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Analysing system of systems performance of a carrier strike group conducting anti-submarine warfare

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Abstract: The operation of US and Allied military forces freely and safely across the world's oceans remains a paramount goal of the US Navy, often to be carried out through the deployment of a carrier strike group (CSG). This paper examines the need for an improved anti-submarine warfare (ASW) system to protect a CSG, focusing on the design of an ASW system that is able to thwart an attack through effective, timely, and precise engagement based on the use of tactically significant detection, localisation, tracking and classification of threat submarines. This effort results in the development of system functions and objectives, appropriate metrics, an operational concept, several competing physical architectural alternatives, and conduct of trade-off analysis regarding system performance. Primarily, the focus is on the operational performance of the competing physical architectures, which is defined as the need to detect and defeat an enemy submarine during a typical CSG mission. Potential ASW and CSG components are described, as well as an assessment of several alternative ASW systems within the CSG system of systems, a brief operational concept, and the specifics of the performance modelling effort to include results.

Keywords: anti-submarine warfare; ASW; modelling and simulation; system of system analysis; ASW systems architecture development.

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Biographical notes: Eugene P. Paulo is an Associate Professor of Systems Engineering at Naval Postgraduate School. He received his PhD in Industrial Engineering from University of Central Florida. His research interests include design and simulation analysis of complex military systems, simulation education, and military systems engineering and architecting.

1 Introduction

The operation of US and Allied military forces freely and safely across the world's oceans remains a paramount goal of the US Navy. The need for this capability is summarised by the Chief of Naval Operations (CNO), who addresses the urgency of

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combating the growing threat of enemy submarines through dedicated anti-submarine warfare (ASW).

> "There are many challenges to our ability to exercise sea control, perhaps none as significant as the growing number of nations operating submarines, both advanced diesel-electric and nuclear propelled. We will continue to hone the tactics, training and technologies needed to neutralise this threat. We will not permit conditions under which our maritime forces would be impeded from freedom of manoeuvre and freedom of access, nor will we permit an adversary to disrupt the global supply chain by attempting to block vital sea-lines of communication and commerce". (Conway et al., 2007)

One of the primary missions for a US Navy ASW system is to protect a carrier strike group (CSG). The combat range of the carrier air wing usually necessitates strike group operations well within the operating range of hostile submarine forces (Jean, 2008). This paper, based on the comprehensive study referenced here (Broadmeadow et al., 2008), examines the need for an improved ASW system to protect a CSG, focusing on the design of an ASW system that is able to thwart an attack through effective, timely, and precise engagement based on the use of tactically significant detection, localisation, tracking, and classification of these quiet acoustic threat submarines in challenging environments. This effort results in the development of system functions and objectives, appropriate metrics, an operational concept, and several competing physical architectural alternatives (Buede, 2000). Trade-off analysis is performed regarding operational system performance, which is defined as the ability to detect and defeat an enemy submarine during a typical CSG mission.

2 CSG operational concept and threats

A comprehensive CSG operational concept (CONOPS) is very complex and multifaceted. It must account for various CSG operations and options, many of which are not necessarily relevant to the ASW mission. In order to a realistic context, a limited CONOPS was developed to concentrate upon the CSG ASW perspective. Virtually all of the CSGs varied missions require it to establish itself in an operating area that is reasonably secured from assault by a threat. Safe CSG operation within an operating area represents the principle concern chosen for the ASW analysis.

For any tactically significant operation of a CSG, an appropriate operating area is selected and a CSG transit route to the operating area is established. Once on station, the CSG conducts the ordered mission for a nominal 14-day period of time, potentially moving among various operating areas as operations may dictate. It was deemed necessary to destroy the threat submarine before it is capable of launching a torpedo at the CSG. Therefore, any successful torpedo launch by the hostile submarine is deemed a mission failure.

For the purposes of this study, a notional ASW Threat to the CSG is defined as a single conventional submarine. The wide proliferation of these advanced, quiet, diesel-electric submarines highlights their role as the primary threat of concern. Two examples of threats of concern are the Russian KILO submarine and the Chinese SONG class submarine (Jane's Underwater Warfare Systems, 2008).

3 Alternative ASW Alternatives for CSG

3.1 Overview

Each of the proposed ASW systems, and primary sub-systems, for the CSG system of systems is described below. Following the description of that alternative is a discussion of the specifics of the modelling effort regarding how that alternative is represented in the simulation.

The key measure of effectiveness for the ASW system is the survival of the carrier from an attack by enemy submarines. The probability of carrier survival can be thought of as one minus the probability of the attacking submarine's survival. This assumes a 'kill or be killed' scenario, as the enemy submarine continues its attack until either it launches a torpedo attack on the carrier or is destroyed by Blue forces. The CSG will not alter operations to avoid a detected submarine.

3.2 Model development for ASW scenario

3.2.1 Summary of recent ASW modelling efforts

In recent years, students and faculty at Naval Postgraduate School have been at the forefront of research in ASW modelling development and analysis. Four of these models are discussed and very briefly summarised below.

In one of these studies, Washburn describes the simulation ITEM, a constructive simulation developed and owned by SAIC, and assesses its capability regarding the portrayal of ASW. While ITEM clearly has capability to address ASW functions, it is a complex deterministic simulation focused broadly on campaign analysis (Washburn, 2005).

Scherer developed and then describes an excel-based ASW model that combines game theory and linear programming software (Scherer, 2009). This model allows for the distinction between visible defender platforms and secret defender platforms, representing the utilisation of either active or passive sonar systems. The Scherer model appears to be an outstanding tool for analysis, yet would likely require a steep learning curve for the potential user, as well as some background in game theory and linear programming.

Akbori (2004) describes the development and use of an agent-based model in the representation of ASW capabilities. One possible disadvantage is that the intent of this model is to support training and planning, rather than analysis. Additionally, this also is a complex model, which would be difficult to implement without some user knowledge of agent based models.

Timmerman developed a simulator that addresses ASW through the use of a genetic algorithm (Timmerman, 1993). This model focuses on a single enemy submarine versus a single surface platform as they attempt to search for and destroy each other.

3.2.2 ASW excel model developed for this study

The ASW excel model developed for analysis had the needs of not only accurately portraying the movement and sensing of all tactical systems, but also representing the different system alternatives and their components in sufficient detail. Therefore, this

ASW model consists of three sub-models corresponding to the first three ASW system alternatives (as described later in this chapter), with the fourth alternative [advanced capabilities build (ACB)] being solely represented by an 'enhanced' version of the first sub-model. The results of these sub-models are combined as appropriate to calculate the probability of the enemy submarine successfully attacking the carrier. Each model also produces a probability of the submarine being killed by a specific alternative. These probabilities are combined, using an event tree approach, to produce the overall probability of carrier survival.

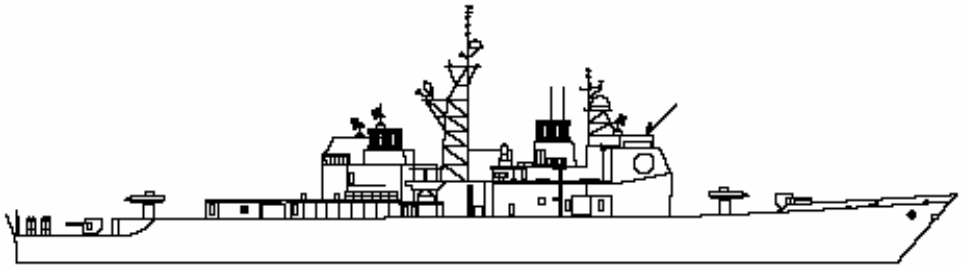
3.3 Baseline ASW system for the CSG

3.3.1 Composition

While there is no single definition of a CSG, a 'standard' CSG composition is defined in terms of the capabilities required to accomplish all tasks in a notional threat environment against a notional threat, thereby the means to provide an initial crisis response mission from a rotationally deployed forward posture (Pike et al., 2007) While this standard CSG composition includes a number of ships and aircraft, this research focuses strictly on the ASW aspect of CSG operations, and therefore, describes only those specific platforms.

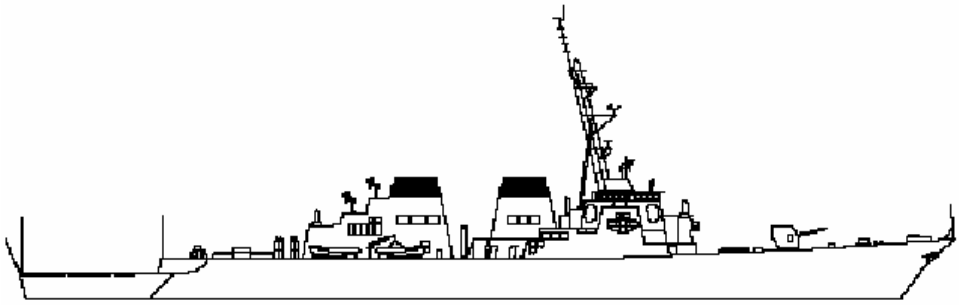
Components in the Baseline system that provide the operational mission functions critical to support ASW Operations in the CSG include four surface combatants. These combatants include three cruisers (CG) with AEGIS air warfare capability and one destroyer (DDG) with the multi-function towed array (MFTA) sonar upgrade (Jane's Fighting Ships, 2008a). The Ticonderoga (AEGIS) Class (CG) Cruisers, Figure 1, are designed to provide a highly capable air warfare platform (United States Naval Reserve Intelligence Program, 2007). The CG Class carries an extensive array of weapons including surface-to-air missiles, surface-to-surface missiles, anti-submarine missiles, Tomahawk missiles and guns, and helicopters.

Figure 1 Ticonderoga class cruiser (CG)



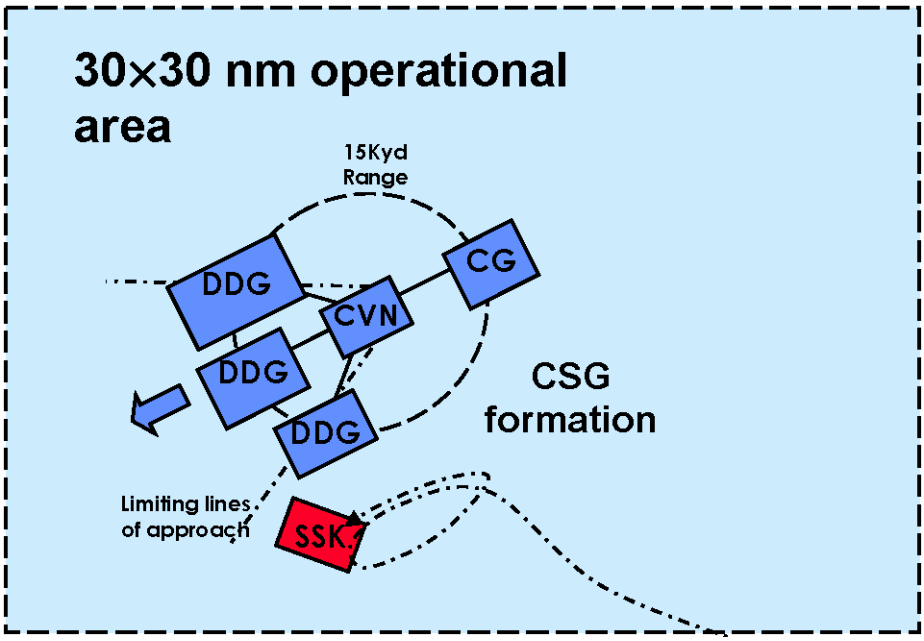
The Arleigh Burke Class DDG, Figure 2 is a very capable strike and anti-air warfare platform, as well as being one of the CSGs primary anti-submarine assets (Jane's Fighting Ships, 2008b). The MFTA upgrade to the DDG Class standard Towed Array sonar system offers improved ASW acoustics tracking and detection. These vessels use their embarked SH-60 helicopters and anti-submarine missiles as their primary ASW weapons.

Figure 2 Arleigh burke class destroyer (DDG)



The focus of the CSG is the Aircraft Carrier (CVN), and all other platforms are included to support its operation. The typical CSG Operational Area is defined by a 30 × 30 nautical mile area that offers the most advantageous operational environment, which is assumed to be an open ocean environment. The Aircraft Carrier maintains a constant forward motion of roughly 15 knots (or approximately 17.3 miles per hour), changing heading to remain within the OA, while launching and recovering aircraft. When compared to the enemy submarine, the CSGs higher speed will limit the primary threat area to a forward cone projected in front of the CSG, bounded by limiting lines of approach. Figure 3 provides a plan view geographic description of the CSG formation and a threat submarine, designated as SSK in the figure.

Figure 3 CSG notional configuration (see online version for colours)



3.3.2 Modelling the baseline alternative

A central element of this model is the computation of the position information for the CSG ships and the opposing force submarine. Using time steps, the model calculates the position of each platform using the speed and course for that specific time step. These equations are implemented in the spreadsheet model to compute the positions for each platform at each time step.

$$\begin{aligned} X(I) &= X(I) + V(I) * COS(\varphi(I)) * \Delta T \\ Y(I) &= Y(I) + V(I) * SIN(\varphi(I)) * \Delta T \end{aligned} \tag{1}$$

where

- X is the X position of the platform in yards
- Y is the Y position of the platform in yards
- I is the platform index (submarine, CVN, DDG, CG)
- V is the velocity of the platform in yards per second
- ΔT is the time step in seconds.

When the position of each platform is updated, the range between the opposing force submarine and each of the CSG platforms is computed and used in the calculation of signal excess and also in the calculation of torpedo run. The range is calculated as:

$$R(I) = \sqrt{\left(X(I) - X_s\right)^2 - \left(Y(I) - Y_s\right)^2} \tag{2}$$

where

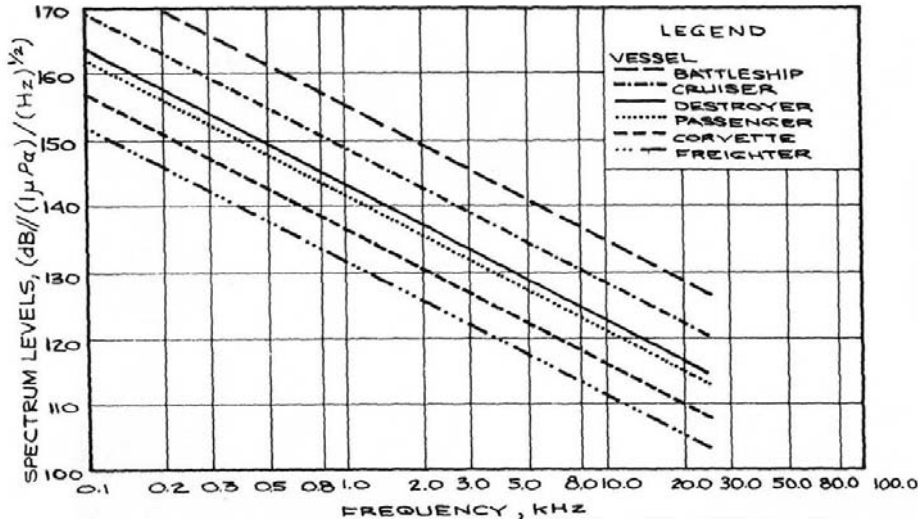
- I is the platform indicator for CVN, DDG or CG
- R is the Range between platform I and the opposing force submarine in yards
- $X(I)$ is the X coordinate of the platform in yards
- X_s is the X coordinate of the submarine in yards
- $Y(I)$ is the Y coordinate of the platform in yards
- Y_s is the Y coordinate of the submarine in yards.

Following the calculation of the position of each platform in the scenario, the model computes the ability of the sensors on each platform to detect the opposing force submarine and also the ability of the opposing force submarine to detect each CSG platform. The cruiser and destroyers utilise active bow sonar to detect and track the opposing submarine, while the opposing submarine uses passive hull sonar to detect and track the CSG platforms. This component of the model requires the implementation of the passive and active sonar equations (United States Naval Reserve Intelligence Program, 2007) into the spreadsheet model in order to compute signal excess. This meant that at each time step in the simulation, each of the parameters of the sonar equation are computed, including the observable, the energy propagation through the environment and the ability of the sensor to detect the received signal. The passive and active sonar

equations are implemented assuming a constant, range independent, iso-velocity sound velocity profile.

Passive and active target strengths utilised by the spread sheet model are derived from the figure below (Green, 2007), which shows the range of passive acoustic noise signatures for various classes/sizes of surface vessels. Utilising this graph, values were approximated for the aircraft carrier from the Battleship operating curve at 15 knots and the CG/DDG values were selected for the destroyer operating at 15 knots.

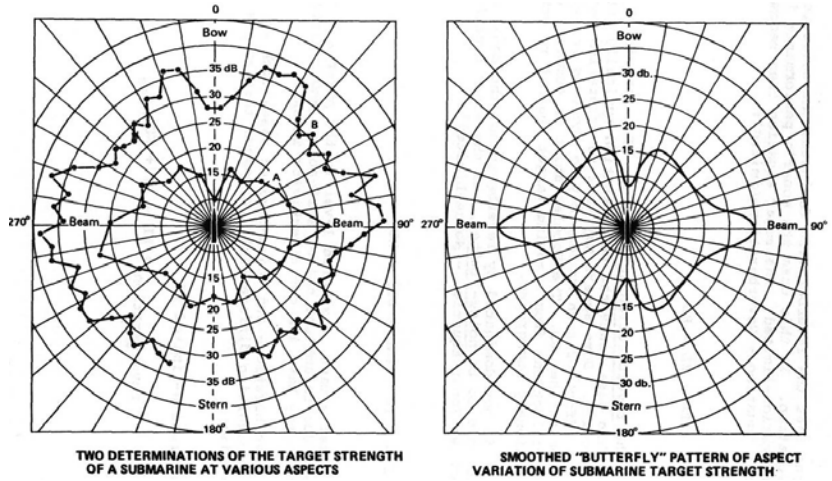
Figure 4 Surface vessel radiated noise levels



Note: Average radiated noise levels of six different classes of ships (L_s)

Source: Bureau of Ships (1965)

Figure 5 Submarine active target strength

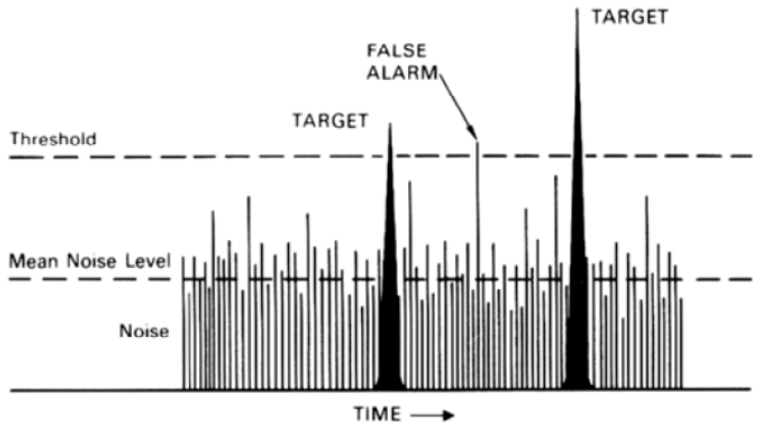


Active target strength of the submarine is also required, and Figure 5 provides a means to estimate submarine active target strength (Green, 2007). A value of 10 decibels (dB) was selected based on the smooth directional estimate, which appears to be an acceptable value, but does not account for the peaks and nulls associated with the beam, bow and stern aspects.

Background noise levels, caused by shipping traffic, wind, rain, biologic activity and seismic activity creates a noise field from which passive sonar signals must be detected. The contribution of each of these factors is frequency dependent, and the amplitude of each noise source is a function of the activity level of that parameter. For the purpose of this research 70 dB was selected as a nominal value.

The detection thresholds selected for the modelling analysis were 20 dB for active sensors and 10 dB for passive sensors. These nominal values were chosen to illustrate the effect of detection threshold on detection range, and are set up as parameters within the spreadsheet model to represent the difficulty associated with detection of active targets in the presence of clutter. In addition, signal and noise fluctuations were introduced into the model using a Gaussian distribution of with a mean of 0 dB and a sigma of 9 dB for passive and 12 dB for active. Figure 6 illustrates the effects of these fluctuations on the detection process (Green, 2007).

Figure 6 Illustration of detection threshold and noise fluctuations



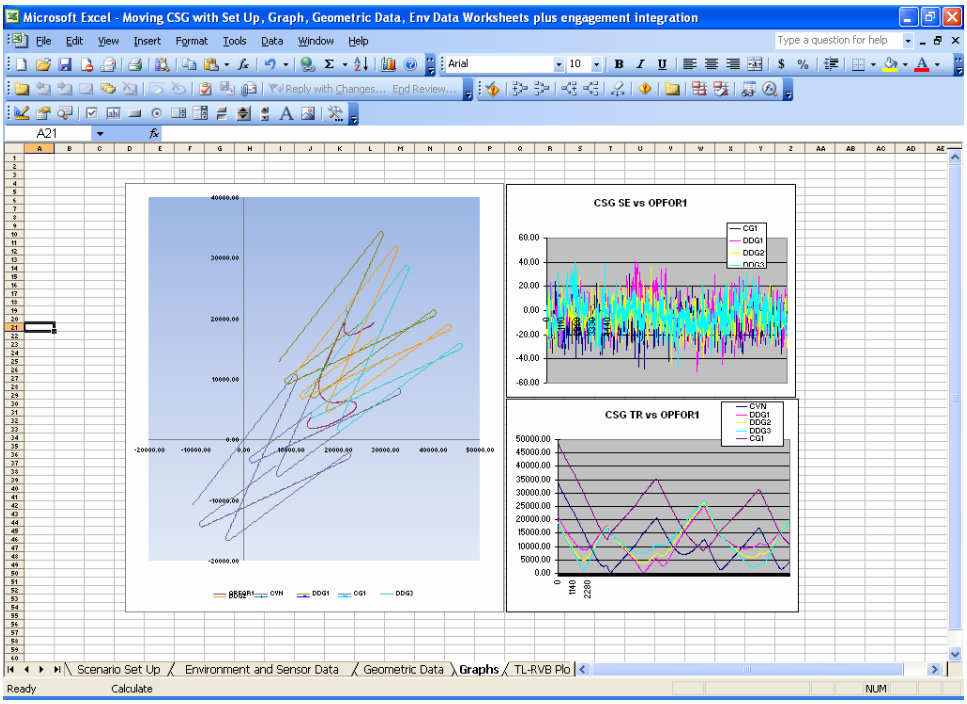
Note: The higher the threshold is above the mean level of the noise, the lower the probability of a spike of noise crossing it and producing a false alarm.

The spreadsheet model included scenario setup parameters, environmental parameters, geometric position data and resultant sensor detection estimates, tracking and engagement analysis and a scorecard to allow for Monte Carlo replication of the results. In addition to these scenario set-up parameters which control the initial starting point and motion of the CSG and submarine platforms, the discrete time event simulation requires inputs for passive signature levels for the surface vessels, active target strength for the submarine and also the background noise level that interferes with passive detection. Also, the fluctuation in signals and noise as seen by the detection process is modelled via this spread sheet.

At problem start the opposing submarine executes manoeuvres every two hours, changing course between 45° and 225°. The submarine maintains this race track pattern

until its sensors can detect the CVN acoustic signature. Upon detection the submarine will execute an attack tactic by assuming an intercept course with the CVN. The course is updated each time step based on the signal excess calculation and calculation of the bearing to the CVN. CSG course, speed and screen formation parameters may also be modified by the user to support sensitivity analysis. The base course and speed utilised was 45° and 15 knots, with course manoeuvres every two hours. This approach allowed the CSG to remain within the 30 × 30 nautical mile operating area without the need for computing the proximity of the CSG to the edge of the operating area. Figure 7 depicts the geometry resulting from one analysis run as well as the signal excess versus time for the CSG against the submarine and the time versus range plots for each platform in the CSG to the submarine.

Figure 7 Geographic plot example (see online version for colours)



The engagement model, used for both torpedoes and missiles, consists of three parts: the calculation of weapon course and run to the target, the decision to launch, and the determination of the result. The weapon course is set to match the weapon's speed across the line of sight to the target's speed across the line of sight. Speed across the line of site is the velocity component perpendicular to a bearing line from the launch platform to the target. Matching the speeds across the line of sight, results in an intercept course. The target's speed across the line of sight is calculated using equation (3). The weapon course that will intercept the target is calculated by equation (4).

$$V_{Tv} = V_T \left(CSE_T - B_T \right) \tag{3}$$

where

- V_{Ty} = target speed across the line of sight
- V_T = target speed
- CSE_T = target course
- B_T = target bearing
- $V_{Ty} = V_T$*(CSE$_T$ – B$_T$).

$$CSE_W = \sin^{-1}\left(V_{Tv} / V_W\right) + B_T \tag{4}$$

where

- CSE_W = weapon course
- V_W = weapons speed.

The distance the weapon travels before it hits the target is calculated by multiplying the target range at time of fire by fraction of total closing speed (weapon's speed in the line of sight plus the target's speed in the line of sight) generated by the weapon. Equation (5) and equation (6) are used to calculate the target's and weapon's speed in the line of sight. Equation (7) calculates the distance travelled by the weapon. Inspection of equation (7) shows that if the target is opening (i.e., V_{Tx} is negative) the distance travelled by the weapon will be greater than the range at time of fire.

$$V_{Tx} = V_T * \cos\left(B_T - CSE_T\right) \tag{5}$$

where

- V_{Tx} = target speed in the line of sight
- V_T = target speed.

$$V_{Wx} = V_W * \cos\left(CSE_W - B_T\right) \tag{6}$$

where

- V_{Wx} = weapon speed in the line of sight.

$$D_W = R_T * \left[V_{Wx} / \left(V_{Wx} + V_{Tx}\right)\right] \tag{7}$$

where

- D_w =distance travelled by weapon
- R_T = target range.

The engagement results are determined by comparing the time the submarine is hit by a weapon with the time the submarine launches a weapon against the carrier. If the submarine is hit before launching a weapon against the carrier, the carrier is scored as surviving. If the enemy submarine launches a weapon against the carrier before being hit by a friendly weapon, the carrier is considered killed.

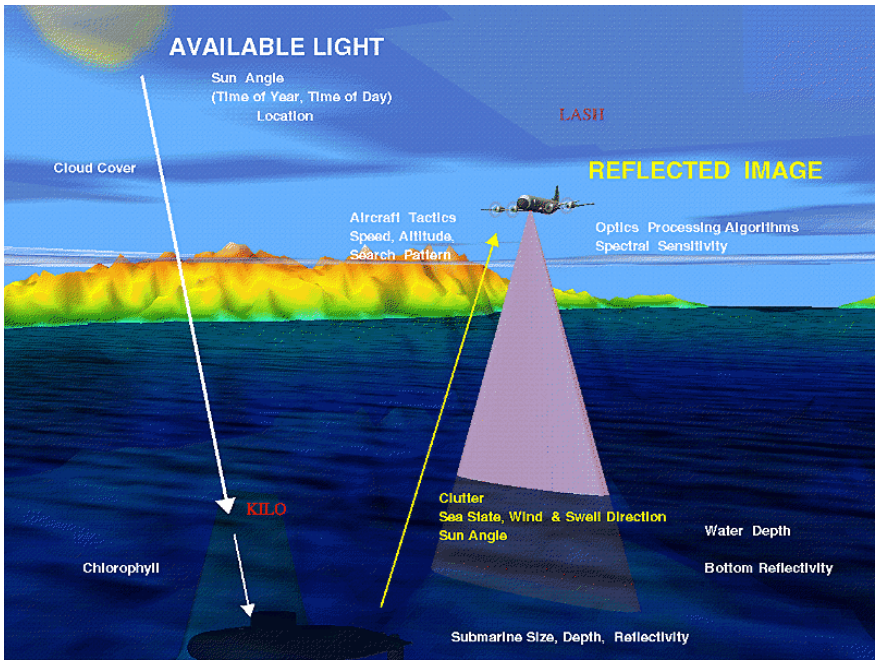
3.4 Alternative 2: baseline plus Maritime Patrol Aircraft (MPA) ASW sensor

3.4.1 Composition

This alternative includes all Baseline systems in addition to a new type of surface search sensor to be mounted on MPA that supports the ASW mission. It is anticipated that this sensor will be able to detect near or on-surface submarine targets at significant altitude and range, thus, providing wide area ASW search capability. The system concept is illustrated in Figure 8.

This new sensor system currently goes by the acronym JMMES (Joint Multi-Mission-Electro-Optic System) and uses four non-acoustic sensors – a visible, multi-spectral imager, a low-light spectral detector, a low-light zoomed camera, and a mid-wave infrared detector (Brown and Schulz, 2009). The MPA are land based, requiring no support from the CSG and have the range and endurance to support CSG operations by rotating on station aircraft. The MPA squadron has ample aircraft quantities to maintain the required non-stop coverage for indefinite periods. The MPA concept will operate outside the CSG operational area, so will not likely interfere with CSG operations.

Figure 8 MPA with ASW sensor concept (see online version for colours)

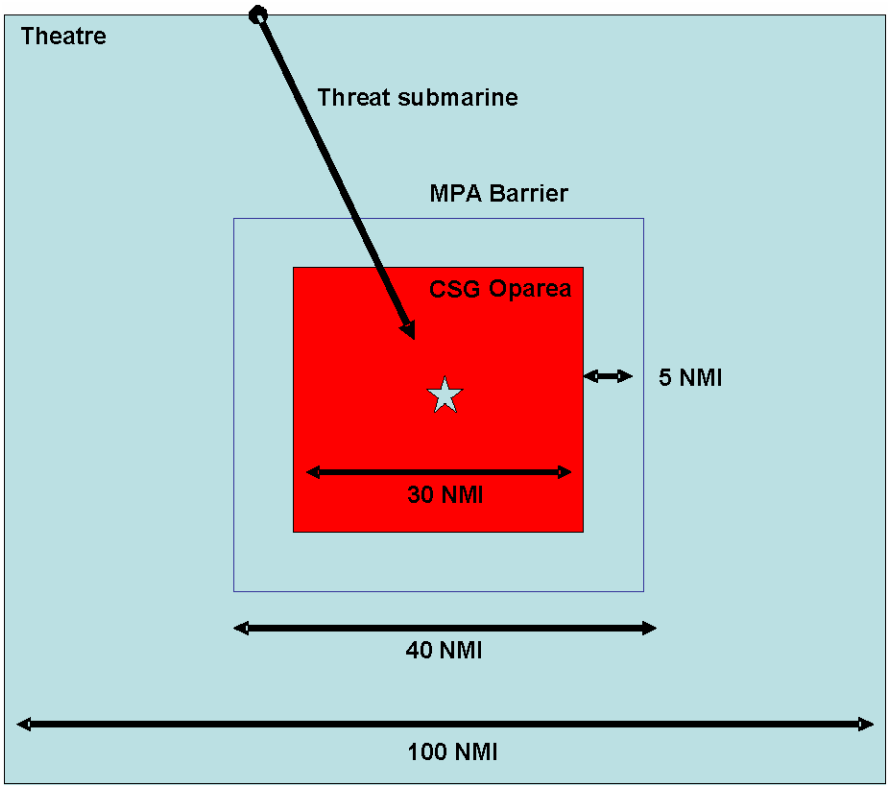


3.4.2 Modelling alternative 2

The operational effectiveness of the MPA system is predicated on the submarine having not yet detected the presence of the CSG. Consequently, it makes the most sense to use this sensor at a significant distance from the CSG, with the MPA operating in a largely autonomous mode. The MPAs response to threat detection will be to attack with

torpedoes. In the event that the threat eludes the initial attack, reacquisition and re-attack can be performed using conventional sensors including sonobuoys. Figure 9 displays the method of employment of the MPA system for this analysis.

Figure 9 MPA employment (see online version for colours)



Because the threat submarine is attempting to get close to the CSG, it will have to transit across the operational theatre, which is defined as a 100 × 100 nautical mile area. In the modelling of other alternatives, the submarine speed is taken to be five knots. In this case its speed is taken as ten knots, under the assumption that it will be less concerned with stealth when outside the CSG operational area. It can be reasonably assumed that prior to entering the CSG operational area, the transiting submarine will change its behaviour to a stealthier, continually submerged mode. Consequently, the MPA system must detect the threat before the submarine reaches this range. The range where the submarine makes this transition is assumed to be within five miles of the operational area perimeter.

Since speed, sweep width and endurance of the search platform are fixed, it is desirable to maximise the number of opportunities for detection. This corresponds to making the Circuit length of the barrier as short as possible. The limiting factor is that the barrier must be maintained outside the range at which the submarine is likely to be alerted to the CSG and submerge. This range is assumed to be five nautical miles, which is equivalent to about 5.75 statute miles.

An important factor in determining the probability of detecting a submarine that is attempting to transit the theatre is the opportunities for detection presented by the threat

submarine. The submarine is characterised as transiting towards the centre of the CSG operational area, beginning at a random point on the periphery of the defined theatre. It is advancing at ten knots and coming to the surface or near surface for one hour out of six, as the time near the surface provides the submarine the opportunity to run diesel engines to charge its batteries or to perform communications functions. It is during this period that it is vulnerable to detection by the MPA system. This is considered to be a reasonable characterisation of behaviour for a diesel electric submarine transiting to an area where it expects to find opposition forces.

The typical mission duration for the MPA is ten to 13 hours. If a 12 hour mission duration is assumed and a transit time of two hours from the MPA base to the CSG operational area, the total on station time per aircraft mission is 8 hours. The typical cruise speed for the MPA is 330 knots, giving the aircraft 2,640 nautical miles of search per mission. The previously described search track is square, 40 nautical miles on a side, or 160 nautical miles for a single circuit. The primary Measure of Effectiveness, P(d), the probability that a submarine is detected as it transits across the theatre to the CSG operational area, is given by the following relationship:

$$P(d) = P(exposure) * P(d_{MPA}) * \times \#Looks \tag{8}$$

where

- $P(exposure)$ is the probability that the submarine will be both within the width of the barrier, defined by the sweep width of the MPA sensor, and at a detectable depth at any given time. The specifics of determining P(exposure) is not addressed here.
- $P(_{MPA})$ is the probability of detection of the MPA sensor system, which is set at 0.9.
- # *Looks* is the number of circuits of the barrier the MPA will make during the time required by the submarine to transit the width of the MPA barrier, which is based on aircraft speed and size of the operational area.

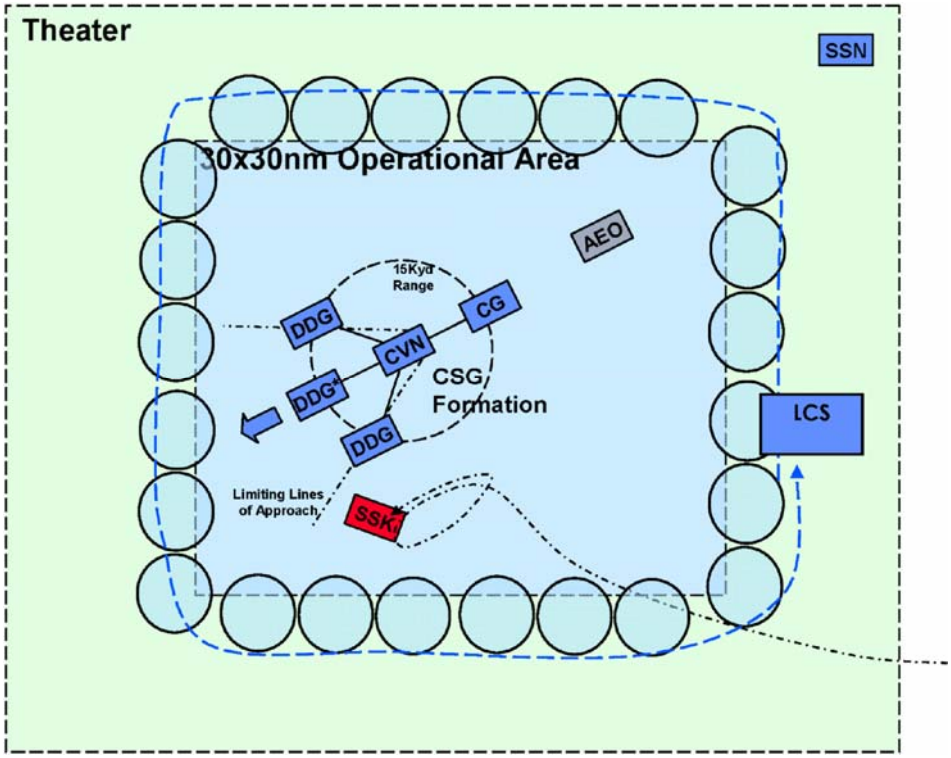
3.5 Alternative 3: littoral combat ship barrier

3.5.1 Composition

The barrier alternative augments the baseline system through the inclusion of a littoral combat ship (LCS) craft supporting the CSG by operating as a surrogate craft for deployment of sensors on buoys. The LCS acts as a support craft for deployment and maintenance of a barrier screen of buoy sensors, which are deployed around the 30 × 30 nautical mile operational area and acts as a detection 'screen' to provide advance warning of an advancing submarine. Figure 10 depicts this alternative graphically.

Six sensor buoys would be placed at fixed intervals on each leg of the operational area for a total of 24 sensors, spaced to provide the optimal coverage for that leg. Following deployment of the sensors, the LCS patrols the perimeter of the screen to ensure that the buoys have not strayed too far from their designated area due to currents, and replace as necessary when the buoy battery life is depleted. The sensors act as a 'tripwire', informing the LCS and CSG via a RF communication link of an approaching enemy submarine. The LCS in this alternative also performs the prosecution of the target through the use of the SH-60 helicopters.

Figure 10 LCS barrier (see online version for colours)



3.5.2 Modelling alternative 3

Due to the symmetry of the square operational area, the barrier alternative perimeter model may be simplified to the examination of the probability of defeating the threat submarine crossing one side of the 30 nautical mile operational area. A Monte Carlo spreadsheet simulation of a red submarine perpendicularly approaching a 30 nautical mile line of buoys was developed to statistically determine this probability.

Each trial of the barrier alternative model starts at time $t = 0$ with the geometry as shown in Figure 11. A single threat submarine is positioned at location (x, y), where x is a random number between zero and 30 nm (~60,000 yards) and y is set equal to 20,000 yards. Ideally, the buoys are uniformly spaced along the x-axis between $x = 0$ and $x =$ 60,000 yards. However, due to buoy drift and varying buoy placement times, the model alters these ideal uniform buoy locations by adding a uniform random variable that adds or subtracts 3,000 yards to both the x and y position of each buoy.

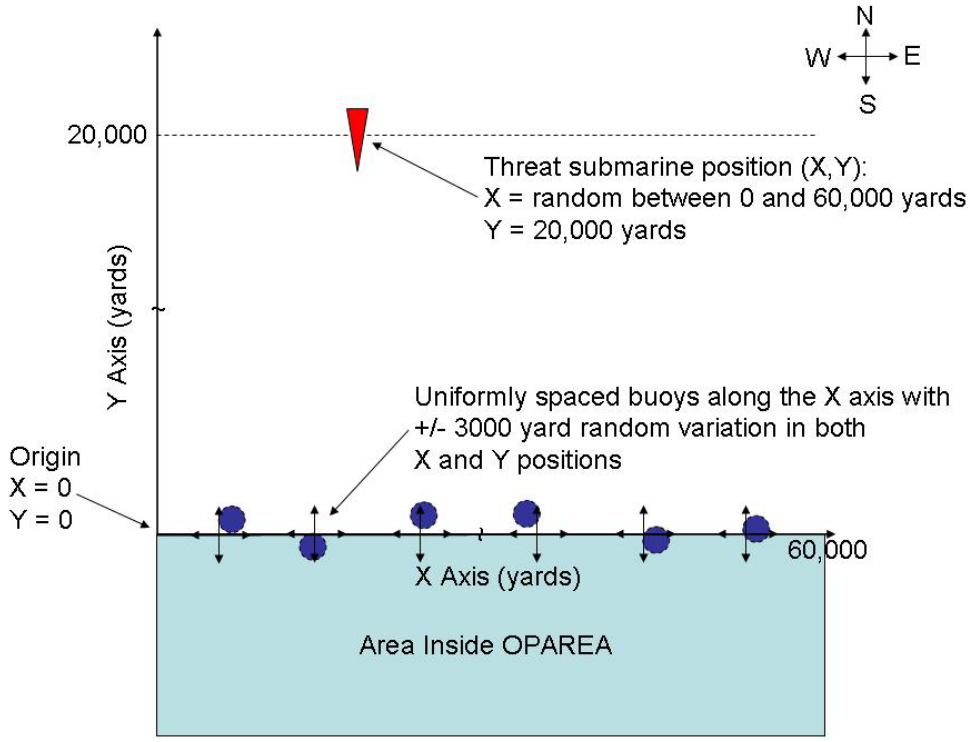
After the threat submarine and buoys are placed as described above at time $t = 0$, the model increments time in one minute intervals. Over time, the threat submarine moves perpendicularly towards the x-axis (south) at a constant speed of five knots and the buoys each drift with independent random motion at an average speed of one knot.

The hold time is the difference in time between detection initiation and cessation on a given buoy. If a buoy detects the threat submarine, the LCS is contacted in order to allow LCS personnel to consider launching an engagement against the threat submarine. The engagement time is total amount of time for the LCS to decide whether to engage, ready the helicopter personnel, and fly the helicopter to the detection location.

The model considers the decision time and ready time to be constants of ten minutes and five minutes, respectively. The flight time is modelled as a random time due to the random LCS location at any given time. The worst-case distance the LCS can be from a buoy is considered to be the case when a buoy is at one corner of the operational area and the LCS is located at the opposite corner of the 30 nm by 30 nm operational square. This distance is ~85,000 yards, and assuming a helicopter speed of 125 knots, the maximum flight time of the helicopter is ~20 minutes. Therefore, the flight time is modelled as a uniform random variable between one and 20 minutes.

For any given trial, an engagement is considered to be successful if the engagement time is less than the hold time. Essentially, if a buoy is still detecting the threat submarine at the time the helicopter arrives on station to engage by dropping a torpedo, the engagement is modelled as being successful. For each trial, the threat submarine may or may not be detected, and if it is detected, the engagement is either successful or it is not.

Figure 11 Barrier alternative perimeter model trial geometry at time = 0 (see online version for colours)



3.6 Alternative 4: ACB

3.6.1 Composition

The ACB alternative is the application of an array of possible technology enhancements combined with planned COTS technology upgrades (hardware and software). By applying this approach to the Surface Sonar baseline system, gains can be made that increase detection performance and improve the 'detect to classification' timeline. Specifically, 'decision latency' can be improved in multiple areas within the detect-to-engage timeline. These include 'time to detect', 'time to classify given detection', and 'time to engage'. The improvement in automatic detection and classification algorithms allow automated detection processors to find detections and classify threat quicker than the operators. These improvements lead to a higher detection probability and support longer classification ranges.

3.6.2 Modelling of alternative 4

The ACB is modelled in the same manner as the baseline. The improvements are represented through the enhancement of specific input parameters that affect 'decision latency,' as mentioned above.

3.7 Model integration

As previously described, the ASW alternatives consist of one or more capabilities added to the baseline, the results of the barrier and MPA models need to be combined with the baseline model results to calculate the overall probability of carrier survival. The ACB result is calculated by running the baseline model with the input parameters changed to reflect the improved performance of the ACB.

4 Modelling results

After verifying that the operational effectiveness spreadsheet model performed as expected through numerous validation runs, conducted while varying controlled parameters (fluctuation standard deviation, source level, detection threshold, target strength, acoustic signature level, initial range and bearing of opposing submarine), 250 simulated engagements for each alternative were conducted and the results evaluated.

Table 1 contains the results of the operational effectiveness modelling. These results are based on combinations of the different alternatives using a series of event trees.

Table 1 Integrated modelling results

Alternative	*Carrier survival*
Baseline	0.665
Barrier	0.857
MPA	0.681
ACB	0.804
ACB plus barrier	0.916

Each circle in the overall carrier survival graphic (Figure 12) represents one of the alternatives ASW systems discussed previously. The 'yes' branches represent the probability of the associated alternative stopping the red submarine. The 'no' branches represent the probability of the red submarine getting through the associated alternative. The sum of the 'yes' branch probabilities is the overall probability of carrier survival. Figure 13 is the event tree for the baseline alternative. Only the baseline node is active, with a probability of kill against the red submarine of 0.665, which is also the probability of carrier survival.

Figure 12 Carrier survival event tree (see online version for colours)

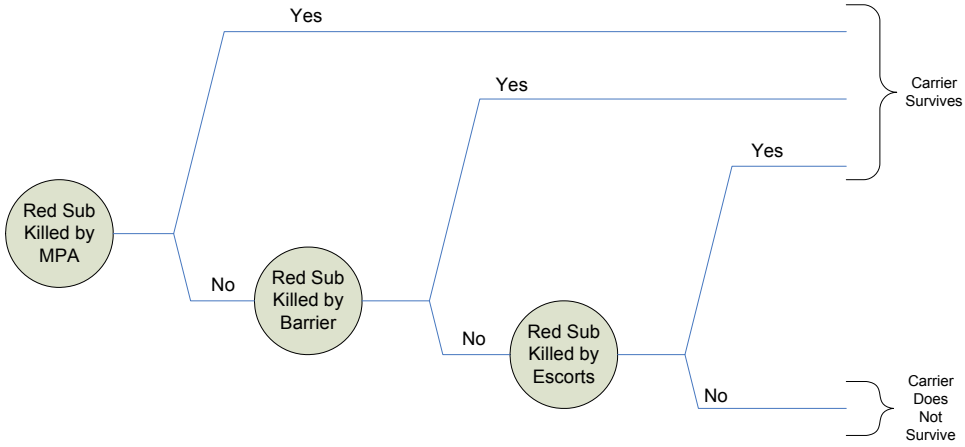


Figure 13 Baseline event tree (see online version for colours)

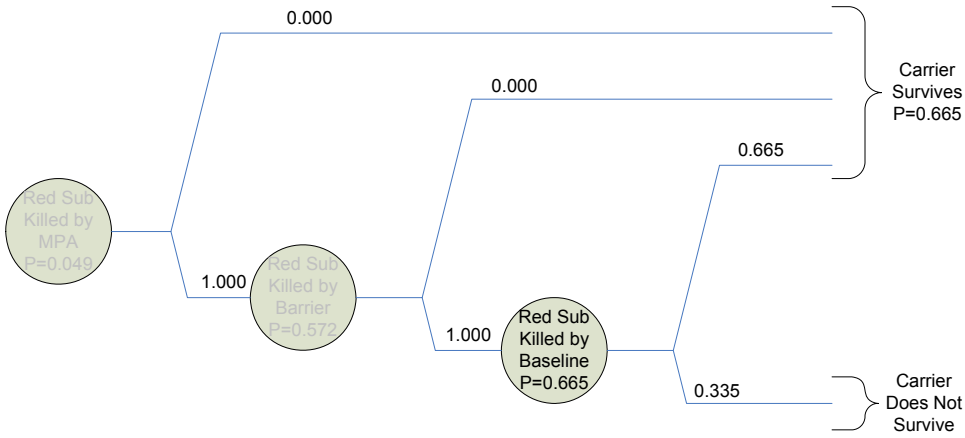


Figure 14 is the event tree for the barrier alternative. It has two active nodes, the baseline and the barrier. As the tree shows, the first opportunity to kill the red submarine is at the barrier. The barrier model calculated the probability that a submarine would be killed passing through the barrier to be 0.572. This leaves a probability of 0.428 ($1 - P_k$) that the red submarine will enter the operational area and be engaged by the Baseline alternative. Multiplying the probability of the submarine entering the operational area by the

probability of the baseline killing the submarine after it enters the operational area, gives the probability that any submarine that approaches the CSG will be killed by the baseline alternative, as part of the barrier alternative. Adding the probability of the submarine being killed by the barrier and the probability of the submarine being killed by the baseline gives the total probability of the submarine being killed, which is equal to the probability of the carrier surviving.

Figure 14 Barrier event tree (see online version for colours)

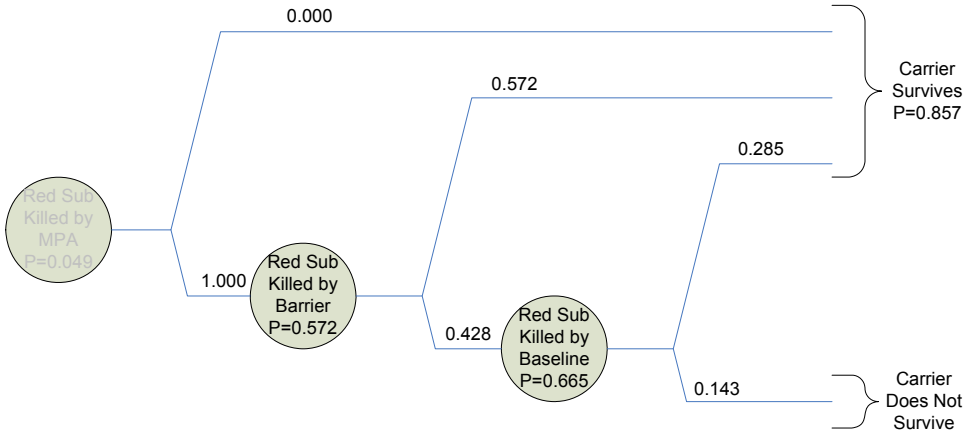


Figure 15 is the event tree for the MPA alternative. This is similar to the barrier event tree, in that two of the three nodes are active. In this case the first opportunity to kill the red submarine occurs outside the OA, in the MPAs patrol area. In this case the Barrier is not present so its node has no bearing on the outcome.

Figure 15 MPA event tree (see online version for colours)

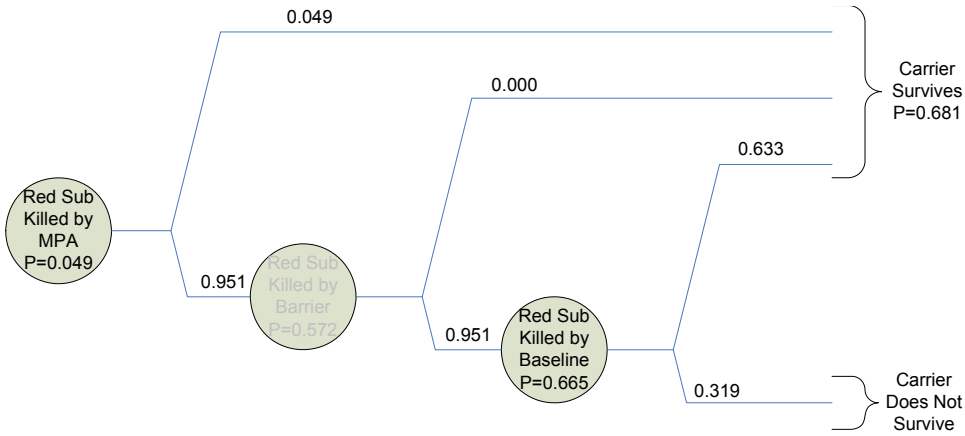
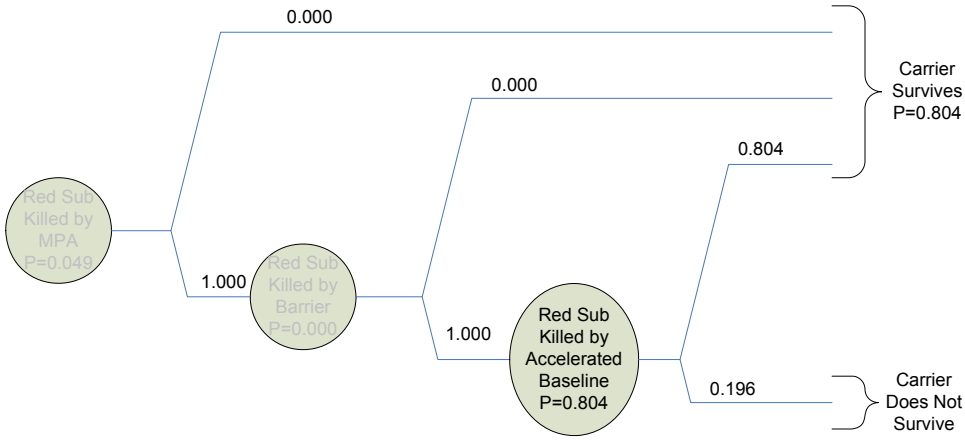


Figure 16 is the event tree for the ACB alternative. Like the baseline event tree it only has one active node, yet its superior performance compared to the baseline comes directly from the improved ASW system components on the ACB.

Figure 16 ACB event tree (see online version for colours)



5 Conclusions

The systems design and analysis of alternatives focused on the protection of the CVN while it is conducting aircraft launch and recovery operations as described in the reports scenario and concept of operations description. The ASW simulation tool included a fairly sophisticated level of detail and rigor, modelling a number of movement and detection algorithms. As results show, Alternative 3 (LCS deployed barrier) and Alternative 4 (ACB) result in nearly identical operational effectiveness outcomes.

Nevertheless, changes to the scenario or behaviour of the threat submarine could lead to different results. These changes may include modelling the enemy submarine such that it pursues the CVN with more caution rather than aggressively until successfully establishing a torpedo launch position, as well as the inclusion of multiple enemy submarines as the threat. Future research in ASW performance in support of CSG system of systems should examine the sensitivity of these key scenario aspects.

References

Akbori, F. (2004) 'Autonomous-agent based simulation of anti-submarine warfare operations with goal of protecting a high value unit', Master's thesis, March, Naval Postgraduate School, Monterey, CA.

Broadmeadow, J., Nguyen, N., Dziekan, F., Roach, P., Frantz, F., Sammis, J., Gudz, R., Santos, S., Kelley, P., Silveria, K., Kennedy, S., Smith, C., Moreira, C., Volk, K. and Wright, S. (2008) *Improved Anti-Submarine Warfare (ASW) Effectiveness*, June, Master of Science in Systems Engineering Capstone Project, Naval Post Graduate School, Monterey, CA.

Brown, B.M. and Schulz, B.L.P. (2009) 'The effects of the joint multi-mission electro-optical system on littoral maritime intelligence, surveillance, and reconnaissance operations', *Master's Thesis*, September, Naval Post Graduate School, Monterey, CA.

Buede, D.M. (2000) *The Engineering Design of Systems*, Wiley, New York.

Bureau of Ships (1965) *Introduction to Sonar Technology*, Figs. 2–3, p.33, Navy Department, Washington, D.C.

Conway, J.T., Roughhead, G. and Allen, T.W. (2007) 'A cooperative strategy for the 21st century seapower', Presented at the *International Seapower Symposium*, October, Newport, Rhode Island.

Green, M. (2007) 'Course notes for SI 4007', *Naval Weapon System Technology*, Naval Post Graduate School.

Jane's Fighting Ships (2008a) *Ticonderoga Class: Guided Missile Cruisers (CGHM)*, March, Jane's Fighting Ships, available at http://www8.janes.com/JDIC/JDET/documentView.do?docId=/content1/janesdata/yb/jfs/jfs_3530.htm@current&pageSelected=&keyword=Ticonderoga&backPath=http://jdet.janes.com/JDIC/JDET&Prod_Name=JFS&activeNav=http://www8.janes.com/JDIC/JDET.

Jane's Fighting Ships (2008b) *Arleigh Burke Class (Flights I and II): Guided Missile Destroyers (AEGIS) (DDGHM)*, March, Jane's Fighting Ships, available at http://www8.janes.com/JDIC/JDET/documentView.do?docId=/content1/janesdata/yb/jfs/jfs_3532.htm@current&pageSelected=&keyword=AEGIS&backPath=http://jdet.janes.com/JDIC/JDET&Prod_Name=JFS&activeNav=http://www8.janes.com/JDIC/JDET.

Jane's Underwater Warfare Systems (2008) March, available at http://juws.janes.com/public/juws/index.shtml.

Jean, G. (2008) 'Diesel-electric submarine, The U.S. Navy's latest annoyance', *National Defense Online,* April, available at http://www.nationaldefensemagazine.org/archive/2008/April/Pages/AntiSub2301.aspx.

Pike, J. et al. (2007) *Battle Group Composition*, November, available at http://www.globalsecurity.org/military/agency/navy/batgru-composition.htm.

Scherer, S.D. (2009) 'Game-theoretic anti-submarine warfare mission planner', Master's thesis, September, Naval Postgraduate School, Monterey, CA.

Timmerman, M.J. (1993) 'A genetic algorithm based anti-submarine warfare simulator', Master's thesis, September, Naval Postgraduate School.

United States Naval Reserve Intelligence Program (2007) *Ready-for-Sea Handbook, Module 2*, available at http://www.fas.org/irp/doddir/navy/rfs/part00.htm (accessed on 23 November 2007).

Washburn, A. (2005) *A Review of ASW Model in ITEM*, February, Technical report NPS-OR-05-004-PR, Naval Postgraduate School, Monterey, CA.

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