.08913	0.10924	0.0000	0.2766	0.32124	0.00000
404_3_7	0.0217	0.02442	0.0092	0.02629	0.02878	0.0116	0.21571	0.24053	0.1496	0.4750	0.54000	0.39604
404_4_7	0.0017	0.00160	0.0000	0.00171	0.00160	0.0000	0.00443	0.00327	0.0000	0.0044	0.00327	0.00000
404_5_7	0.0178	0.01471	0.0058	0.01783	0.01471	0.0058	0.02600	0.02000	0.0088	0.0260	0.02000	0.00882
404_6_7	0.0097	0.00817	0.0000	0.00971	0.00817	0.0000	0.01671	0.01200	0.0000	0.0167	0.01200	0.00000
404_7_7	0.0048	0.00542	0.0000	0.00529	0.00577	0.0000	0.01229	0.00885	0.0000	0.0822	0.02840	0.00000
405_1_2	0.0035	0.00368	0.0000	0.00625	0.00536	0.0000	0.02713	0.01481	0.0000	0.1146	0.08044	0.00000
405_2_2	0.0093	0.00918	0.0000	0.01600	0.01258	0.0000	0.04025	0.02497	0.0000	0.1277	0.09059	0.00000
406_1_7	0.0116	0.01039	0.0000	0.01575	0.01374	0.0000	0.17188	0.17000	0.0877	0.3450	0.36550	0.22359
406_2_7	0.0045	0.00382	0.0000	0.00543	0.00476	0.0000	0.10929	0.08786	0.0000	0.1721	0.14654	0.00000
406_3_7	0.0217	0.02404	0.0084	0.02629	0.02839	0.0105	0.16586	0.14971	0.0398	0.3515	0.33067	0.06354
406_4_7	0.0228	0.02246	0.0000	0.02988	0.03019	0.0129	0.13938	0.17000	0.0828	0.3256	0.40262	0.21985
406_5_7	0.0347	0.03215	0.0000	0.00729	0.00833	0.0000	0.09786	0.08167	0.0000	0.2192	0.16225	0.00000
406_6_7	0.0060	0.00576	0.0000	0.01171	0.00924	0.0000	0.05014	0.04922	0.0000	0.0301	0.03163	0.00000
406_7_7	0.0491	0.04500	0.0000	0.00500	0.00409	0.0000	0.08157	0.05600	0.0180	0.1401	0.08916	0.02323
407_1_2	0.0585	0.05023	0.0000	0.01443	0.01042	0.0062	0.07643	0.05325	0.0185	0.1978	0.12605	0.03362
407_2_2	0.0515	0.03961	0.0000	0.00171	0.00100	0.0000	0.02229	0.01981	0.0000	0.0222	0.01981	0.00000
408_1_5	0.0040	0.00388	0.0000	0.00800	0.00638	0.0000	0.10263	0.07121	0.0000	0.2038	0.14810	0.00000
408_2_5	0.0047	0.00462	0.0000	0.00467	0.00430	0.0000	0.04833	0.04500	0.0286	0.0533	0.05067	0.03635
408_3_5	0.0025	0.00243	0.0000	0.00443	0.00417	0.0000	0.06214	0.04075	0.0000	0.1621	0.08132	0.00000
408_4_5	0.0121	0.01194	0.0000	0.01357	0.01366	0.0058	0.07586	0.05823	0.0000	0.0987	0.08285	0.00000
408_5_5	0.0021	0.00143	0.0000	0.00250	0.00162	0.0000	0.07683	0.04633	0.0000	0.1118	0.05911	0.00000
409_1_1	0.0111	0.00678	0.0040	0.01300	0.00833	0.0054	0.05643	0.02750	0.0117	0.1564	0.09583	0.02267
410_1_1	0.0121	0.00695	0.0039	0.01350	0.00818	0.0051	0.01583	0.01147	0.0097	0.0991	0.07206	0.01890
411_1_1	0.0105	0.00952	0.0038	0.02050	0.01876	0.0052	0.05788	0.05956	0.0144	0.0604	0.06752	0.01485
412_1_2	0.0105	0.00952	0.0038	0.02050	0.01876	0.0052	0.05788	0.05956	0.0144	0.0604	0.06752	0.01485
412_1_2	0.0060	0.00585	0.0000	0.00733	0.00757	0.0000	0.07833	0.06100	0.0000	0.0883	0.07300	0.00000
415_1_3	0.0466	0.04524	0.0123	0.06050	0.05803	0.0235	0.24750	0.25083	0.1322	0.5312	0.53043	0.32318
415_2_3	0.0460	0.04604	0.0155	0.04886	0.04961	0.0161	0.18886	0.18577	0.0370	0.3215	0.33119	0.07368
415_3_3	0.0182	0.01952	0.0092	0.02114	0.02246	0.0150	0.10571	0.09412	0.0527	0.2228	0.21294	0.13814
416_1_1	0.0121	0.01143	0.0042	0.01417	0.01350	0.0053	0.27533	0.24153	0.0388	0.5501	0.51900	0.13004
418_1_1	0.0727	0.04656	0.0000	0.042857	0.0372	0.0285	0.11857	0.109473	0.0586	0.2442	0.24316	0.12416

ANNEX F - OPTIMISTIC AND PESSIMISTIC RISK MODEL FOR FOUR ENVIRONMENTS

Experts	Open water		Coastal		Sea ice		Ice shelf	
Failure	**Optimistic**	**Pessimistic**	**Optimistic**	**Pessimistic**	**Optimistic**	**Pessimistic**	**Optimistic**	**Pessimistic**
384_1_2	0.0043	0.0446	0.0037	0.0682	0.0173	0.2600	0.4000	0.8389
384_2_2	0.0038	0.0477	0.0030	0.0729	0.0173	0.2500	0.3600	0.7131
385_1_1	0.0981	0.1277	0.1127	0.1329	0.1944	0.3000	0.6500	0.7842
386_1_1	0.0071	0.0377	0.0014	0.0663	0.0010	0.0988	0.0010	0.1062
387_1_1	0.0045	0.0421	0.0055	0.0847	0.0189	0.2293	0.2733	0.5600
388_1_2	0.0006	0.0431	0.0015	0.0653	0.0023	0.1821	0.0150	0.5343
388_2_2	0.0003	0.0418	0.0004	0.0938	0.0008	0.1953	0.0050	0.5383
389_1_3	0.0013	0.1338	0.0046	0.1788	0.0300	0.3375	0.0250	0.6923
389_2_3	0.0052	0.1036	0.0216	0.2136	0.1614	0.4706	0.2860	0.7235
389_3_3	0.0007	0.0643	0.0038	0.0533	0.0066	0.1287	0.0055	0.4287
391_1_3	0.0022	0.0720	0.0195	0.0491	0.0182	0.1640	0.0134	0.4491
391_2_3	0.0285	0.0355	0.0010	0.0850	0.0037	0.1418	0.0081	0.2603
391_3_3	0.0019	0.0004	0.0003	0.0033	0.0003	0.0348	0.0005	0.0178
392_1_1	0.0031	0.0345	0.0601	0.0585	0.0700	0.1821	0.1050	0.2222
393_1_1	0.0043	0.0618	0.0106	0.0608	0.0119	0.1607	0.0275	0.4433
394_1_1	0.0059	0.0633	0.0052	0.0925	0.1433	0.3063	0.4100	0.6764
395_1_1	0.0048	0.0633	0.0040	0.0925	0.4100	0.3063	0.9786	0.8293
396_1_1	0.0010	0.0327	0.0015	0.0273	0.0010	0.1020	0.0010	0.2324
397_1_1	0.0032	0.0433	0.0021	0.0775	0.0144	0.2821	0.0055	0.6127
398_1_1	0.0005	0.0188	0.0029	0.0203	0.0006	0.0532	0.0008	0.1944
401_1_2	0.0007	0.0533	0.0073	0.0463	0.0112	0.1875	0.0215	0.3393
401_2_2	0.0025	0.0185	0.0032	0.0200	0.0038	0.0338	0.0050	0.0041
402_1_5	0.0111	0.0667	0.0119	0.0594	0.3549	0.3750	0.8929	0.6684
402_2_5	0.0269	0.0692	0.0359	0.0618	0.6667	0.3063	0.7333	0.7611
402_3_5	0.0055	0.0508	0.0037	0.0456	0.0400	0.3125	0.3000	0.7250
402_4_5	0.0154	0.0400	0.0179	0.0363	0.0424	0.0931	0.0367	0.3053
402_5_5	0.0005	0.0062	0.0007	0.0076	0.0006	0.0102	0.0005	0.0083
403_1_3	0.0025	0.0318	0.0044	0.0280	0.0144	0.1600	0.0055	0.2486
403_2_3	0.0004	0.0200	0.0010	0.0306	0.0050	0.0148	0.0050	0.0148
403_3_3	0.0055	0.0464	0.0037	0.0420	0.0400	0.2900	0.2400	0.7133
404_1_7	0.0006	0.0370	0.0039	0.0340	0.0360	0.1802	0.0434	0.5158
404_2_7	0.0006	0.0370	0.0009	0.0340	0.0028	0.1802	0.0040	0.4214
404_3_7	0.0058	0.0464	0.0040	0.0420	0.0550	0.2900	0.2500	0.6455
404_4_7	0.0004	0.0044	0.0005	0.0029	0.0004	0.0062	0.0006	0.0047
404_5_7	0.0111	0.0219	0.0116	0.0173	0.0156	0.0225	0.0156	0.0225
404_6_7	0.0030	0.0219	0.0008	0.0173	0.0007	0.0225	0.0006	0.0177
404_7_7	0.0057	0.0050	0.0030	0.0089	0.0023	0.0137	0.0006	0.0441
405_1_2	0.0030	0.0046	0.0008	0.0092	0.0006	0.0258	0.0005	0.1168
405_2_2	0.0031	0.0179	0.0010	0.0222	0.0006	0.0439	0.0005	0.1315
406_1_7	0.0017	0.0260	0.0032	0.0236	0.0386	0.2357	0.2400	0.4073
406_2_7	0.0032	0.0067	0.0068	0.0025	0.0383	0.1250	0.1750	0.1339
406_3_7	0.0055	0.0500	0.0037	0.0443	0.0340	0.1960	0.1007	0.4227
406_4_7	0.0068	0.0433	0.0114	0.0431	0.0343	0.2333	0.1500	0.4816
406_5_7	0.0018	0.0894	0.0058	0.0114	0.0100	0.1354	0.0171	0.2404
406_6_7	0.0004	0.0133	0.0006	0.0162	0.0032	0.0846	0.0075	0.0492
406_7_7	0.0018	0.1267	0.0028	0.0055	0.0260	0.0830	0.1320	0.0739
407_1_2	0.0018	0.1417	0.0058	0.0159	0.0100	0.0886	0.0171	0.1896
407_2_2	0.0004	0.1356	0.0005	0.0018	0.0004	0.0425	0.0005	0.0319
408_1_5	0.0004	0.0109	0.0008	0.0127	0.0004	0.1373	0.0005	0.2258
408_2_5	0.0007	0.0100	0.0026	0.0058	0.0260	0.0536	0.0200	0.0583
408_3_5	0.0018	0.0042	0.0058	0.0023	0.0100	0.0659	0.0171	0.1188
408_4_5	0.0122	0.0114	0.0135	0.0138	0.0157	0.1008	0.0004	0.1265
408_5_5	0.0007	0.0033	0.0014	0.0018	0.0049	0.0727	0.0200	0.0669
409_1_1	0.0048	0.0125	0.0058	0.0114	0.0100	0.0450	0.0171	0.1459
410_1_1	0.0047	0.0125	0.0050	0.0114	0.0100	0.0131	0.0171	0.1105
411_1_1	0.0032	0.0209	0.0010	0.0353	0.0037	0.0968	0.0081	0.1041
412_1_2	0.0032	0.0209	0.0010	0.0353	0.0037	0.0968	0.0081	0.1041
412_1_2	0.0034	0.0100	0.0012	0.0145	0.0050	0.0983	0.0100	0.1150
415_1_3	0.0387	0.0567	0.0298	0.0862	0.1822	0.2920	0.4143	0.5812
415_2_3	0.0405	0.0600	0.0206	0.0831	0.0307	0.3150	0.0756	0.4885
415_3_3	0.0062	0.0500	0.0074	0.0375	0.0143	0.1500	0.0640	0.2750
416_1_1	0.0050	0.0500	0.0034	0.0313	0.2673	0.2125	0.3863	0.6222
418_1_1	0.0037	0.1322	0.0454	0.0283	0.0257	0.1583	0.0640	0.3071

ANNEX G - KAPLAN-MEIER STATISTICS

Table G.1 Probability of loss for the proposed Jenkins Scenarios using the optimistic (left) and the pessimistic (right) Kaplan Meier statistics.

Scenario 1 Optimistic					Scenario 1 Pessimistic				
Mission no	distance (km)	Environment	P survival	P loss	Mission no	distance (km)	Environment	P survival	P loss
501	60	Open water	0.994	0.006	501	60	Open water	0.969	0.031
502	60	Open water	0.994	0.006	502	60	Open water	0.969	0.031
503	60	Open water	0.994	0.006	503	60	Open water	0.969	0.031
504	60	Ice shelf	0.912	0.088	504	60	Ice shelf	0.783	0.217
505	60	Ice shelf	0.912	0.088	505	60	Ice shelf	0.783	0.217
506	60	Ice shelf	0.912	0.088	506	60	Ice shelf	0.783	0.217
			Overall	0.255022				Overall	0.56322
Scenario 2	Optimistic				Scenario 2	Pessimistic			
Mission no	distance (km)	Environment	P survival	P loss	Mission no	distance (km)	Environment	P survival	P loss
501	120	Sea ice	0.955	0.045	501	120	Sea ice	0.836	0.164
502	120	Sea ice	0.955	0.045	502	120	Sea ice	0.836	0.164
503	120	Sea ice	0.955	0.045	503	120	Sea ice	0.836	0.164
504	60	Sea ice	0.966	0.034	504	60	Sea ice	0.898	0.102
504a	60	Ice shelf	0.912	0.088	504a	60	Ice shelf	0.783	0.217
505	60	Sea ice	0.966	0.034	505	60	Sea ice	0.899	0.101
505a	60	Ice shelf	0.912	0.088	505a	60	Ice shelf	0.783	0.217
506	60	Sea ice	0.966	0.034	506	60	Sea ice	0.898	0.102
506a	60	Ice shelf	0.912	0.088	506a	60	Ice shelf	0.783	0.217
			Overall	0.404439				Overall	0.79666
Scenario 3	Optimistic				Scenario 3	Pessimistic			
Mission no	distance (km)	Environment	P survival	P loss	Mission no	distance (km)	Environment	P survival	P loss
501	60	Open water	0.994	0.056	501	60	Open water	0.969	0.031
502	60	Open water	0.994	0.006	502	60	Open water	0.969	0.031
503	60	Open water	0.994	0.006	503	60	Open water	0.969	0.031
504	60	Ice shelf	0.912	0.088	504	60	Ice shelf	0.783	0.217
505	60	Ice shelf	0.912	0.088	505	60	Ice shelf	0.783	0.217
506	60	Ice shelf	0.912	0.088	506	60	Ice shelf	0.783	0.217
507	120	Ice shelf	0.871	0.129	507	120	Ice shelf	0.686	0.314
508	120	Ice shelf	0.871	0.129	508	120	Ice shelf	0.686	0.314
509	120	Ice shelf	0.871	0.129	509	120	Ice shelf	0.686	0.314
			Overall	0.532498				Overall	0.85899
Scenario 4	Optimistic				Scenario 4	Pessimistic			
Mission no	distance (km)	Environment	P survival	P loss	Mission no	distance (km)	Environment	P survival	P loss
501	120	Sea ice	0.955	0.045	501	120	Sea ice	0.836	0.164
502	120	Sea ice	0.955	0.045	502	120	Sea ice	0.836	0.164
503	120	Sea ice	0.955	0.045	503	120	Sea ice	0.836	0.164
504	60	Sea ice	0.966	0.034	504	60	Sea ice	0.898	0.102
504a	60	Ice shelf	0.912	0.088	504a	60	Ice shelf	0.783	0.217
505	60	Sea ice	0.966	0.034	505	60	Sea ice	0.898	0.102
505a	60	Ice shelf	0.912	0.088	505a	60	Ice shelf	0.783	0.217
506	60	Sea ice	0.966	0.034	506	60	Sea ice	0.898	0.102
506a	60	Ice shelf	0.912	0.088	506a	60	Ice shelf	0.783	0.217
507	60	Sea ice	0.966	0.034	507	60	Sea ice	0.898	0.102
507a	120	Ice shelf	0.871	0.129	507a	120	Ice shelf	0.686	0.314
508	60	Sea ice	0.966	0.034	508	60	Sea ice	0.898	0.102
508a	120	Ice shelf	0.871	0.129	508a	120	Ice shelf	0.686	0.314
509	60	Sea ice	0.966	0.034	509	60	Sea ice	0.898	0.102
509a	120	Ice shelf	0.871	0.129	509a	120	Ice shelf	0.686	0.314
			Overall	0.645259				Overall	0.95251

ANNEX H - Weibull survival Analyses of the Dr. Jenkins Scenarios - Unmitigated

Beta parameters:

Optimistic	alpha	beta
open water	182166.08	0.6419493
sea ice	3902.091	0.7794621
ice shelf	1774.7144	0.6613925

Scenario 1

Mission no	distance (km)	environment	P loss
501	60	Open water	0.0058
502	60	Open water	0.0058
503	60	Open water	0.0058
504	60	Ice shelf	0.1010
505	60	Ice shelf	0.1010
506	60	Ice shelf	0.1010
		Overall	*0.286*

Scenario 2

Mission no	distance (km)	environment	P loss
501	120	Sea ice	0.0641
502	120	Sea ice	0.0641
503	120	Sea ice	0.0641
504	60	Sea ice	0.0379
504a	60	Ice shelf	0.1010
505	60	Sea ice	0.0379
505a	60	Ice shelf	0.1010
506	60	Sea ice	0.0379
506a	60	Ice shelf	0.1010
		Overall	*0.470*

Scenario 3

Mission no	distance (km)	environment	P loss
501	60	Open water	0.0058
502	60	Open water	0.0058
503	60	Open water	0.0058
504	60	Ice shelf	0.1010
505	60	Ice shelf	0.1010
506	60	Ice shelf	0.1010
507	120	Ice shelf	0.1549
508	120	Ice shelf	0.1549
509	120	Ice shelf	0.1549
		Overall	*0.569*

Scenario 4

Mission no	distance (km)	environment	P loss
501	120	Sea ice	0.0641
502	120	Sea ice	0.0641
503	120	Sea ice	0.0641
504	60	Sea ice	0.0379
504a	60	Ice shelf	0.1010
505	60	Sea ice	0.0379
505a	60	Ice shelf	0.1010
506	60	Sea ice	0.0379
506a	60	Ice shelf	0.1010
507	60	Sea ice	0.0379
507a	120	Ice shelf	0.1549
508	60	Sea ice	0.0379
508a	120	Ice shelf	0.1549
509	60	Sea ice	0.0379
509a	120	Ice shelf	0.1549
		Overall	*0.715*

Beta parameters:

Pessimistic	alpha	beta
open water	10330.907	0.6372318
sea ice	1574.4984	0.6143415
ice shelf	521.67488	0.5648403

Scenario 1

Mission no	distance (km)	environment	P loss
501	60	Open water	0.0369
502	60	Open water	0.0369
503	60	Open water	0.0369
504	60	Ice shelf	0.2553
505	60	Ice shelf	0.2553
506	60	Ice shelf	0.2553
		Overall	*0.631*

Scenario 2

Mission no	distance (km)	environment	P loss
501	120	Sea ice	0.1859
502	120	Sea ice	0.1859
503	120	Sea ice	0.1859
504	60	Sea ice	0.1257
504a	60	Ice shelf	0.2553
505	60	Sea ice	0.1257
505a	60	Ice shelf	0.2553
506	60	Sea ice	0.1257
506a	60	Ice shelf	0.2553
		Overall	*0.851*

Scenario 3

Mission no	distance (km)	environment	P loss
501	60	Open water	0.0369
502	60	Open water	0.0369
503	60	Open water	0.0369
504	60	Ice shelf	0.2553
505	60	Ice shelf	0.2553
506	60	Ice shelf	0.2553
507	120	Ice shelf	0.3534
508	120	Ice shelf	0.3534
509	120	Ice shelf	0.3534
		Overall	*0.900*

Scenario 4

Mission no	distance (km)	environment	P loss
501	120	Sea ice	0.1859
502	120	Sea ice	0.1859
503	120	Sea ice	0.1859
504	60	Sea ice	0.1257
504a	60	Ice shelf	0.2553
505	60	Sea ice	0.1257
505a	60	Ice shelf	0.2553
506	60	Sea ice	0.1257
506a	60	Ice shelf	0.2553
507	60	Sea ice	0.1257
507a	120	Ice shelf	0.3534
508	60	Sea ice	0.1257
508a	120	Ice shelf	0.3534
509	60	Sea ice	0.1257
509a	120	Ice shelf	0.3534
		Overall	*0.973*

ANNEX H - Weibull survival Analyses of the Dr. Jenkins Scenarios - Mitigation Strategy A

Mitigation

1. D306 high impact underway fault removed I.e. their cause established and retired for future missions
2. Where successful open water/under sea ice runs are assumed pre-ice shelf, and the weibull parameters recalculated
3. Also includes Conditional probability - where vehicle monitored for first 25 km
4. Optimistic scenario only

Optimistic — **Without conditional probability through tracking** / **With conditional probability through tracking**

	alpha	beta
open water	307210.27	0.5942454
sea ice	26124.243	0.5484013
ice shelf	4217.7159	0.5320937

Mission no	distance (km)	environment	P loss	P loss	alpha	beta
501	60	Open water	0.0062	0.0025	307210	0.594
502	60	Open water	0.0062	0.0025	307210	0.594
503	60	Open water	0.0062	0.0025	307210	0.594
504	60	Ice shelf	0.0943	0.0364	4520	0.535
505	60	Ice shelf	0.0943	0.0364	4520	0.535
506	60	Ice shelf	0.0943	0.0364	4520	0.535
		Overall	*0.271*	*0.112*		

Scenario 2

Mission no	distance (km)	environment	P loss	P loss	Recalculated alpha	beta
501	120	Sea ice	0.0510	0.0297	26124	0.548
502	120	Sea ice	0.0510	0.0297	26124	0.548
503	120	Sea ice	0.0510	0.0297	26124	0.548
504	60	Sea ice	0.0327	0.0125	31244	0.544
504a	60	Ice shelf	0.0927	0.0353	4995	0.527
505	60	Sea ice	0.0327	0.0125	31244	0.544
505a	60	Ice shelf	0.0927	0.0353	4995	0.527
506	60	Sea ice	0.0327	0.0125	31244	0.544
506a	60	Ice shelf	0.0927	0.0353	4995	0.527
		Overall	*0.422*	*0.210*		

Scenario 3

Mission no	distance (km)	environment	P loss	P loss	Recalculated alpha	beta
501	60	Open water	0.0062	0.0025	307210	0.594
502	60	Open water	0.0062	0.0025	307210	0.594
503	60	Open water	0.0062	0.0025	307210	0.594
504	60	Ice shelf	0.0943	0.0364	4520	0.535
505	60	Ice shelf	0.0943	0.0364	4520	0.535
506	60	Ice shelf	0.0943	0.0364	4520	0.535
507	120	Ice shelf	0.1281	0.0751	4825	0.538
508	120	Ice shelf	0.1281	0.0751	4825	0.538
509	120	Ice shelf	0.1281	0.0751	4825	0.538
		Overall	*0.517*	*0.297*		

Scenario 4

Mission no	distance (km)	environment	P loss	P loss	Recalculated alpha	beta
501	120	Sea ice	0.0510	0.0297	26124	0.548
502	120	Sea ice	0.0510	0.0297	26124	0.548
503	120	Sea ice	0.0510	0.0297	26124	0.548
504	60	Sea ice	0.0327	0.0125	31244	0.544
504a	60	Ice shelf	0.0923	0.0352	4995	0.528
505	60	Sea ice	0.0327	0.0125	31244	0.544
505a	60	Ice shelf	0.0923	0.0352	4995	0.528
506	60	Sea ice	0.0327	0.0125	31244	0.544
506a	60	Ice shelf	0.0923	0.0352	4995	0.528
507	60	Sea ice	0.0299	0.0115	34175	0.551
507a	120	Ice shelf	0.1200	0.0700	5649	0.534
508	60	Sea ice	0.0299	0.0115	34175	0.551
508a	120	Ice shelf	0.1200	0.0700	5649	0.534
509	60	Sea ice	0.0299	0.0115	34175	0.551
509a	120	Ice shelf	0.1200	0.0700	5649	0.534
		Overall	*0.640*	*0.386*		

ANNEX H - Weibull survival Analyses of the Dr. Jenkins Scenarios - Mitigation Strategy B

Mitigation
1. D306 high impact underway fault removed I.e. their cause established and retired for future
2. Simulates June 2008 trials and its one HIU fault included
3. Also includes Conditional probability - where vehicle monitored for first **25** km
4. Optimistic scenario only

Optimistic	**Without conditional probability through tracking**			**With conditional probability through**
	alpha	beta		
open water	510584	0.5591252		
sea ice	27283	0.5492827		
ice shelf	3718.2239	0.5369655		

Scenario 1

Mission no	distance (km)	environment	P loss	P loss
501	60	Open water	0.0063	0.0025
502	60	Open water	0.0063	0.0025
503	60	Open water	0.0063	0.0025
504	60	Ice shelf	0.1033	0.0401
505	60	Ice shelf	0.1033	0.0401
506	60	Ice shelf	0.1033	0.0401
		Overall	**0.293**	**0.122**

Scenario 2

Mission no	distance (km)	environment	P loss	P loss
501	120	Sea ice	0.0495	0.0289
502	120	Sea ice	0.0495	0.0289
503	120	Sea ice	0.0495	0.0289
504	60	Sea ice	0.0341	0.0132
504a	60	Ice shelf	0.1033	0.0401
505	60	Sea ice	0.0341	0.0132
505a	60	Ice shelf	0.1033	0.0401
506	60	Sea ice	0.0341	0.0132
506a	60	Ice shelf	0.1033	0.0401
		Overall	**0.442**	**0.221**

Scenario 3

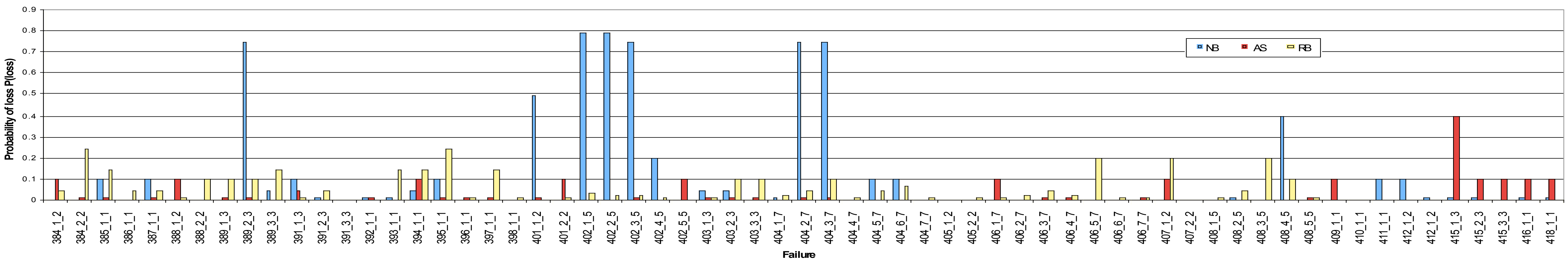
Mission no	distance (km)	environment	P loss	P loss
501	60	Open water	0.0063	0.0025
502	60	Open water	0.0063	0.0025
503	60	Open water	0.0063	0.0025
504	60	Ice shelf	0.1033	0.0401
505	60	Ice shelf	0.1033	0.0401
506	60	Ice shelf	0.1033	0.0401
507	120	Ice shelf	0.1464	0.0861
508	120	Ice shelf	0.1464	0.0861
509	120	Ice shelf	0.1464	0.0861
		Overall	**0.560**	**0.330**

Scenario 4

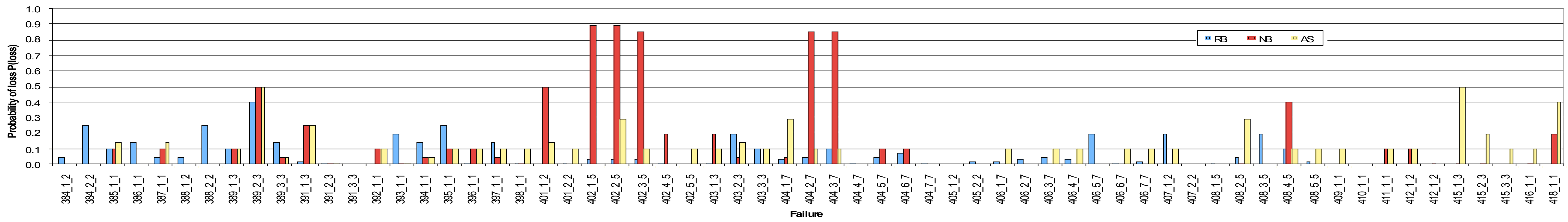
Mission no	distance (km)	environment	P loss	P loss
501	120	Sea ice	0.0495	0.0289
502	120	Sea ice	0.0495	0.0289
503	120	Sea ice	0.0495	0.0289
504	60	Sea ice	0.0341	0.0132
504a	60	Ice shelf	0.1033	0.0401
505	60	Sea ice	0.0341	0.0132
505a	60	Ice shelf	0.1033	0.0401
506	60	Sea ice	0.0341	0.0132
506a	60	Ice shelf	0.1033	0.0401
507	60	Sea ice	0.0341	0.0132
507a	120	Ice shelf	0.1464	0.0861
508	60	Sea ice	0.0341	0.0132
508a	120	Ice shelf	0.1464	0.0861
509	60	Sea ice	0.0341	0.0132
509a	120	Ice shelf	0.1464	0.0861
		Overall	**0.687**	**0.429**

ANNEX I - FAILURE PROBABILITY JUDGMENT DISTRIBUTION FOR ANNEX B

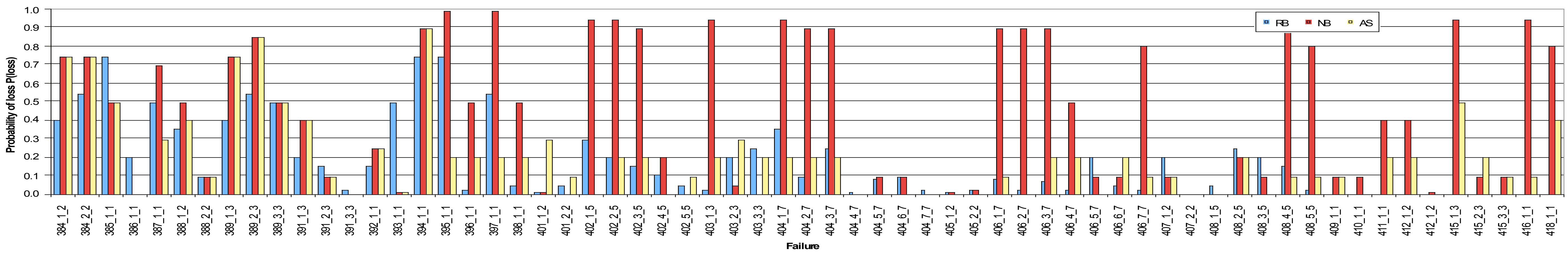
OPEN WATER



COASTAL WATER



SEA ICE



ICE SHELF