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Analysis of causation of loss of communication with marine autonomous systems: A probability tree approach

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ABSTRACT

The last decade has seen the eagerly anticipated introduction of marine autonomous systems as a pragmatic tool for ocean observation. However, outstanding reliability problems means that these vehicles are not yet fulfilling their true potential. Of the classes of problems, loss of communication with a marine autonomous system is both fundamental and difficult to diagnose. In our view, this is due to two reasons: first in many cases users are not technologists and secondly if a vehicle is lost the task of diagnosing the root cause is subject to epistemic uncertainty that users are often reluctant to quantify in a formal manner. As a result users may accept the first hypothesis considered as the main root cause for loss of communication. We show that this approach can result in an increased unreliability of marine autonomous systems through failure to ascertain and then address the true root causes. Consequently, we propose a probability tree approach to help diagnose root cause(s) for loss of communication with a marine autonomous system (MAS). The model was developed based on the results of two detailed investigations and a body of failure data collected from 205 undersea glider operations.

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1. Introduction

Our understanding of marine physical, biological and geological processes forms the basis for the implementation of local, national, and international strategies for addressing major societal and global challenges (European Marine Board, 2013).

For many years ocean monitoring has been heavily dependent on the use of research ships (Martin, 2005). However there are significant limitations with ship based monitoring. From the financial perspective, the cost is heavily dependent on fuel price and this has an increasing trend. From the ocean sampling perspective, ship based observations do not allow us to understand complex large and mesoscale processes (Martin, 2005). A typical ship survey takes approximately 3 days to sample a 150 × 150 km area. This is not fast enough to map the physical circulation before it changes, the asynopticity problem (Allen et al., 2001). Satellites can be used to infer the ocean circulation but cannot observe subsurface properties (Martin, 2005).

The last decade has seen the eagerly anticipated emergence of underwater gliders as a practical tool for marine science (Webb et al., 2001; Sherman et al., 2001; Eriksen et al., 2001). Underwater glider manufacturers and users have presented several case studies showing the effective use of these platforms for oceanographic research. For example, the University of Washington deployed Seagliders through most of 2005 in the subtropical North Pacific gyre to help quantify the net community production at station ALOHA (A Long-term Oligotrophic Habitat Assessment) in the Hawaii Ocean Time (HOT) series (Nicholson et al., 2008). The Scripps Institution of Oceanography used an array of Spray gliders to measure the El Niño effect on the California Current Circulation between October 2006 and October 2010 (Todd et al., 2011). The manufacturer of the Slocum glider, Teledyne Webb Research, supported the Rutgers University Coastal Ocean Observation Laboratory in the deployment of a fleet of underwater gliders to obtain time series of transects across the New Jersey shelf (Glenn et al., 2008). A more recent effort from this partnership is the successful crossing of the Atlantic ocean with a Slocum glider (Rutgers, 2013). The community of underwater glider users is rapidly increasing, not only providing new demands for survey design and longer glider presence (L'Hévéder et al., 2013; Hodges and Fratantoni, 2009; Alvarez and Mourre, 2012a,b) but also requiring ease of use and confidence in completing deployments. Underwater gliders have also a very important role in future Autonomous Ocean Sampling Networks (AOSN) (Curtin et al., 1993; Ramp et al., 2009). However, in light of the reliability issues, there is insufficient confidence that underwater gliders will operate for long missions (Brito et al., in press). In this study the authors quantified the reliability of underwater gliders based on the data of an unbiased group of users, which comprised 205 missions conducted by 12 European institutes. The research concluded that the probability of a shallow underwater glider having pre-mature mission end due to technical failure, in a 30 day mission, is 0.59; and for a deep glider, the probability of pre-mature mission end, for a 90 day mission, is 0.5.

Studies of glider risk hitherto reported have focused on the risk of collision with ships (Merckelbach, 2013a), risk of loss or of technical failure (Brito et al., in press), or risk of not achieving the sampling objectives due to adverse currents (Pereira et al., 2011). In these studies, the authors provide means to mitigate specific risks. The problem of fault diagnosis for long endurance autonomous vehicles, operating with very limited communications has not been addressed.

A method for diagnosing internal faults for propeller-driven autonomous underwater vehicles was proposed by Dearden and Ernits (2012). The authors propose a discrete, consistency based diagnosis system, which diagnoses faults by finding inconsistencies between predictions made by the model and telemetry on the states of the internal sensors of the system. A fundamental element of this model-based diagnosis (MBD) is a discrete state diagram of the vehicle's internal functionality. Their case study was designed to help diagnose faults in a subset of Autosub 6000 autonomous underwater vehicle (AUV) critical systems: depth control, rudder control and batteries.

As far as we are aware the task of diagnosing faults has not been addressed for underwater gliders. On underwater gliders, as on marine autonomous systems (MAS) in general, the main failure concern is loss of communication. If communication is lost it becomes impossible to pilot the underwater glider and in addition vehicle recovery becomes difficult and often impossible.

When one investigates an accident one needs to choose between different possible explanations. The task of diagnosing the root cause for an accident is therefore a decision problem. Many decision supporting techniques have been proposed over the years (Raiffa, 1968). These techniques force the decision maker to specify a utility or a value to each potential decision. However, for an investigation there is no value or utility associated with a potential failure path. Instead the task of diagnosing the root cause for failure can be captured with a type of decision tree denoted as a probability tree (Raiffa, 1968).

In this paper we propose a probability tree to diagnose the root cause for communication faults in an MAS. In essence, hypotheses that may explain the loss of communication are captured in the probability tree.

The European Framework 7 project Gliders for Research, Ocean Observation and Management (GROOM)[1] resulted in a collective effort, from all project partners, to understand and quantify underwater glider reliability. As a result this project collected details of 205 underwater glider missions, which included, amongst other parameters, missions length, maximum depth, whether or not the mission ended prematurely, and if so, what was the root cause (Brito et al., in press). The probability tree proposed in this paper is designed based on the analysis of previous investigations in which root causes are known with a reasonable confidence and a body of data from 65 incidents that occurred with underwater gliders operated by six different glider operation centres (Brito et al., in press).

When we developed a probability tree for diagnosing failure to establish communication with an underwater glider we realised that this diagnosis model could also be used to diagnose failure to establish communication with any marine autonomous system, which includes propeller-driven underwater vehicles and surface vehicles.

This paper is organised as follows. Section 2 gives some background to communication methods implemented on marine autonomous systems, drawing especially on underwater gliders. In Section 3 we present the theory supporting the implementation of probability trees. In Section 4 we describe two documented events that led to loss of communication with underwater gliders. The proposed probability tree for diagnosing loss of communication with a marine autonomous system is presented in Section 5, with the conclusions in Section 6.

2. Background

The primary means of communication between an operator and a marine autonomous system is generally by through-air radio (Webb et al., 2001; Sherman et al., 2001; Eriksen et al., 2001). There are some circumstances where through-water acoustic communication is used, and some evolving specialised applications, such as near a docking station, where short-range through-water light beam communications are feasible and suitable (Chitre et al., 2008).

As through-air radio communications is the primary means, it requires underwater vehicles to surface (or deploy a surfacing float with antenna) and clearly, the method is eminently suitable for marine autonomous surface or airborne vehicles. The exact solution chosen depends on the vehicle type and the manufacturer, but generally solutions fall into two main categories: satellite, and Ultra High Frequency (UHF) or microwave terrestrial line-of-sight.

Vehicle manufacturers may offer one or both of satellite and terrestrial options. While some users may add additional one-way, vehicle-to-shore communications links, to provide a degree of redundancy in being able to locate a vehicle (for example an ARGOS beacon), it would be unusual for a user to add a secondary two-way communication channel to a vehicle where that facility had not been provided by the manufacturer.

Potential vulnerabilities in these communications systems include:

- No communications is possible if the vehicle fails to surface.
- Inappropriate user commands or combinations of commands.
- Software errors in the vehicle or in the communications modems.

[1] http://www.groom-fp7.eu/doku.php.

- Component failure in the vehicle modems or their interconnecting cables.
- Physical damage to the antennas or water ingress into the antennas.
- Problems somewhere along the chain between vehicle and user when using satellite communications.
- Problems at the user location with antennas, modems, software and user understanding of electromagnetic signal transmission (Griffiths, 2012).

The difficulty in the diagnosis of the root cause for failure to establish communication is that a set of symptoms may indicate that two or more of the explanations above could be true. This is a type of epistemic uncertainty denoted as subjectivity (Colyvan, 2008). The challenge is to accurately quantify this uncertainty so risk mitigation procedures are robust, resulting in reliability improvement.

Therefore, there are two different aspects to the problem of diagnosing the root cause for failure to establish communication with an MAS. First is the identification of different hypotheses and second is the quantification of the likelihood of each hypothesis leading to failure to establish communication with an MAS. In the next section we present a probability formalism that allows us to do both.

3. Probability trees

There a number of paths that can explain the sequence of events that led to loss of communication with an MAS. Therefore, the task of diagnosing the root cause for failure to establish communication is a decision problem. A decision problem comprises two components: how to structure the problem and how to structure the preferences.

The structuring of the problem requires identification of all possible actions and definitions of how they are linked to other actions. The preference structuring deals with how to organise the decision maker actions according to a set of preferences. Graphical decision trees or influence diagrams are typical approaches for structuring a decision problem (Raiffa, 1968).

We decided to use probability trees for modelling the decision problem of diagnosing failure to establish communication with an MAS because of their reliance on an integrative approach of graphical and analytic presentations. The graphical component is descriptive and simple to understand. The analytical component builds on Bayes' theorem (Pearl, 2000).

A probability tree comprises a number or branches, also denoted as nodes. Each node captures an event. A node can lead to another node until the decision problem cannot be broken into further nodes. The end node in that sequence is denoted as a leaf. For the purpose of our problem, a leaf in the decision problem captures a root cause.

A generic decision tree is presented, in Fig. 1, for helping to diagnose the root cause for failure $\mathcal{D}$. At level 1, it is possible to take decision that one of the hypotheses $\mathcal{H}_i$, with $i = 1, N$, is the cause for failure $\mathcal{D}$. The likelihood ($\mathcal{L}$) of $\mathcal{H}_i$ given failure $\mathcal{D}$ is θ_i, $\mathcal{L}(H_i|\mathcal{D}) = \theta_i$. The model captured in a probability tree must obey the basic law of probability. Therefore the sum of all likelihoods in each level must be equal to one.

If the aim is to add more details, then the decision maker must identify the causes for the hypothesis in level 1. If we consider the first hypothesis, $\mathcal{H}_1$, the decision maker can further break down the decision into branches $\mathcal{H}_{1,j}$ with $j = 1, \ldots, M$. The likelihood of a sequence of decisions being correct is calculated using the product rule (Raiffa, 1968). For example, the likelihood of the sequence of decisions ($\mathcal{H}_1$, $\mathcal{H}_{1,1}$) being correct given the occurrence of $\mathcal{D}$ is $\mathcal{L}(\mathcal{H}_1, \mathcal{H}_{1,1}, \mathcal{D}) = \mathcal{L}(\mathcal{H}_1|\mathcal{D}) \cdot \mathcal{L}(\mathcal{H}_{11}|\mathcal{H}_1) = \theta_1 \cdot \theta_{1,1}$.

A probability tree can be constructed via induction, for example using data mining techniques, or deduction. The loss of communication with an MAS is subject to epistemic uncertainty. This uncertainty can be captured in expert judgement. In this case a probability tree is deduced from a human expert.

In the next section we describe two incidents of loss of communication where the most likely root cause can be diagnosed by a probability tree. The probability assignments for each path, where possible, must be informed by evidence. A modest amount of probability theory is required to provide these assessments and to ensure consistency in the assignments.

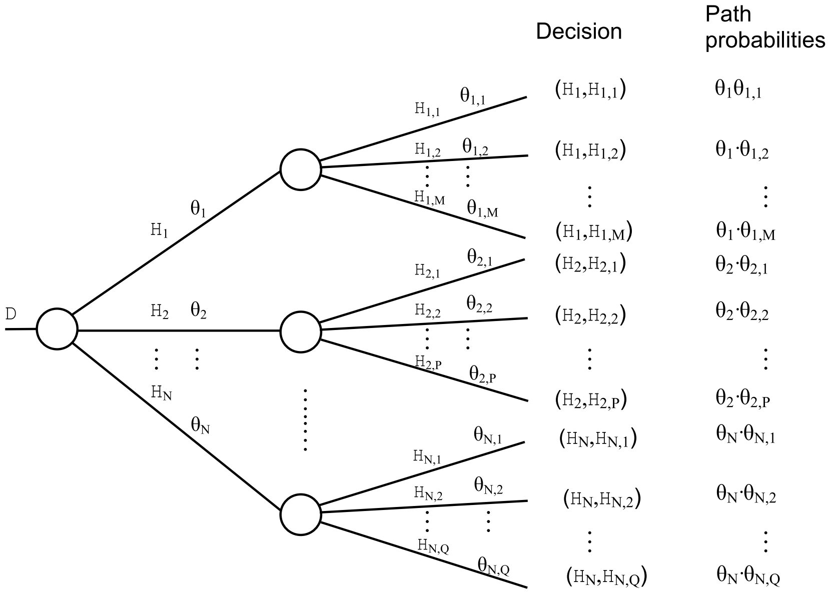

Fig. 1. Generic probability tree for a combinatorial decision problem capturing a sequence of two decisions.

When dealing with a panel of experts, the assessments can be aggregated mathematically or behaviourally. In a mathematical aggregation, experts provide their assessments individually, and these are combined using analytical methods. In behavioural aggregation the experts must agree of a judgement that represents the groups' views. More details about these different types of expert judgement elicitation are given in O'Hagan et al. (2006). For the formal accident investigations presented in the following sections a behavioural approach for eliciting expert judgements was used.

4. Past events and operational data

Most often one learns about incidents in informal discussions, in the form of an anecdote rather than objective analysis. In the following sub-sections we present summaries of two events that led to loss of communication that were the subject of rigorous investigation, to act as case studies for the probability tree approach argued in this paper and also to encourage others to perform root cause analysis and share their findings. We then draw on the results of a study of the reliability of gliders being used by European marine laboratories to give a broader context to the problem of loss of communication.

4.1. Past events

This section presents a summary of two formal investigations into the loss of communication with an underwater glider. The investigations were conducted by an expert panel, which consisted of senior engineers, scientists and mariners. In both investigations, a probability decision tree was used to structure the hypothesis that could explain the loss of communication with the underwater glider.

The expert panel process, as well as identifying the most likely cause for loss of communication also resulted in a number of recommendations that would reduce the likelihood of loss if similar events occurred again. A summary of recommendations is presented in Appendix B of this paper.

4.1.1. Seaglider SG531 off the coast of El Hierro, Canary Islands

In October 2011, the underwater eruption of a volcano off the coast of the island of El Hierro led to major public concern, particularly in the Canary Islands, about potential impacts to public safety (Martí et al., 2013).

On October 17, the Oceanic Platform of the Canary Islands (PLOCAN) made a request to use the National Oceanography Centre's underwater glider to monitor the water conditions close to the volcano site. NOC's Seaglider SG531 'Altair' was awaiting deployment from Gran Canaria as part of NERC's RAPID-WATCH programme (RAPID-WATCH, 2013). This vehicle was commissioned to carry out the mission objectives set by PLOCAN. SG531 was deployed on the 19th of October 2011. Problems connecting the glider to the PLOCAN basestation meant that the vehicle had to be piloted by technicians from the National Oceanography Centre, based at Southampton, UK, under instruction from scientists at PLOCAN. The problems connecting the glider to the PLOCAN basestation were not diagnosed.

Prior to handing the vehicle over to PLOCAN a series of events took place; these were deemed relevant to the later investigation. On March 6th 2011, iRobot conducted shallow water tests prior to the shipment of the glider to NOC. These consisted of 15 shallow water dives of approximately 12 h. The manufacturer concluded that the glider was in good order. On May 19th, 2011, the glider was tested at NOC prior to the shipment to Gran Canaria. On the 5th of July 2011, pre-deployment tests on Gran Canaria found problems with the Iridium communications. As a result, the deployment was cancelled and iRobot informed. On the 8th of July 2011, iRobot performs further tests using an iRobot basestation, concluding that the modem needed replacing. On the 11th of July 2011, iRobot engineer attends on Gran Canaria and replaces the malfunctioning modem. At this stage the communication issues with the glider seemed to have been solved.

On the morning of October 18th PLOCAN team runs test dives and prepares for deployment. Communications problems emerged. The manufacturer recommends an antenna change. This modification was carried out and later that day the glider is shipped by helicopter to El Hierro. On October 19th successful communication is established between the glider and the NOC basestation. PLOCAN asks NOC to pilot the Seaglider and the vehicle is deployed at 13:45. On October 19th at 16:29, following three successful dives the glider is set on its way to the first waypoint. On October 20th, the glider completes 11 dives with maximum depth varying from 300 to 400 m. On October 20th, 08:03, the vehicle depth was increased to 1000 m. PLOCAN was expected to take over piloting from this point onwards. On October 20th, 11:30, the last communication from the glider was received. On October 21st, 20 h since last communication, PLOCAN conducts visual search along the glider track. No sighting of the glider. On October 24th, PLOCAN conducts acoustic search, with no response. At this point the search for the glider was stopped.

Following loss of the glider an expert panel was convened comprising scientists and engineers from NOC and PLOCAN and engineers from iRobot. A number of hypotheses were proposed by the experts and these were organised into a probability tree (Fig. 2). For some hypotheses agreement on the likelihood was agreed at a meeting of the panel. For others it was decided to pursue further investigations to quantify their likelihood.

The investigation tested several hypotheses. Analyses of the operational data from the last dive and a study of the last mission script indicated that the systems on the underwater glider were working normally before disappearing. Analysis of the assembly procedure of the antenna did not identify a fault with the procedure. Data from the glider was used to diagnose the mass of the glider during each dive and no evidence was found for the hypothesis that the material in the water column had accreted on the vehicle. The outcome of the investigation was that modem failure was most likely to have caused failure to communicate with the glider (Probability = 0.46).

4.1.2. University of East Anglia's Seaglider SG522 loss

On the 20th January 2012 *RRS* James Clark Ross set sail from Port Stanley, for a campaign in the Northwest Weddell Sea, with five underwater gliders onboard. This cruise was led by the University of East Anglia, UK. Seaglider SG522 ('Beluga') was deployed at around midday, at 63.37° S, 52.98° W, on 23rd of January 2012. SG522 lost communication on 14th of February 2012 13:15 UTC after

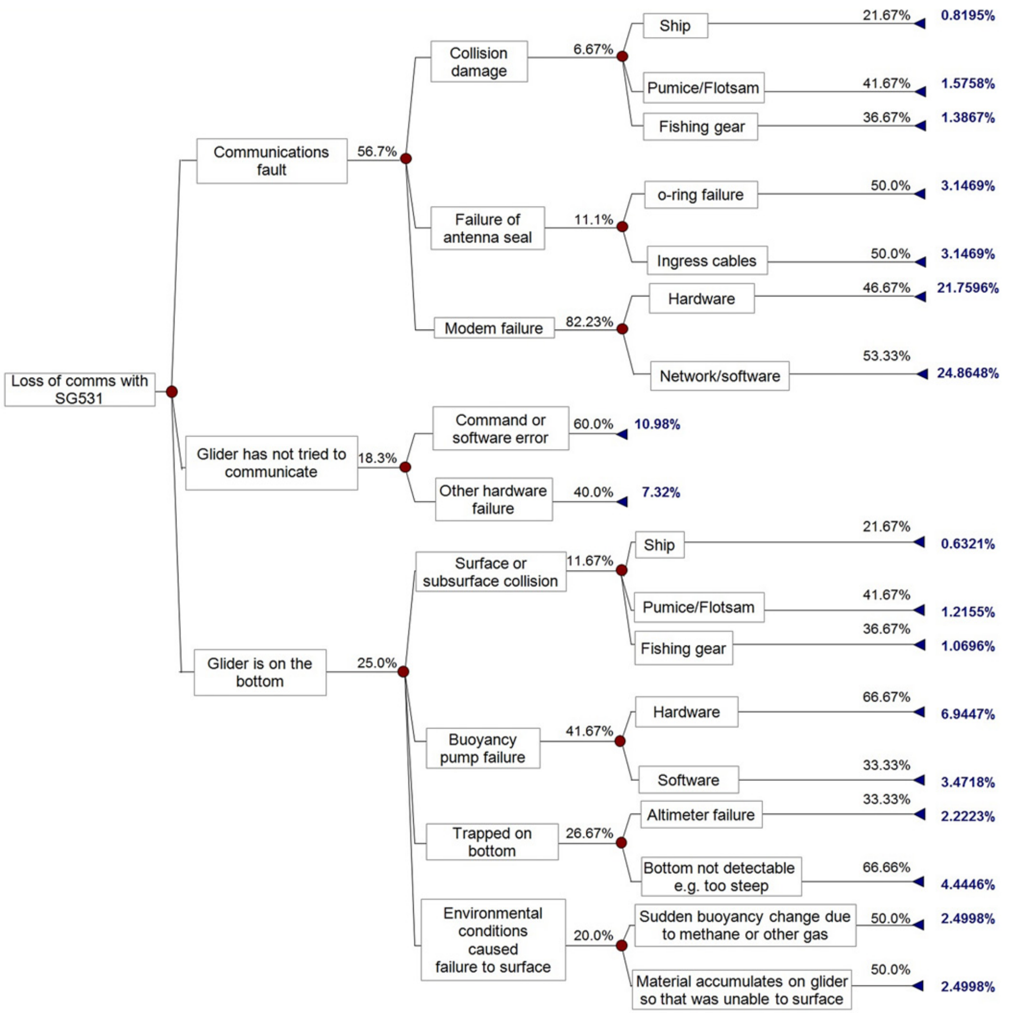

Fig. 2. Probability tree for the loss of communication with Seaglider SG531 off the coast of El Hierro, Canary Islands.

completing 156 known dives. Attempts at recovery were made using the ARGOS positioning but were unsuccessful. Recovery attempts for SG522 were aborted on 14th of March 2012 at 13:00 LT (16:00 UTC). An inquiry was held to establish the root cause for the loss of communication. The inquiry panel concluded beyond doubt that the last command script sent to the glider, after dive 156, inadvertently contained a combination of parameter values that put the vehicle in an unsafe state; the script set the Seaglider to make Iridium calls whilst it was under water. The probability tree used for supporting this investigation is presented in Fig. 3. The command script is presented in Appendix A (see Fig. A.1).

4.2. Historic data from the GROOM project

The underwater glider reliability study conducted for the European Commission funded project, Gliders Research for Ocean Observation and Management (GROOM) collected glider operational data from year 2008 to 2010 (Brito et al., in press). The data collected as part of this project was used to support the arguments captured in the probability tree presented in this paper. A total of 205 underwater glider missions were recorded during this period. During the period of this study ten

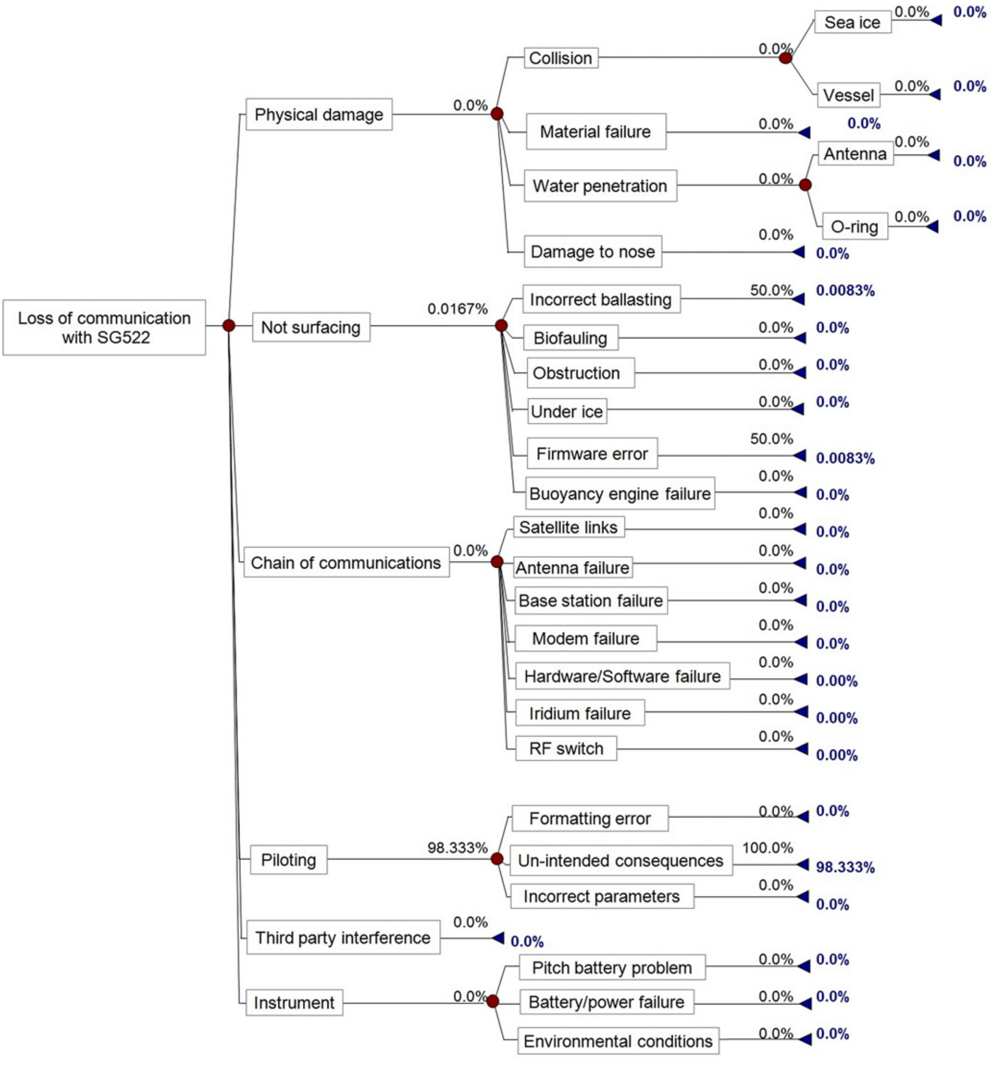

Fig. 3. Probability tree for the loss of communication with Seaglider SG522 'Beluga' near the Drake Passage.

gliders were lost: three Slocums and seven Seaglider1000s. The causes for Slocum losses are unknown. The Seaglider1000 losses are suspected to have been caused by:

- Iridium communication failure (three gliders): iRobot's SG546 (TFP), NOC/PLOCAN's SG531 (Altair) and Alfred Wegener Institut für Polar und Meeresforschung's (AWI) MK501 (Brito et al., in press).
- Power/battery failure (two gliders): AWI's MK 557 and MK 544 (Brito et al., in press).
- Command and control failure (one glider) SG522 (UEA) (Merckelbach, 2013b).
- Collision with a vessel (one glider), SG507 'Narwhal' (UEA) (Webber, 2013).

With these facts it is not possible to conclude that one underwater glider make is more prone to loss of communication than the other. In fact, in Brito et al. (in press) the authors showed that the differences in the loss rate for Seagliders and Slocums were not statistically significant.

5. Diagnosis model for loss of communication with marine autonomous systems

When a loss of communication occurs it is important to quickly diagnose the reasons. In this section we present a causation model that captures possible explanations for the loss of communication. The model can be applied to diagnose loss of communication with any type of MAS.

The hypotheses presented in this section can be organised in a probability tree. To maintain simplicity we argue that at level 1 there are three main causes for loss of communication with an MAS:

- The vehicle is on the surface and it has not established communication because there is a communication fault.
- The vehicle is on the surface, there is no communication fault, rather the vehicle has not tried to communicate.
- We assume that the vehicle is underwater, where communication with a shore based station is impossible.

These hypotheses are mutually exclusive. In the next sub-sections we decompose each of these failure modes to identify potential failure paths that give structure to the probability tree, taking into account events that have happened and those that could happen.

In the following sections we consider each hypothesis for level 1 in turn. Details about the hypothesis for levels 2 and 3 are discussed in their respective sections. To facilitate the interpretation of the discussions we provide exploded diagrams of both Slocum G2 and Seaglider as supplemental material which can be found online at http://dx.doi.org/10.1016/j.mio.2014.07.003.

5.1. Communications fault

This hypothesis captures the scenario where there is a communication failure and the evidence suggests that the vehicle is on the surface. Communication failure can be caused by collision damage, leak damage or modem failure. Here we consider the communication failures from the MAS perspective.

Communications are sometimes lost due to problems with systems external to the MAS. For example, there maybe interruptions to the satellite services or internet connections, or there may be hardware or software failures of the user's communications server. However users and service providers are normally able to test these and take action to rectify their equipment and such interruptions are temporary and so we do not consider them further here.

Loss of communication caused by damage resulting from a collision with a vessel has occurred before. The University of East Anglia's Seaglider, SG 507 "Narwhal", lost communication (and was subsequently lost) after a collision on the 24th of March 2010. However, there are incidents where a collision with a vessel has not resulted in loss of communication. The Centre National de la Recherche Scientifique (CNRS) has recorded three glider collisions with vessels, resulting in mission aborts but not loss of communication.

Environment-specific factors such as flotsam may also cause damage to the vehicle, especially antennas, affecting communications. Close to a coast where there are rocks and tidal currents there is a likelihood that the vehicle will suffer damage beyond repair (Griffiths and Trembanis, 2007).

Leaks on MAS can lead to communication failure by destroying the electronic boards inside the vehicle, as has occurred on CNRS's Slocum glider Nearchos during mission Elodie (Beguery, 2013a) or by affecting cables and connectors, for example a leak inside the tail fin/rudder assembly on a Slocum glider may lead to water running inside and outside the antenna cable. Slocum gliders have moisture sensors for detecting leaks and on Seagliders humidity in the vehicle is monitored. Thus in cases where a slow rather than catastrophic leak leads to loss of communication it is very likely that the user will have evidence of the leak from data received prior to the loss of communication.

We identified six main causes for leaks. A leak can occur due to an antenna seal failure, sensor leak, a stern tube failure, O-rings failures, pressure-sensing port failure, or vacuum port failure. Previous research has shown that leaks are the most frequent cause for premature mission termination on underwater gliders (Brito et al., in press). CNRS had eight leaks prior to the leak reported in Beguery

(2013b), none of those leaks led to loss of communication. Two of those leaks were antenna cable water ingress, two were sensor leaks. In one incident the pressure tube was separated and the other incident was a leak in the Bellow frame. In all these cases the amount of water was not sufficient to cause loss of communication.

In contrast, the Slocum G1 glider (Willy) operated by CSIC, Spain had a loss of communication that lasted approximately 4 months. Deployed on 25th February, 2008 north of Mallorca it was found on 11th June 2008 on a beach in Porto Gulf (West Corsica) (Simón, 2013a,b). After evaluation of the damage, the supplier concluded that there was a design error in the hull that favoured a significant leak, which destroyed all the internal communication systems (Iridium, GPS, Argos) (Martínez and Ruiz, 2008).

In terms of technical failure, GROOM missions suggested that for those deployments modem failure was most likely caused by hardware or software problem, Fig. 4. The Seaglider SG531 Altair loss of communication is thought to have been caused by a modem software failure (Section 4.1.1).

5.2. *MAS has not tried to communicate*

What if one is very confident that the systems are working and that the vehicle is on the surface, what can cause failure to communicate? At a higher level we have identified two failure modes, piloting failure and other hardware failure.

Three independent events can result from piloting error:

- An unintended result from a combination of parameters (e.g. Section 4.1.2). Some autonomous vehicles use mission script checkers to verify that the combination of parameters will not put the vehicle in an unsafe situation. Other manufacturers give more freedom to the user to set parameters (Griffiths, 2012).
- Incorrect choice of parameters.
- Formatting error by the pilot, where the vehicle does not then read the intended parameter value.

Unintended consequences have, on some occasions, led to loss of communication. This can occur because a mission script is not set correctly or because the mission planning or a hardware failure puts the vehicle in an un-expected configuration. The underwater glider SN205 owned by Helmholtz-Zentrum Geesthacht Zentrum für Material und Küstenforschung GmbH (HZG) lost communication due to a battery failure. However, it was later discovered that the pilot misjudged how quickly a battery would deplete, compounded by recovery a day later than planned. Due to the depleted batteries, Iridium communications caused a low voltage abort, that could not be fixed, as that would require stable Iridium communications (Griffiths, 2012).

We have no examples in the GROOM dataset of where incorrect parameters led to loss of communication, but we do postulate that failure due to incorrect parameters is a possibility.

5.3. *MAS is below the surface*

The scenarios considered in the previous sub-sections assume that the vehicle is able to reach the sea surface and that a technical or human fault is stopping communication from taking place. Here we consider that the loss of communication is because the vehicle is not able to reach the sea surface.

At the highest level, failure to reach the sea surface can be caused due to a surface or sub-surface collision; hardware fault; the vehicle is trapped on the bottom; or due to incorrect ballast. The hypotheses identified for surface or sub-surface collision are the same as those identified for collision damage, discussed in Section 5.1. However, here, instead of considering that the factors captured in these hypotheses will cause damage to the vehicle communication systems we consider that these factors will stop the vehicle from reaching the sea surface. For example, during deployments in Polar Regions we argue that collision with sea ice would not allow the vehicle to reach the surface rather than causing irreversible damage to the vehicle.

Hardware failures can also cause the vehicle to remain underwater. These hypotheses are not backed by hard evidence, since the GROOM database does not have examples of when the buoyancy engine, pitch battery or battery failure kept the vehicle underwater, unable to communicate.

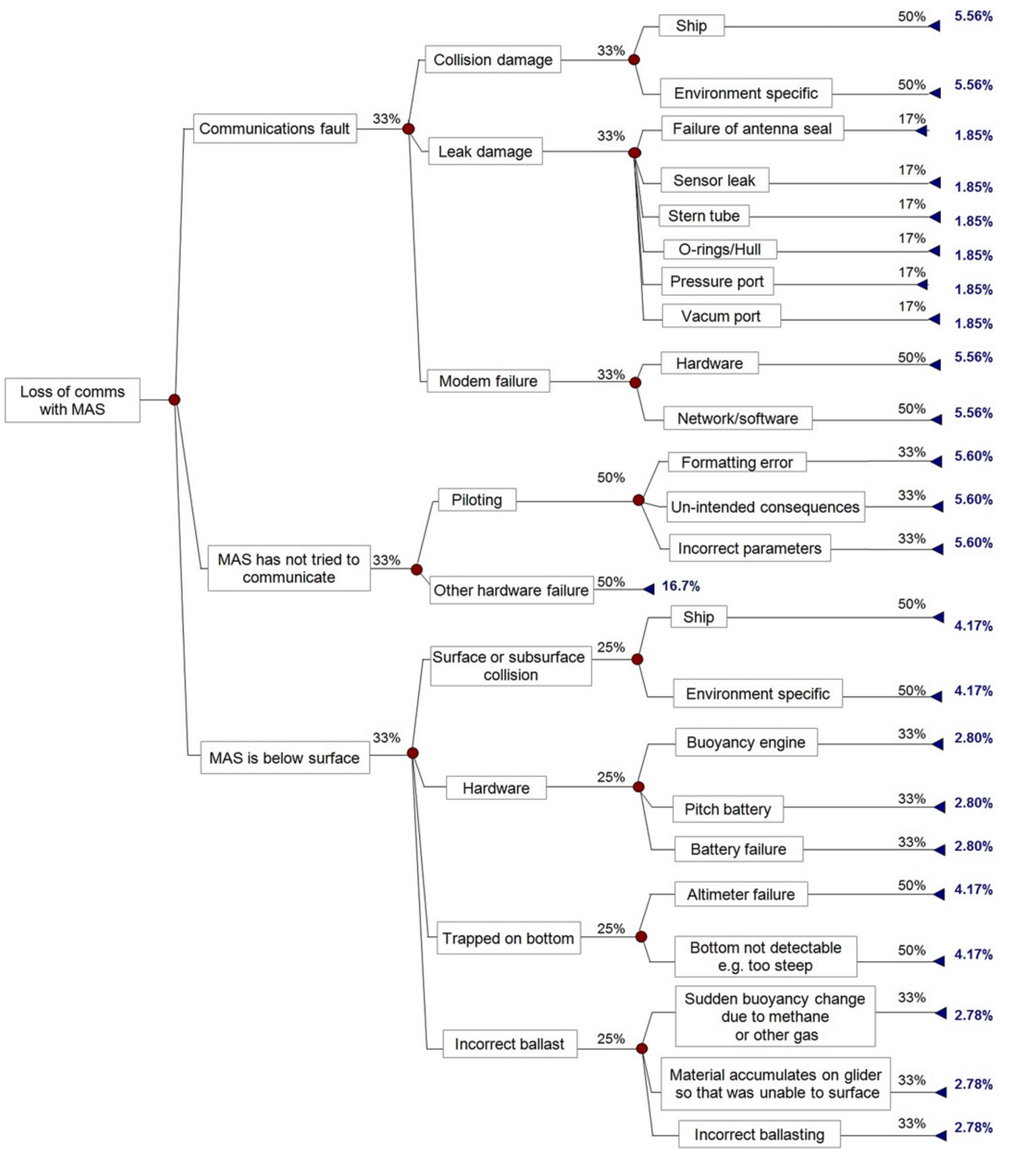

Fig. 4. Causation model for loss of communication with MAS.

6. Discussions

The probabilistic tree for supporting the diagnoses of the root cause for communication failure is generic. Whilst some branches of the tree apply to underwater vehicles only, for example buoyancy pump failure or underwater collision, other branches apply to autonomous surface vehicles also, for example piloting error or leak damage.

The application of the proposed probabilistic tree starts from left to right. Experts must provide their estimates of likelihood that a communication failure was caused by the three hypotheses identified in level 1. The likelihoods given to all hypotheses need to add to 100%. As illustrated in Section 3, the same process is carried out for the other branches.

There are several fault defence systems on MAS. For example leak detection sensors and collision avoidance systems. Failure of defence mechanisms are not captured, explicitly, on the probabilistic tree. The effectiveness of these mechanisms must therefore be considered in the assessments of the hypotheses that they may affect.

7. Conclusions

Arguably, loss of communication with a marine autonomous system is the most critical fault in marine autonomous systems—this is discussed in detail in Section 2 of this paper. The work presented in this paper builds on previous research, in which the issue of loss of communication was highlighted as a frequent type of failure but the root cause for such incidents was not addressed.

Incorrect fault diagnosis occurs with alarming frequency. In our research we have found situations where a fault initially diagnosed as a battery fault was in fact a leak, traced back to human error.

When incidents are not formally investigated faults can easily be misdiagnosed, resulting in an increased unreliability of a system and a lost opportunity to correct the underlying problem.

In this paper we proposed a probability tree for diagnosing the root cause for failure to communicate with a marine autonomous system. The probability tree was developed, largely, on incidents that led to loss of communication but some branches comprise hypotheses that arose during formal incidents investigations, in which these hypotheses have been identified as potential causes for loss of communications, these were discussed in Section 4.

The huge benefit of the proposed probability tree is that it encourages the investigation team to consider a breadth of events that can lead to loss of communication. So, in addition to help identifying the most likely root cause, the investigation team can also identify near misses. The correction of issues identified as factors in near misses can increase the reliability of the marine autonomous system. A summary of the recommendations for improving underwater glider reliability, based on the investigations of the incidents presented in Section 4 is presented in Appendix B of this paper.

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Appendix A. Details on the command file sent to Seaglider SG522 after dive 156

The command file was sent to the glider to avoid drifting sea ice which was heading North West after a change in wind direction. The last command file is presented in Fig. A.1. The relevant details within this command file were:

$*NAV_MODE*, 0—This command switched off the glider's navigational mode, where it headed for its navigational way-points and instead used a different mode of navigation.

$*HEADING*, 0—This command instructed the glider to head on a path Northwards at a bearing of 0°. This command was intended to fly the glider to an area free of sea-ice.

$*N_NOSURFACE*, 2—This command instructed the glider to only surface on alternate dives. When the glider did not surface, it finished the dive at a depth of 5 m.

($*D_FINISH*, 5). The command was again initiated in an effort to avoid the sea-ice, potentially at the surface.

$*ALTIM_PING_DEPTH*, 350—This is the depth at which the glider initiated its acoustic transponder to start pinging to identify the bottom. Although irrelevant in this context this command later became relevant in that its power consumption aided in using the battery power and putting the glider into recovery mode (in conjunction with science instruments).

```
Cmdfile.156
        $C_ROLL, 2433
        $C_ROLL_CLIMB, 2210
        $NAV_MODE, 0
        $HEADING, 0
        $ALTIM_PING_DEPTH, 350
        $ALTIM_SENSITIVITY, 2
        $D_TGT, 990
        $T_DIVE, 280
        $T_MISSION, 400
        $CALL_TRIES, 5
        $CALL_NDIVES, 2
        $UPLOAD_DIVES, 2
        $UPLOAD_DIVES, 2
        $UPLOAD_DIVES_MAX, 1
        $T_NO_W, 240
        $SM_CC, 250
        $N_NOSURFACE, 2
        $D_FINISH, 5
$GO
```

Fig. A.1. The last command file sent to SG522 (when still communicating) is detailed in Appendix A.

$CALL_NDIVES, 2—This is also a critical line, its unintended interaction with $*N_NOSURFACE*, 2 is crucial as detailed below (Bozzone, 2012).

The investigation of the log files showed that the pilot made the following changes which resulted in the loss of Iridium communications:

$*N_NOSURFACE* was enabled going from 0 on dive #156 to 2 on dive #157
$CALL_NDIVES was changed from 1 on dive #156 to 2 on dive #157.

These commands have the following implications:

N_NOSURFACE, 2 specifies that the glider is to do subsurface finishes when the DiveNumber/2 has no remainder (even numbered dives) and do surface finishes when the DiveNumber/2 has a remainder (odd numbered dives).
CALL_NDIVES, 2 specifies that the glider makes an Iridium call every 2nd dive based on the last dive number. In this case the last dive number was 156 so picking up the new command on dive 157 means that the glider will not attempt to make a call until dive 158 and every even dive after that.

Appendix B. Lessons learnt from underwater glider investigations

Acoustic characteristics assessment—for vehicles with acoustic communications.

Users should be prepared for a very poor acoustic range when the glider is on the surface. It would be valuable to conduct trials with an acoustic transducer to better understand at what range and in what conditions this may be used to find a glider below the surface. During the deployment the acoustic transponder on the undersea glider should be tested, and the range of the operation determined, ideally with the glider on the surface, when diving and climbing, and when on a known path relative to the ship.

Ability to send an acoustic abort from the ship—for vehicles so equipped.

At present an acoustic abort command cannot be sent from the support ship to standard undersea gliders. Such a facility is very useful for propelled autonomous underwater vehicles such as Remus and Autosub (McPhail and Pebody, 2009). With propelled AUVs, typically if an abort command is sent to the AUV the vehicle drops the abort weight.

Servicing

When servicing gliders close attention should be paid to following the manufacturer's recommended procedures.

a. Cleaning of the o-rings. It is possible for any o-ring to leak, however well designed. Some o-rings are difficult to insert and remove, as a result they can go un-serviced for the life of a connector. They can accrue small quantities of salt, or even grit, if the connector is made and unmade, especially if it is left open for any length of time. In the investigation of the SG531 loss it was showed that if the o-ring at the antenna connector had not been cleaned a leak past the piston seal, in the absence of the face seal, was not impossible. O-ring cleanliness and proper lube application are vital operations, which can be helped with proper training.
b. Proper o-ring assembly and structural inspection. As identified during the Ammonite leak incident incorrect assembly can lead to catastrophic leak (Merckelbach et al., 2008). There were other incidents; engineers from the Agencia Estatal Consejo Superior De Investigaciones Cientificas (CSIC) believe that their Slocum G1 deep, ideep2, leak on the 24th of October 2012 during the CanalesOct12 mission, was caused by improper assembly (Simón, 2013b). '', and correct if necessary. In this case the vehicle was recovered. In a first check of the glider unit, they detected an anomalous hook-up of the rings of the science-bay. The engineers believe as a result of this anomalous assembly, the rings could be damaged and produce the leak. Other components can also leak if the assembly is not done properly. The Slocum G1 shallow Wallis owned by Centre National de la Recherche Scientifique (CNRS) had a leak caused by failure on the Bellow frame. The screws on the outside of the glider, holding the rubber material of the piston became loose (Beguery, 2013b).

Review piloting functions.

Even experienced pilots may not fully understand the logic behind the commands and parameters as encoded within the vehicle's software. A lesson learnt is that on the Seaglider, it is possible to inadvertently put the glider into a condition where it cannot communicate over Iridium through a combination of otherwise-sensible command parameters. There are simulators commercially available for the Slocum. Similar simulators should also be made available for other vehicles.

Review mission abort conditions.

The Seaglider1000 manufacturer should review the existing circumstances that generate an abort into recovery mode is sufficient. One suggestion is that no communications for a user-settable time should trigger an immediate surface and force an Iridium communications session. This is a standard procedure on Teledyne Slocums.

Aerial improvement.

Antenna failure is a single point of failure that will cause the loss of communication with the vehicle once it is under way.

To mitigate the risk three specific recommendations were made appertaining to the Seaglider, but similar comments may be applicable to other vehicles.

1. For most users the only time the antenna is unplugged is when the Seaglider is returned for refurbishment and battery change. At this time both o-rings in the D.G.O'Brien connectors should be changed, if that is not already the case.
2. D.G.O'Brien Inc can supply screw-in blanking plugs for both the plug and the bulkhead, these could be kept with the antenna(e) and glider respectively, for use whenever an antenna is removed from a glider.
3. The face seal is relatively easy to remove and clean or replace in the field and this should be done before a new antenna is plugged in. This has the dual function of cleaning, and ensuring that the user checks that the o-ring is present. An instruction note attached to any spare antenna carried would be useful in ensuring this. Removal of the piston seal o-ring by inexperienced users in the field is, on the other hand, more likely to cause a problem than to prevent it.

Backup communications.

When Iridium communication is lost there is no other means to communicate with the glider. An ARGOS tag would provide a means of backup communications for the case of Iridium failure.

Consideration needs to be given to the length of time a glider would need to remain at the surface to be able to communicate with an ARGOS satellite. There are a number of activation options; alternatives to the wet/dry switch for surface activation; flashing lights; energy supply; installation, including mounting points; and whether an X-band radar transponder would be feasible. One suggested alternative is a combined Argos and GPS tag (Costa et al., 2010).

Seaglider energy management.

There should be a standard documented procedure for energy management for a glider in recovery mode. Once pilots are certain that a Seaglider is at the surface everything should be done to minimise energy consumption. Both battery packs must be functioning, as they are both used in recovery mode: the processor and GPS run on the 10 V battery pack, and the modem on the 24 V pack. Recommendations are:

1. Reduce data transmitted to strict minimum
   a. Only GPS fixes and alerts.
   b. No targets, science and pdoscmds.bat files left on basestation.
   c. Cmdfile as small as possible.
   d. No datafiles transmission, unless needed for diagnosis (e.g. internal pressure, humidity to assess whether or not to recover).
2. The call interval should be reduced to a minimum (e.g. once every 12 h) until an increased rate is required when the recovering ship is approaching.
3. Seaglider pilots may wish to consider setting higher thresholds for minimum battery voltages early in the missions so that if the Seaglider loses the Iridium communication link it would enter recovery early and still have enough energy to call until recovered. That is, to use higher values than the recommended 22 for $MIN_24 V and 8 for $MIN_10 V. They would need to be adjusted progressively throughout the mission, down to the recommended limits. This can be helped by the community sharing their experiences of actual battery performance.

Risk Assessment prior to the campaign.

A risk assessment prior to deployment should be implemented to facilitate the identification of environmental and other local risks (e.g. shipping, fishing, etc.) and the definition of mitigating actions.

References

Allen, J.T., Smeed, D.A., Nurser, A.J.G., Zhang, J.W., Rixen, M., 2001. Diagnosis of vertical velocities with the QG omega equation: an examination of the errors due to sampling strategy. Deep Sea Res. 48, 315–346.
Alvarez, A., Mourre, B., 2012a. Optimum sampling designs for a glider-mooring observing network. J. Atmos. Ocean. Technol. 29, 601–612.
Alvarez, A., Mourre, B., 2012b. Oceanographic field estimates from remote sensing and glider fleets. J. Atmos. Ocean. Technol. 29, 1657–1662.
Beguery, L., 2013a. In: Brito, M. (Ed.), Re: Loss of Communication with Glider Incidents. National Oceanography Centre.
Beguery, L., 2013b. In: Brito, M. (Ed.), Re: Glider Leaks Info. National Oceanography Centre.
Bozzone, S., 2012. In: Gwyn, G. (Ed.), RE: Board of Inquiry into the Loss of UEA Seaglider SG522: Dates for Event Tree Analysis. National Oceanography Centre.
Brito, M.P., Smeed, D., Griffiths, G., 2014. Undersea glider reliability and implications for survey design. J. Atmos. Ocean. Technol. http://dx.doi.org/10.1175/JTECH-D-13-00138.1. in press.
Chitre, M., Shahabudeen, S., Stojanovic, M., 2008. Underwater acoustic communications and networking: recent advances and future challenges. Mar. Technol. Soc. J. 42, 103–116.
Colyvan, M., 2008. Is probability the only coherent approach to uncertainty? Risk Anal. 28, 645–652.
Costa, D.P., Robinson, P.W., Arnould, J.P.Y., Harrison, A.-L., Simmons, S.E., Hassrick, J.L., Hoskins, A.J., Kirkman, S.P., Oosthuizen, H., Villegas-Amtmann, S., Crocker, D.E., 2010. Accuracy of ARGOS locations of pinnipeds at-sea estimated using Fastloc GPS. PLoS One 5, e8677.
Curtin, T.B., Bellingham, J.G., Catipovic, J., Webb, D., 1993. Autonomous oceanographic sampling networks. Oceanography 6, 86–94.
Dearden, R., Ernits, J., 2012. Automated fault diagnosis for an autonomous underwater vehicle. IEEE J. Ocean. Eng. 38, 484–499.
Eriksen, C.C., Osse, T.J., Light, R.D., Wen, T., Lehman, T.W., Sabin, P.L., Ballard, J.W., Chiodi, A.M., 2001. Seaglider: a long-range autonomous underwater vehicle for oceanographic research. IEEE J. Ocean. Eng. 26, 424–436.
European Marine Board 2013. Navigating the Future IV. Position Paper 20 of the European Marine Board, Ostend, Belgium.
Glenn, S., Jones, C., Twardowski, M., Bowers, L., Kerfoot, J., Kohut, J., Webb, D., Schofield, O., 2008. Glider observations of sediment resuspension in a Middle Atlantic Bight fall transition storm. Limnol. Oceanogr. 53, 2180–2196.
Griffiths, G., Circumstances surrounding the loss of two gliders deployed as part of the NERC AFI Project GENTOO in January—May 2012. National Oceanography Centre, Southampton 2012, 135 pp. (confidential).

Griffiths, G., Trembanis, A., 2007. Eliciting expert judgement for the probability of AUV loss in contrasting operational environments. In: Proc: 15th International Symposium on Unmanned Untethered Submersible Technology. (UUST 07). Autonomous Undersea Systems Institute, Lee, USA, p. 17.
Hodges, B.A., Fratantoni, D.M., 2009. A thin layer of phytoplankton observed in the Philippine Sea with a synthetic moored array of autonomous gliders. J. Geophys. Res. 114, C10020.
L'Hévéder, B., Mortier, L., Testor, P., 2013. A glider network design study for a synoptic view of the oceanic mesoscale variability. J. Atmos. Ocean. Technol. 30, 1472–1493.
Martí, J., Pinel, V., López, C., Geyer, A., Abella, R., Tárraga, M., Blanco, M.J., Castro, A., Rodríguez, C., 2013. Causes and mechanisms of the 2011–2012 El Hierro (Canary Islands) submarine eruption. J. Geophys. Res.-Sol. Ea. 118, 823–839.
Martin, A., 2005. The kaleidoscope ocean. Phil. Trans. R. Soc. A 363, 2873–2890.
Martínez, M., Ruiz, S., 2008. WILLY Leak detect. Institut Mediterrani d'Estudis Avancats 2008.
McPhail, S.D., Pebody, M., 2009. Range-only positioning of a deep-diving autonomous underwater vehicle from a surface ship. IEEE J. Ocean. Eng. 34, 669–677.
Merckelbach, L., 2013a. On the probability of underwater glider loss due to collision with a ship. J. Mar. Sci. Technol. 18, 75–86.
Merckelbach, L., 2013b. In: Brito, M. (Ed.), Re: GROOM Project—Loss of Communication with a Glider. National Oceanography Centre.
Merckelbach, L., Stevenson, P., Griffiths, G., Investigation as to the cause of undersea glider Ammonite flooding, April 2008. Reliability Case Notes No. 1. National Oceanography Centre, Southampton, 2008, p. 27.
Nicholson, D., Emerson, S., Eriksen, C.C., 2008. Net community production in the deep euphotic zone of the subtropical North Pacific gyre from glider surveys. Limnol. Oceanogr. 53, 2226–2236.
O'Hagan, A., Buck, C.E., Daneshkhah, A., Eiser, J.E., Garthwaite, P.H., Jenkinson, D.J., Oakley, J.E., Rakow, T., 2006. Uncertain Judgments: Eliciting Expert Probabilities. John Wiley & Sons Ltd., Chichester.
Pearl, J., 2000. Causality: Models, Reasoning, and Inference. Cambridge University Press, New York.
Pereira, A.A., Binney, J., Ragan, M., Sukhatme, G., 2011. Toward risk aware mission planning for autonomous underwater vehicles. In: Proc. International Conference on Intelligent Robots and Systems, IEEE/RSJ, San Francisco, pp. 3147–3153.
Raiffa, H., 1968. Decision Analysis. Introductory Lectures on Choices Under Uncertainty. Addison-Wesley, Reading.
Ramp, S.R., Davis, R.E., Leonard, N.E., Shulman, I., Chao, Y., Robinson, A.R., Marsden, J., Lermusiaux, P.F.J., Fratantoni, D.M., Paduan, J.D., Chavez, F.P., Bahr, F.L., Liang, S., Leslie, W., Li, Z., 2009. Preparing to predict: the Second Autonomous Ocean Sampling Network (AOSN-II) experiment in the Monterey Bay. Deep Sea Res. Part II 56, 68–86.
RAPID-WATCH 2013. RAPID-WATCH 2008–2014. Available from http://www.rapid.ac.uk/rw/ (accessed 15.04.2014).
Rutgers 2013. The Scarlet Knight's Trans-Atlantic Challenge. Available: http://rucool.marine.rutgers.edu/atlantic/about_atlantic.html (accessed 15.04.2014).
Sherman, J., Davis, R.E., Owens, W.B., Valdes, J., 2001. The autonomous underwater glider "Spray". IEEE J. Ocean. Eng. 26, 437–446.
Simón, R., 2013a. In: Brito, M. (Ed.), Re: GROOM Project—Loss of Communication. National Oceanography Centre.
Simón, R., 2013b. In: Brito, M. (Ed.), Re: ideep02 Leak. National Oceanography Centre.
Todd, R.E., Rudnick, D.L., Davis, R.E., Ohman, M.D., 2011. Underwater gliders reveal rapid arrival of El Niño effects off California's coast. Geophys. Res. Lett. 38, L03609.
Webb, D.C., Simonetti, P.J., Jones, C.P., 2001. SLOCUM: an underwater glider propelled by environmental energy. IEEE J. Ocean. Eng. 26, 447–452.
Webber, B., 2013. In: Brito, M. (Ed.), Re: GROOM Project—Loss of Communication with a Glider. National Oceanography Centre, National Oceanography Centre.