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**A METHOD TO QUANTIFY SHORTFALLS
AND COST BENEFITS FOR THE
MO2015 ASW ADVANCED CONCEPTS STUDY**

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A. Ferraro, G. Arcieri*

June 1997

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NORTH ATLANTIC TREATY ORGANIZATION

**A method to quantify shortfalls and
cost benefits for the MO2015 ASW
advanced concepts study**

**P. Saunders, E. Verhoeff, A. Ferraro,
G. Arcieri**

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Executive Summary: An ASW Advanced Concepts Study (ACS) has been initiated as part of Phase 2 of NATO Study, "Implications of New Technology for Maritime Operations in 2015 (MO2015)". The aim of the study is to recommend the most promising directions for Allied and National ASW R&D leading to development of affordable systems packages in the 2005-2015 timeframe that reduce the most significant ASW shortfalls. The most critical ASW shortfall identified during Phase 1 of the study dealt with the limited capability to detect modern submarines under difficult environmental and tactical conditions.

In this paper, a method to assess ASW search operations is described for use during the study that will allow various sensor/platform options to be examined in a consistent manner. The method avoids the necessity to carry out detailed modeling of ASW tactics and threat behavior which is very difficult to predict. It provides a means of examining the synergy between different sensor systems in covering the entire threat submarine operating envelope and also includes system/platform cost benefit analysis and resource optimization.

The methodology was presented to a meeting of the ASW Advanced Concept Team in March 1997 in Toulon, France and was adopted for use during Phase 2 of MO2015.

The algorithms and computer program described in this paper were developed to demonstrate the methodology and only deal with a specific ASW scenario. Presently these algorithms and the program are being expanded to include the many options that are presented in this paper. The enhanced computer program will be used extensively for the analyses required during the ASW Advanced Concepts Study. Other reports will follow describing the enhanced version of the model and the analyses and results from the study.

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A method to quantify shortfalls and cost benefits for the MO2015 ASW advanced concepts study

P. Saunders, E. Verhoeff, A. Ferraro, G. Arcieri

Abstract: An ASW Advanced Concepts Study (ACS) has been initiated as part of Phase 2 of NATO Study, "Implications of New Technology for Maritime Operations in 2015". In this paper, a method to assess ASW search operations is described for use during the study, which will allow various sensor/platform options to be examined in a consistent manner. The method avoids the necessity to carry out detailed modeling of ASW tactics and threat behavior which is very difficult to predict. It provides a means of examining the synergy between different sensor systems in covering the entire threat submarine operating envelope. It also includes system/platform cost benefit analysis and resource optimization using Integer Programming techniques. Presently the algorithms and the computer program that were developed to demonstrate the methodology are being expanded to include several options that are presented in this paper. The enhanced computer program will be used extensively for the analyses required during the ASW Advanced Concepts Study.

Keywords: NATO maritime operations

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1

Introduction

The "Implications of New Technology for Maritime Operations in 2015" is a study initiated by SACLANT and sponsored by the NATO Defence Research Group. The aim of the study is to help NATO planning staffs and Nations with long-term defence planning and requirements for new systems in the light of the changing world, the new NATO strategy and shrinking defence budgets. Phase I of the study has been completed [1,2,3,4] and Phase II has commenced.

An ASW Advanced Concepts Study (ACS) has been initiated as part of Phase 2 of MO2015. France is leading this Study with support from several of the NATO Nations and Agencies. SACLANTCEN is participating and has membership on the Core Team. The aim of the study is to recommend the most promising directions for Allied and National ASW R&D leading to development of affordable systems packages in the 2005-2015 timeframe that reduce the most significant ASW shortfalls. The study will be conducted in four steps that are described briefly below:

- Step 1: Review, define, quantify and determine causal factors for the major ASW shortfalls identified in Phase 1 of the study, projected to the new reference timeframe of 2015.
- Step 2: Assess the impact of emerging systems and formulate suitable systems' packages which are based on operational merit.
- Step 3: Evaluate the cost benefits of promising systems and identify affordable packages.
- Step 4: Military review of findings in the context of wider system issues and recommendations for Alliance R&D.

During Phase 1 of the MO2015 study, one particular ASW shortfall was identified as being the most critical over the scenarios examined. This shortfall dealt with the limited capability to detect modern submarines under difficult environmental and tactical conditions. As indicated above, the approach to Phase 2 of the study will require the quantification of shortfalls in the light of future security challenges which the NATO Alliance could face and the assessment of the impact and cost benefit of new systems that could be introduced. This quantification process will have to be done in a consistent manner over a relatively short period of time.

One approach to this analysis requirement is to use a detailed ASW mission simulation program that models individual sensor systems and platforms (including ships, submarines, helicopters and aircraft). This simulation would have to include search tactics, coordination of assets and threat submarine behavior in order to provide a representative result. This is a very complex problem, especially when some of the sensors under consideration are not in service yet and tactics have not yet been developed. The modeling of coordinated ASW operations is also difficult, particularly when both acoustic and non-acoustic sensors are involved. Threat submarine behavior can drive the results and this behavior and reaction to events is very difficult to predict. For example, the submarine's time at periscope depth, mast exposure and reaction to detecting MPA radar transmissions will have significant impact on the effectiveness of a periscope detection radar (PDR). This problem is further compounded by the uncertainty surrounding the behavior of submariners from non-Western nations.

Another factor to consider in the simulation is the 'synergy' between different sensors and platforms. For example, the presence of say a PDR may alter a submarine's behavior thus improving the effectiveness of acoustic sensors or the use of LFAS below the surface layer may cause submarines to stay shallow where they are more vulnerable to non-acoustic sensors. Another example is active and passive sonars, where the presence of passive sonars may prevent a submarine from using speed to escape from active sensors. This 'synergy' between sensors must somehow be modeled.

The combination of these requirements, the lack of suitable models and the limited time available to complete the Phase II analysis mean that another solution to the analysis requirements must be found. This paper proposes a methodology that will assist in conducting the analysis of the ASW detection shortfall. This report discusses the merits of this methodology and describes possible future options.

2

Methodology

2.1. INTRODUCTION

The methodology is summarised in the five steps below:

- a. Step 1: For a given scenario, divide the water column into 'Zones' based on the potential operating behavior of the threat submarine.
- b. Step 2: Produce a matrix which shows sensor/platform performance against each operating 'zone'. The area of interest is considered homogeneous throughout.
- c. Step 3: Determine the mission effectiveness over the area of interest based on the ASW assets that are available. Each 'zone' is treated independently so different effectiveness values are likely for each 'zone'. (different combinations of sensors can be considered). The overall measure of effectiveness (MOE) would be the minimum mission effectiveness over all of the 'zones'.
- d. Step 4: Optionally, submarine operating behavior can be considered. Given the percentage of time the threat submarine spends in each 'zone', an overall MOE can be determined.
- e. Step 5: Optionally, system or platform cost can be included for a cost benefit type analysis. Given system/platform costs, optimization of mission effectiveness for a fixed cost or minimum cost to achieve a given level of effectiveness can be determined.

Each of these steps is described in more detail below by means of simple examples. An attempt will be made to indicate what other options are available as the example proceeds and a summary of these options will be presented later in the paper.

2.2. SCENARIO

For the examples used in this paper, it is assumed that an area of operation with a specified environment has been defined for an ASW area search operation. NATO forces and the threat submarine(s) have been identified. The numbers presented in this example are illustrative only.

2.3. STEP 1: DEFINE ZONES

The first step is to break the threat submarine's operating envelope or behavior into 'Zones' representing the submarine's vulnerability to different ASW sensor systems. This vulnerability would vary with the environment, the NATO sensors/platforms and the threat. An example is shown in Figure 1, where the 'Zones' are defined as follows:

- a. Zone 1a: A conventional submarine snorkeling.
- b. Zone 1b: A submarine at periscope depth with some masts exposed.
- c. Zone 1c: A submarine in the surface duct at quiet speed.
- d. Zone 1d: A submarine in the surface duct at fast speed.
- e. Zone 2a: A submarine below the surface duct at quiet speed.
- f. Zone 2b: A submarine below the surface duct at fast speed.
- g. Zone 3a: A submarine deep at quiet speed
- h. Zone 3b: A submarine deep at fast speed

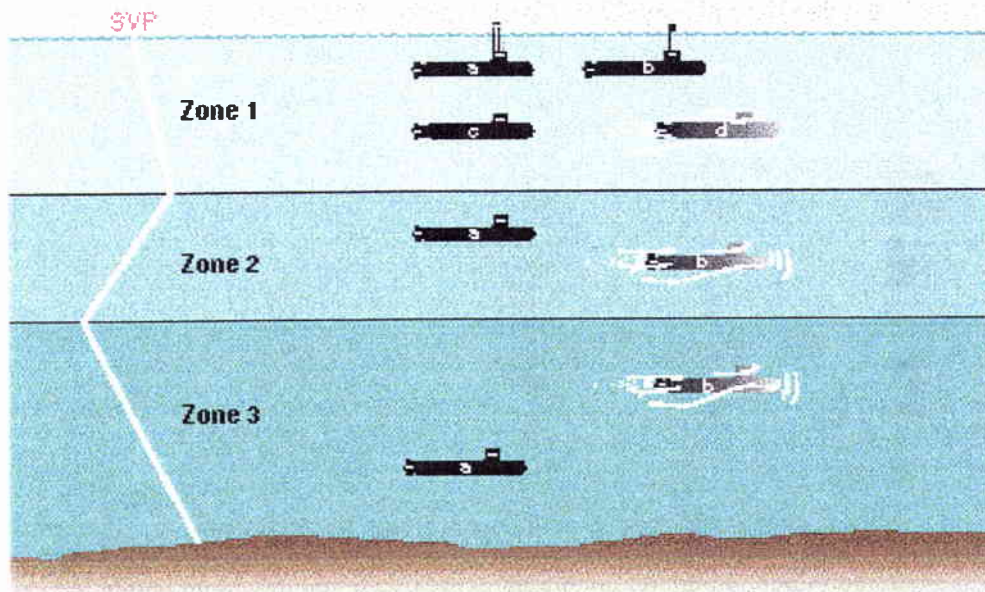


Figure 1: *An illustration of possible submarine operating zones and behavior for a specific environment and submarine type.*

In this example, the zone number represents a depth interval that has been determined by the different gradients in the sound velocity profile (SVP). The letter represents a different behavior within the depth interval, which could change the submarine's vulnerability to the various sensors. For example in the deep zone, the submarine could either be at quiet speed or fast speed as this would change the vulnerability to active and passive sensors.

2.4. STEP 2: SENSOR/PLATFORM PERFORMANCE

In this step, a matrix is produced which represents the capability of the various ASW sensors or platforms to detect the submarine operating in each of the zones. Table 1 shows an example of such a matrix. The matrix must show all combinations of sensors/platforms versus the various submarine operating zones. Because some sensors can be operated differently depending on the submarine zone of interest, these sensors are given more than one column in the matrix. For example, variable depth sensors may be operated differently to detect a submarine in the surface duct than below the surface duct and since they can't operate in more than one zone simultaneously, the two possibilities are treated in separate columns.

Each of the sensors in the matrix is described briefly below:

- a. HMS: Hull Mounted Sonar;
- b. VDS(Z-1): Variable Depth Sonar, operating so as to detect submarines in the surface layer;
- c. VDS(Z-2,3): Variable Depth Sonar, operating so as to detect submarines below the surface layer;
- d. LFAS: Low Frequency Active Sonar with a variable depth capability;
- e. TASS: a passive Towed Array Sonar System with a variable depth capability; and,
- f. Radar: a periscope detection radar operated by a Maritime Patrol Aircraft (MPA).

The matrix in Table 1 uses sensors as opposed to platforms. If platforms had been used, then the combined performance of all ASW sensors available on the platform would have to be determined for each cell. In this case, a separate column would be required for the different operating characteristics of the platforms. For example, an MPA using both radar and acoustic sonobuoys to search an area, can operate at an altitude to maximize radar coverage or an altitude to maximize the sonobuoy monitoring capability. If both situations are to be considered, then a column is required for each with the appropriate sensor performance.

The performance indicator used in this example is the search rate in square nautical miles per hour for the sensor against the given target behavior, in the specified area. It is assumed that the submarine's behavior is constant within each of the zones.

Table 1: *Sensor search rate in square nautical miles per hour versus the various submarine operating zones*

	Sensor System							
	HMS	VDS (Z-1)	VDS (Z-2,3)	LFAS (Z-1)	LFAS (Z-2,3)	TASS (Z-1)	TASS (Z-2,3)	Radar
Zone 1a	20	15	10	20	10	500	100	1600
Zone 1b	20	15	10	20	10	10	10	600
Zone 1c	100	15	10	20	10	10	10	0
Zone 1d	90	10	8	15	8	60	20	0
Zone 2a	8	15	60	25	80	10	20	0
Zone 2b	5	10	50	20	70	10	100	0
Zone 3a	15	15	40	100	500	10	80	0
Zone 3b	10	10	35	80	450	15	100	0

Note: These values are purely illustrative.

The choice of performance indicator is important as it must be in a form that is consistent across all sensor systems and it must allow combinations of systems to be examined. It also must be in a form that Technologists can use to evaluate emerging or conceptual systems that may be proposed during the study. Search Rate is a good measure to use as different systems' values can readily be combined to produce a Probability of Detection. It is important, however, that Search Rate be determined in a consistent manner especially as different types of sensor systems are being compared. The search rate is based on the speed of the searcher and an effective search width that is twice the range of a definite range law of detection [5]. It can also be enhanced to include target speed or adjusted to account for false contact rate. Other options are to use probability of detection, effective search width or lateral detection range.

The format of this table makes it easy to examine and compare the effectiveness of each of the sensors versus the various submarine operating zones. This format clearly shows which submarine operating zones could be a problem and which sensor/platforms offer the best cross-zonal performance. This first result merely allows the relative detection performances

of individual sensors systems or platforms to be compared. To establish what this would mean in an actual ASW mission, more computations are required.

2.5. STEP 3: MISSION EFFECTIVENESS

An important requirement of the study is to determine the effectiveness of a group of sensors and platforms in a Multi-National Maritime Force (MNMF) conducting a coordinated ASW mission. The above methodology could be used to accomplish this with the addition of another parameter; number of units. Table 2 illustrates this, using the example from Step 2. In this case, each cell reflects the hourly search rate of all assigned units of a particular sensor type versus a submarine operating zone. The overall search rate in each zone is given, indicating the combined hourly search capability of all sensors versus each zone. Also given is the probability of detection (P_D) for each zone. Assuming independence between the different platforms and systems, P_D is calculated using the combined hourly search rates across each zone and an equation for random search [5] as follows:

$$P_D(t) = 1 - e^{-\frac{\sum(\text{all SR in zone}) \times t}{A}}$$

where $P_D(t)$ is the probability of detection in a zone over time t in hours,

A is the size of the area to be searched in n. mi.².

For the calculations shown in Table 2, the search is assumed to last for 8 hours over an area of size 10,000 n. mi.². The equation described above is a simple equation for random search where the target is assumed to be uniformly distributed in the area

The overall mission effectiveness could be the minimum value over all of the zones (.26), which assumes that the submarine has a lot of information on the ASW force and has chosen the best zone to avoid detection. This result may well be all that is required to meet the first objective of the study in terms of addressing the detection shortfall. It ensures that all potential submarine operating behavior is examined without the need to predict actual behavior. In a sense, this approach considers the synergy between different sensor systems since the combined action of the sensors in covering the various threat options is evident. What it doesn't do is to weight the importance of some submarine behavior in the context of an actual mission. For example, in an anti-surface ship operation, a submarine may remain at periscope depth for extended periods for targeting and weapon launch. However, if the submarine's main objective is to remain undetected then it would stay at best depth to avoid detection as much as possible, only snorkelling when required. The next step will incorporate probable submarine behavior.

Table 2: Combined search rate (SR) and detection probability (P_D) in zones with numbers of units identified. P_D based on 8 hour search operation in an area of 10,000 sq. n. mi.

Zone	Sensor System [Number of Units]								Overall Search Rate	P_D
	HMS [6]	VDS (Z-1) [0]	VDS (Z-2,3) [2]	LFAS (Z-1) [0]	LFAS (Z-2,3) [2]	TASS (Z-1) [0]	TASS (Z-2,3) [2]	Radar [1]		
1a	120	0	20	0	20	0	200	1600	1960	.79
1b	120	0	20	0	20	0	20	600	780	.46
1c	600	0	20	0	20	0	20	0	660	.41
1d	540	0	16	0	16	0	40	0	612	.39
2a	48	0	120	0	160	0	40	0	368	.26
2b	30	0	100	0	140	0	200	0	470	.31
3a	90	0	80	0	1000	0	160	0	1330	.65
3b	60	0	70	0	900	0	200	0	1230	.63

Note: These values are purely illustrative.

2.6. STEP 4: INCLUDING SUBMARINE BEHAVIOR

It is possible with this methodology to introduce probable submarine behavior. Submarine tactics depend on a number of factors, many of which are unpredictable; however the introduction of submarine behavior does allow the overall zone effectiveness numbers to be combined in a meaningful way to produce an overall expected detection probability. Some of the more important factors affecting submarine behavior are the submarine type, its mission, the threat it faces and its knowledge of the threat and the environment. Table 3 introduces submarine behavior continuing with the same example.

Table 3: An example that includes probable submarine behavior and detection probability for a 24 hour search operation in an area of 10,000 sq. n. mi.

Zone (% time in Zone)	Sensor System [Number of Units]								Overall Hourly SR	P_D
	HMS [6]	VDS (Z-1) [0]	VDS (Z-2,3) [2]	LFAS (Z-1) [0]	LFAS (Z-2,3) [2]	TASS (Z-1) [0]	TASS (Z-2,3) [2]	Radar [1]		
1a (5%)	120	0	20	0	20	0	200	1600	1960	.04
1b (5%)	120	0	20	0	20	0	20	600	780	.02
1c	600	0	20	0	20	0	20	0	660	0
1d	540	0	16	0	16	0	40	0	612	0
2a (90%)	48	0	120	0	160	0	40	0	368	.23
2b	30	0	100	0	140	0	200	0	470	0
3a	90	0	80	0	1000	0	160	0	1330	0
3b	60	0	70	0	900	0	200	0	1230	0
Note: These values are purely illustrative									Overall	.29

In the table, the percentage of time that the submarine spends in each particular zone and state is indicated in the first column. Also in this table, Probability of Detection (P_D) includes the expected submarine behavior. This is determined as follows:

$$P_D(t, z_a) = f_a \times \left(1 - e^{-\frac{\sum (\text{all hourly SRs in zone } a) \times t}{A}} \right)$$

where $P_D(t, z_a)$ is the probability of detection in zone a over time t ,

f_a is the expected fraction of time the submarine spends in zone a , and

The overall probability of detection is the expected value for the mission as shown. Caution should be used with this approach because of the uncertainty in the submarine behavior. It is important that the entire operating envelope is covered regardless of the behavior, since it may be the sensors in other zones that drive the submarine's behavior.

2.7. STEP 5: INCLUDING COST BENEFIT ANALYSIS

One final factor can be included in this simple methodology; cost and cost benefit analysis. This analysis will be most useful in achieving the second and third objectives of the study. By incorporating cost in the analysis, a better indication of the relative merits of the various systems can be examined. Table 4 introduces a per unit system cost. This does not necessarily have to be the actual cost but more a reflection of the relative costs. In Table 4, the detection probability per hour of search time is given for each submarine behavior zone for a search area of 10,000 n.mi.².

Table 4: *An example that includes a measure of system cost*

Zone	Sensor System [Number of Units] {cost per unit}								P_D (t=1 hr)
	HMS {6} {10}	VDS (Z-1) {3} {12}	VDS (Z-2,3) {2} {12}	LFAS (Z-1) {0} {20}	LFAS (Z-2,3) {2} {20}	TASS (Z-1) {0} {15}	TASS (Z-2,3) {4} {15}	Radar {1} {8}	
1a	120	0	20	0	20	0	200	1600	.18
1b	120	0	20	0	20	0	20	600	.08
1c	600	0	20	0	20	0	20	0	.06
1d	540	0	16	0	16	0	40	0	.06
2a	48	0	120	0	160	0	40	0	.04
2b	30	0	100	0	140	0	200	0	.05
3a	90	0	80	0	1000	0	160	0	.12
3b	60	0	70	0	900	0	200	0	.12
Cost	60	36	24	0	40	0	60	8	228 (Total)

Note: These values are purely illustrative

In the example in Table 4, the hourly detection probabilities in each of the zones range from 0.04 to 0.18 and the total cost is 228. The cost is determined by the number of units and not affected by the submarine behavior or the system effectiveness. The use of cost must be treated very carefully. It could be any of the following:

- operating costs of the platform or sensor (this could be related to time of the operation);
- acquisition costs of the sensors or platforms;
- life cycle costs of the sensors or platforms;
- research and development costs; or

- e. a combination of the above costs.

It may also be misleading in that platforms and even sensors are for multiple uses. For example, an ASW frigate may have a role in air defence, may carry an ASW helicopter and may be valuable in some other ASW mission different from the scenario under consideration. Despite these problems, the addition of cost does introduce a means of comparing the cost effectiveness of the different systems in the scenario of interest.

2.7.1. Optimization

One final option can be added to the methodology presented in this paper and that is optimal resource allocation. This will provide a means of examining optimal mixes of systems/platforms in terms of performance and cost to achieve a given capability or to maximize capability within certain limits. The area search scenario that has been used in the above examples, can be formulated into simple optimization problems. Three Cases are considered:

- a. Case 1: Maximize the minimum probability of detection over all zones within a given cost.
- b. Case 2: Minimize the cost to achieve a given probability of detection over all of the zones.
- c. Case 3: Minimize the cost to achieve a given probability of detection when the distribution of submarine behavior is known.

These three cases have been formulated mathematically as Integer Programming problems and a computer program, which has been named "*Cost Cutter*", has been written to solve them. The mathematics and the computer program are described in detail in Annex A. An example for each of the cases will be presented below using the computer program input/output window.

2.7.1.1 Case 1

As stated above, the objective with Case 1 is to maximize the minimum probability of detection over all zones within a given cost. This could also be stated as maximizing the probability of detection within a given cost, while assuming that the submarine optimizes its choice of zone. This Case ensures that all potential submarine behavior is taken under consideration while remaining within a fixed cost. To illustrate this case, the example and system costs presented in Table 4 will be used. It will be assumed that the objective is to maximize the probability of detection for a 24-hour search operation in a 10,000 n.mi.² area, while keeping the total costs within 150 units. The input/output window from the computer program is shown in Figure 2.

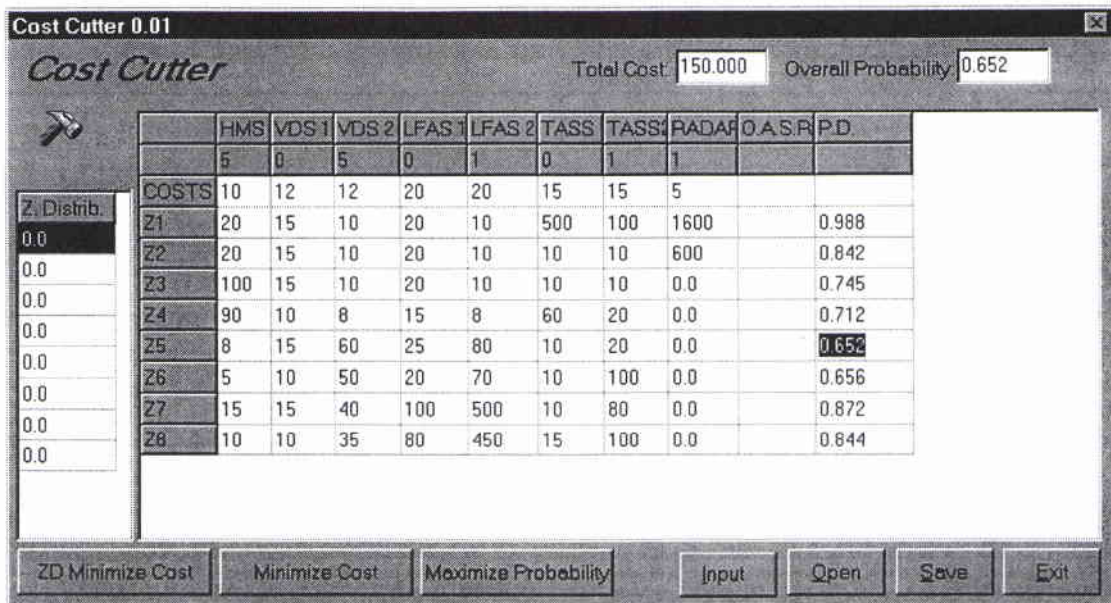


Figure 2: Illustration of Case 1 where total costs cannot exceed 150 units (search time = 24 hours, search area 10,000 sq. n. mi.)

In the figure, the results of the optimization are shown in the row under the sensor system names. For example, the solution calls for 5 HMSs, 5 VDSs (operating deep), 1 LFAS (operating deep), 1 TASS (operating deep) and 1 Radar and the minimum probability of detection is 0.652. The eight zones indicated on the input/output screen have been renamed Z1 to Z8 corresponding to 1a, 1b ... 3b from the example.

2.7.1.2 Case 2

For this case, the objective is to minimize the cost to achieve a given probability of detection over all of the zones. Like Case 1, this presupposes that the submarine will choose to operate in the zone where it is least vulnerable to detection. Figure 3 illustrates this case where it has been specified that the probability of detection must be at least 0.80 in each zone. The resulting total cost to achieve this overall effectiveness is 226. Again, the numbers of platforms/sensors required are indicated in the row under the sensor names.

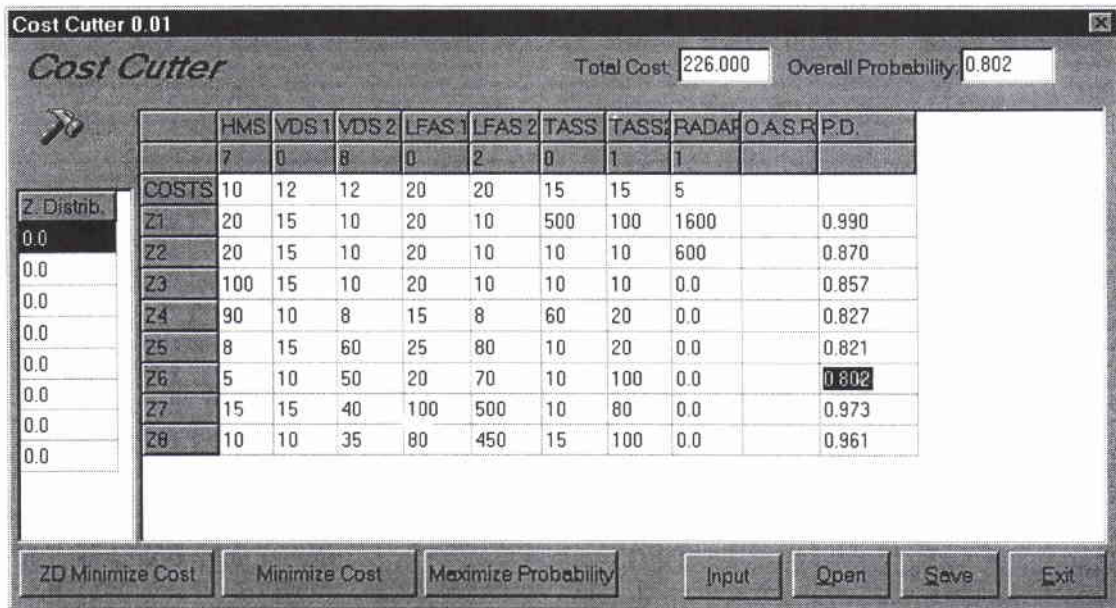


Figure 3: Illustration of Case 2 where probability of detection must be at least 0.80 in all Zones. The minimum cost to achieve this is 226 units (search time = 24 hours, search area 10,000 sq. n. mi.).

2.7.1.3 Case 3

For case 3, the objective is to minimize the cost to achieve a given overall probability of detection when the distribution of submarine behavior is known. Figure 4 illustrates this case where the submarine behavior is specified in the column under the label 'Z. Distrib.' as follows: 5% of the time snorkelling (Z1, formerly 1a); 5% of the time with periscope exposed (Z2, formerly 1b); and, 90% of the time below the surface layer (Z5, formerly 2a). The minimum cost to achieve an overall probability of detection of 0.80, is 145.

Care must be taken when using these optimization algorithms as they are very sensitive to the search rates and the costs. These parameters do not reflect sensor/platform characteristics and capabilities for other missions. Also, the search rates are greatly influenced by the environmental factors and the scenario and do not necessarily reflect other cases which may be more likely.

	HMS	VDS 1	VDS 2	LFAS 1	LFAS 2	TASS	TASS	RADAR	O.A.S.R	P.D.
	0	0	10	0	1	0	0	1		
COSTS	10	12	12	20	20	15	15	5		
Z1	20	15	10	20	10	500	100	1600		0.983
Z2	20	15	10	20	10	10	10	600		0.818
Z3	100	15	10	20	10	10	10	0.0		0.232
Z4	90	10	8	15	8	60	20	0.0		0.190
Z5	8	15	60	25	80	10	20	0.0		0.804
Z6	5	10	50	20	70	10	100	0.0		0.745
Z7	15	15	40	100	500	10	80	0.0		0.885
Z8	10	10	35	80	450	15	100	0.0		0.853

Buttons at the bottom: ZD Minimize Cost, Minimize Cost, Maximize Probability, Input, Open, Save, Exit.

Figure 4: Illustration of Case 3 where submarine behavior is specified and total costs are minimized to achieve an overall probability of detection of at least 0.80. The resulting cost is 145. (search time = 24 hours, search area 10,000 sq. n. mi.)

3

Limitations and Options

The series of examples described in this paper illustrate a concept for assessing systems' effectiveness in an ASW operation where the combined effectiveness of different types of systems can be evaluated. It is apparent that there are many limitations with such a simple methodology, however, many of these limitations can be addressed by using the methodology in a slightly different manner or by making some enhancements in the "Cost Cutter" program. Several of these options are described below:

- a. In the examples above, an area search type operation was used. This methodology could also be adapted for other ASW operations that involve search. For example, a barrier search operation or a screening operation could also be included. In this case, the measure of effectiveness could be the probability of detecting a submarine that is attempting to penetrate the barrier in each of the zones.
- b. The search equation used in the above examples is for random search for a target which is uniformly distributed in an area. Other search equations could be used, although the formulation of the linear program for the optimization would have to change.
- c. In the example in this paper, the unit cost was held constant. This could have been related to the time of the operation by using something like a daily or hourly operating cost. This would be useful in evaluating surveillance and tracking type operations which could go on for extended periods. There are also several options for cost as described in Section 2.5.
- d. The optimization routine provides no facility for specifying or restricting the numbers of platforms/sensors. It would be desirable to have this capability. For example, it is conceivable that only a specific number of sensors of a certain type can operate in an area because of mutual interference. Another possibility is that certain platforms may be assigned to a mission regardless of their effectiveness because they are required for other reasons.
- e. Three different optimization possibilities are presented in this paper. Other formulations are possible.
- f. The search rate was used as the performance indicator for the sensor. It is a good metric as it is easy to combine in the case of multiple systems and also easy to calculate detection probabilities. One problem with using Search Rate is that it can be estimated in a number of ways and can be enhanced to include target speed. In

the case of the MO2015, various Nations will be providing sensor performance information to be used for the analysis. There is a risk that Search Rate is not determined in a consistent manner. To avoid this kind of inconsistency, other performance measures could be used. Other possibilities are as follows:

- i. lateral detection range;
 - ii. sweep width;
 - iii. 50% detection range from which search rate can be estimated; or,
 - iv. raw sensor system characteristics which can be used to generate performance predictions.
- g. In this paper, sensor systems have been used for evaluating and comparing ASW mission capability. Another option is to use total platform performance. In this case, the performance of all the sensors on a platform would be combined. For example, an ASW frigate could have a combined search rate which includes a towed array, a hull mounted sonar, a search radar and visual.
- h. The methodology assumes a constant detection performance within a zone for each sensor and that the entire operating area has the same zone structure. This was a necessary assumption in order to keep the methodology and the optimization simple. To account for changes in zonal sensor performance over an area, average values could be used. If the zone structure changes significantly because of bathymetry or other environmental changes over the area, then the area could be subdivided into smaller areas and each treated separately. The sensor/platform requirements would have to be considered for each sub-area and then combined in some manner to determine total requirements.
- i. In the example, all of the sensor systems perform in a continuous sweep mode. This does not cover sensors such as helicopter dipping sonar, sonobuoys and sensor systems where an intermittent policy is used. These types of sensors can be included by adjusting the search accordingly or by treating them separately in the program.

4

Summary

A method to assess ASW search operations has been described for use during the MO2015 advanced Concepts Study that will allow various sensor/platform options to be examined in a consistent manner. The method avoids the necessity to carry out detailed modeling of ASW tactics and threat behavior which is very difficult to predict. The method provides a means of examining the synergy between different sensor systems in covering the entire threat submarine operating envelope and also includes system/platform cost benefit analysis and optimization.

The methodology was presented to a meeting of the ASW Advanced Concept Team in March 1997 in Toulon, France. It was well received and adopted for use during Phase 2 of MO2015.

The algorithms and computer program described in Annex A were developed simply to demonstrate the methodology and only deal with the specific ASW scenario used in this paper. Presently these algorithms and the program are being expanded to include many of the options presented in the previous chapter. This enhanced computer program will be used extensively for the analysis required during the four steps of ASW Advanced Concepts Study and will be made available to use at MO2015 Mission Analysis Workshop and Multi-National Exercise. Other reports will follow describing the enhanced version of the model and the analyses and results from the study.

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Annex A

Optimal Allocation in a Linear Programming Environment

A1. INTRODUCTION

This Annex provides the mathematical formulations to solve the optimization problems posed in the main text of this paper. The problems are solved as Linear Programs. A computer program called '*Cost Cutter*' was written to carry out the computations and to provide a user-friendly interface for program execution and data entry. As the purpose of this 'prototype' computer program is to demonstrate a methodology, the program only deals with the sensor and submarine operating zones presented in the main text. Presently the program is being expanded to cope with other options.

A2. PROBLEM DEFINITION

Suppose that the x_i represent the number of sensors or units of the various types and c_i , the cost of each unit. Here x_i is integer, and $c_i \geq 0$. The water column is divided into 8 zones representing the potential operating behavior of the threat submarine and each sensor/zone combination has an associated search rate based on the sweep width of the sensor (W) and its velocity (v). This is indicated in the following table.

	HMS	VDS 1	VDS 2	LFAS 1	LFAS 2	TASS 1	TASS2	RADAR	D.A.S.R.	P.D.
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8		
CDSTS	c1	c2	c3	c4	c5	c6	c7	c8		
Z1										
Z2										
Z3										
Z4					W-v					
Z5										
Z6										
Z7										
Z8										

Assuming the probability of unit i detecting the submarine in zone j is given by $1 - e^{-\alpha_{i,j}}$, then the overall probability of detecting the submarine in zone j (assuming independence) will be

$$1 - \prod_{i=1}^8 e^{-x_i \alpha_{i,j}} = 1 - e^{-\sum_{i=1}^8 x_i \alpha_{i,j}}.$$

Here $\alpha_{i,j} = \frac{W \cdot v \cdot T}{A}$, where $W \cdot v$ is the search rate of sensor i in zone j , T the search time, and A the size of the investigated area.

This terminology is taken from the well known random search formula $P(t) = 1 - e^{-\frac{W \cdot v \cdot t}{A}}$ [5].

Note that maximizing $1 - e^{-\sum_{i=1}^8 x_i \alpha_{i,j}}$ is the same as maximizing $\sum_{i=1}^8 x_i \cdot \alpha_{i,j}$, since $f(z) = 1 - e^{-z}$ is a monotonous function of z .

There are three cases of interest, which will be treated separately:

- a. Case 1: With a given (maximum) cost, maximize the probability of detection. This assumes the submarine optimizes its choice of zone to minimize the chances of being detected.
- b. Case 2: Minimize the cost to obtain a given probability of detection. This assumes the submarine optimizes its choice of zone to minimize the chances of being detected.
- c. Case 3: Minimize the cost to obtain a given probability of detection assuming the submarine distribution in the zones is given.

The mathematical formulations of these cases are provided below.

A3. CASE FORMULATION

Case 1

In this Case, the problem is to maximize, the minimum probability over all of the zones while remaining within a maximum cost, C . An extra non-integer variable, x_9 , is introduced.

The integer program is :

maximize x_9

constraints: $x_i \geq 0$ for $i = 1..8$, and x_i integer

$$\sum_{i=1}^8 \alpha_{ij} x_i - x_9 \geq 0 \text{ for } j = 1..8$$

$$\sum_{i=1}^8 c_i x_i \leq C \text{ (the maximum cost)}$$

Note that the resulting probability is now given by $1 - e^{-x_9}$.

Case 2:

The problem here is to minimize the cost to achieve a given probability of detection. The desired probability of detection p is first transformed into \tilde{p} by defining $\tilde{p} = -\ln(1 - p)$

The integer program is:

minimize $\sum_{i=1}^8 c_i x_i$

constraints: $x_i \geq 0$ for $i = 1..8$, and x_i integer

$$\sum_{i=1}^8 \alpha_{ij} x_i \geq \tilde{p} \text{ for } j = 1..8$$

Case 3:

In this case, the distribution of submarine time spent in each of the zones (v_j) is required and the problem is to minimize the cost to obtain a given probability of detection. This case cannot be solved in an IP environment, since one of the constraints will be

$$\sum_{j=1}^8 \left[v_j \cdot \left(1 - e^{-\sum_{i=1}^8 \alpha_{ij} x_i} \right) \right] = 1 - \sum_{j=1}^8 \left[v_j \cdot e^{-\sum_{i=1}^8 \alpha_{ij} x_i} \right] \geq p$$

One solution to this problem is to force every row with a non-zero v_j to satisfy

$$\sum_{i=1}^8 \alpha_j x_{i,j} \geq \tilde{p}.$$

$$\text{Then } \sum_{j=1}^8 \left[v_j \cdot \left(1 - e^{-\sum_{i=1}^8 \alpha_{ij} x_i} \right) \right] = \sum_{v_j \neq 0} \left[v_j \cdot \left(1 - e^{-\sum_{i=1}^8 \alpha_{ij} x_i} \right) \right] \geq \sum_{v_j \neq 0} (v_j \cdot p) = p$$

The program is:

$$\text{minimize } \sum_{i=1}^8 c_i x_i$$

constraints: $x_i \geq 0$ for $i = 1..8$, and x_i integer

$$\sum_{i=1}^8 \alpha_{ij} x_i \geq \tilde{p} \text{ for all } j \text{ with } v_j \neq 0$$

This is the same as Case 2, but now only the non-zero rows are considered.

A4. COMPUTATIONAL ASPECTS

This first version of the 'Cost Cutter' program is intended to demonstrate the methodology using a very specific scenario. It is based on a public domain Linear Programming Library, which has been modified in order to be used in the Windows Operating System.

The library is based on the Simplex algorithm, and on the *Branch & Bound* technique for the integer programming. The conversion of the routines to the M.S. Windows Operating System has been done only to the extent needed to complete the *Cost Cutter* program, and will be completed at a later stage.

The Library has been recompiled in a DLL (Dynamic Link Library) which can be used by any Windows program.

The interface of the program has been implemented in Borland Delphi, which is a tool based on an extension of Pascal called Object Pascal. It is a RAD tool (Rapid Application Development) which permits the visual design of an application and relies on the Linear Programming module **lpdll.dll**.

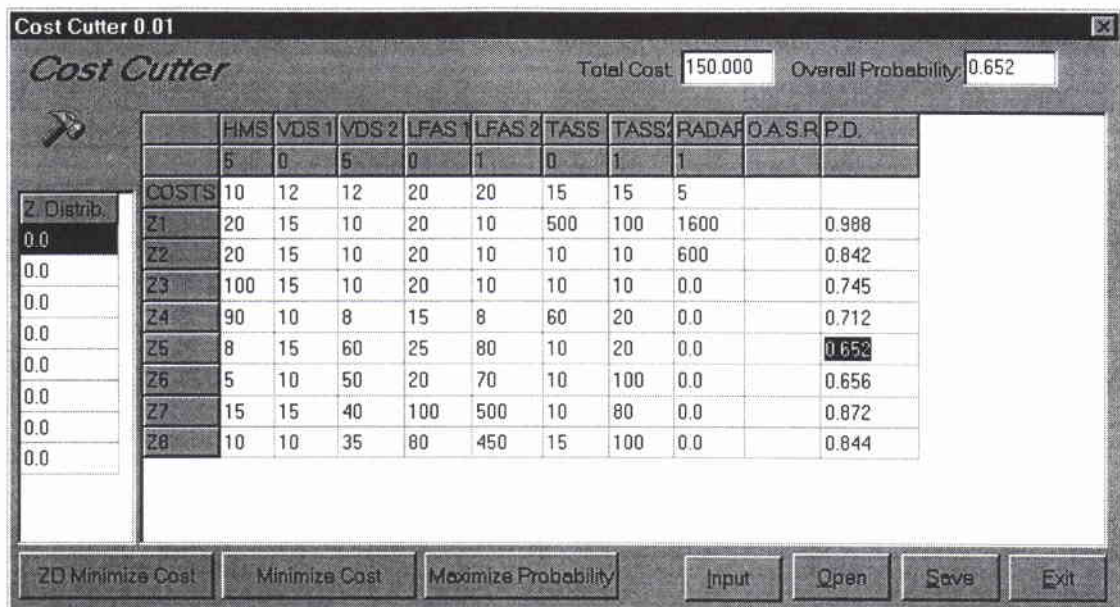
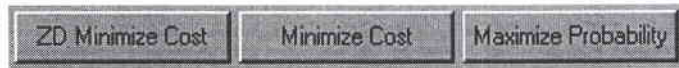


Figure A1: *Cost Cutter* program main input/output window, illustrating results from running the Case 1 option.

The application allows the user to specify sensor search rates for a fixed number of sensor types (various sonars types and one radar) and a fixed number of submarine zones (Z1 to Z8). The unit costs are also specified. The configuration can be saved and loaded by the **Open** and **Save** command buttons.

There are two main parameters that can be changed or **Input** at any time during the program execution. These are the search time and the area size.

The three Cases of the previous chapter are activated by the three buttons depicted below: (**ZD Minimize** for Case 3, **Minimize Cost** for Case 2 and **Maximize Probability** for Case 1)



The **Z. Distrib** column contains the sub v_j values of Case 3 and is not taken into account in the other two cases.

The second line from the top of the main grid will contain the solutions that are the number of sensors of each type, which are necessary to complete the operation, depending on the case chosen by the user. The program does not check the validity of the input, except in a few cases. It is the user's responsibility to enter the values correctly.

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<i>Abstract</i> An ASW Advanced Concepts Study (ACS) has been initiated as part of Phase 2 of NATO Study, "Implications of New Technology for Maritime Operations in 2015". In this paper, a method to assess ASW search operations is described for use during the study, which will allow various sensor/platform options to be examined in a consistent manner. The method avoids the necessity to carry out detailed modeling of ASW tactics and threat behavior which is very difficult to predict. It provides a means of examining the synergy between different sensor systems in covering the entire threat submarine operating envelope. It also includes system/platform cost benefit analysis and resource optimization using Integer Programming techniques. Presently the algorithms and the computer program that were developed to demonstrate the methodology are being expanded to include several options that are presented in this paper. The enhanced computer program will be used extensively for the analyses required during the ASW Advanced Concepts Study.		
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