Future MCM System-of-System Studies

Appendix A: Supporting Papers and Briefs

Overview: During the course of this MCM system a number of supporting papers were written and briefs were presented. These includes supporting investigations into aspects of the small UUV capabilities, descriptions of the assessments process, selections of the MCM scenarios to be used in the system assessments, and descriptions of alternative mine hunting approaches. These documents are provided in this appendix to provide more details about topics presented in the other parts of this document

Papers and Briefs

1) Concept Developments for the ONR Future MCM Systems Alternatives Project

2) Problem Definition, Missions, Threats, MOEs/MOPs, and Baseline Capabilites

3) Scenario Descriptions

4) Roving Mine

5) Catskill Concept and Issues

6) A Minimalist Approach to UUV Minehunting

7) Mine Neutralization Using Unmanned Underwater Vehicles (UUVs)

8) Mine IdentificationUsing Unmanned Underwater Vehicles (UUVs)

9) Tactically Flexible Minehunting UUVs

10) Information-Based Functions for Minehunting with
Unmanned Underwater Vehicles (UUVs)

11) Cost and Affordability

12) Sonar Performance Assessment Process: Target Detection and Close-Tethered Target Discrimination

13) Type I: Bird-Dog Deployment Requirements

14) Parallel Lane Search and Neutralize Clearance Probabilities

15) En-masse Search, Multi-Vehicle Control Strategy

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CONCEPT DEVELOPMENTS FOR THE ONR FUTURE MCM SYSTEMS ALTERNATIVES PROJECT

1. General. The ONR Future Mine Countermeasures (FMCM) Systems Alternatives Project was the combined effort of three laboratories: the Applied Research Laboratory, University of Texas (ARL:UT), the Coastal Systems Station (COASTSYSTA), and the Johns Hopkins University Applied Physics Laboratory (JHU/APL). Among the program functions given to JHU/APL were the initial problem definition and development of a set of scenarios within which to analyze later system concepts. All three laboratories developed FMCM system concepts for comparative analysis. One of the concepts that JHU/APL selected to analyze included a Type II system in which small vehicles perform mine search functions independently, but because of their small size require assistance in being transported to the search area and certain support functions, such as battery recharging, while there. The other concept selected and analyzed by JHU/APL was a Type III very small UUV that was delivered like a sonobuoy and used the sonobuoy canister as a communications link with the operators. Other concepts were articulated during the concept down-selection process and those are also documented here.

2. Problem Definition. The problem definition was drafted on 23 February 1999 as an expansion of the Statement of Work and was distributed among the laboratory teams and sponsor. Updates were made on 8 March 1999 and 6 September 2000 and the problem definition was finalized on 12 January 2001. It was agreed that a methodology should be developed early in the project to calculate representative values for detection and classification probabilities and that a single set of performance values would be generated for use by all three laboratories in the analysis of concepts. For those subsystems that did not lend themselves to this type of modeling, Rules of Thumb (ROTs) were generated from empirical data and agreed among the participants. ARL:UT took the lead in generating performance parameters and rules of thumb. This use of agreed performance values provided commonality between vehicle subsystems used in different concepts and focused the analyses on comparison of the system concepts themselves. It is noteworthy that the FMCM project collaborated with the ONR Cooperative Organic Mine Defense (COMID) Project and the OPNAV N87 Winter Study to produce the same performance values for similar applications of minehunting systems. The methodology to produce detection and classification was documented by ARL:UT and COASTSYSTA and appended to the Problem Definition for completeness. Other changes to the Problem Definition included the decision to use only unclassified scenarios and the deletion of a Warfare Analysis Laboratory Exercise. The final Problem Definition is at <PROBLEM DEFINITION>.

3. Scenarios. Four scenarios were generated to assess a variety of conceptual systems in widely disparate operational circumstances. The objective here was to ensure that the performance of a system would not be driven by a single operational application. For

example, mine densities varied from densely populated anti-amphibious minefields to zero, in the case of one Carrier Battlegroup (CVBG) operating area. (As a point of interest, in exploratory reconnaissance the zero mines case is the most stressing because it takes a long time to infer the absence of mines.) The initial set of scenarios was distributed among the team and sponsor on 15 March 1999 and the final was distributed on 20 May 2000. The scenarios are at <SCENARIOS>.

4. Future MCM System Concepts. After the problem and scenarios were defined, the laboratories generated a series of concepts, which they presented to the ONR sponsor. Members of the acquisition and operational communities participated in the discussions on two occasions. Among the concepts presented early, but not selected for detailed analysis, were the application of long endurance solar powered or Slocum vehicles as roving mines <ROVING MINES>, the use of a Fleet amphibious ship as a small vehicle tender <CATSKILL>, and a classified and undocumented influence sweeping concept.

5. Type II Vehicles. MCM concepts that appear feasible and effective when first conceived often lose their perceived viability when their employment is examined in detail. UUVs, in particular, are relatively new as operational systems. The practical aspects of employing systems of any kind to hunt for and destroy dangerous ordnance, using their own judgment, warrant development of operational concepts beyond mere system specifications. For these reasons, a series of issue paper were written to describe how the Type II UUVs would be utilized, including how they would interact with their support systems and how data would be exchanged.

a. Minimalist UUVs. Issue papers for a Type II vehicle centered on the design of a relatively simple and modestly priced search vehicle that could detect, classify, identify, and mark mines autonomously. It was referred to as the Minimalist UUV <MINIMALIST UUV> because of the attempt to minimize the operational requirements placed upon the vehicle itself.

b. Neutralization. It became clear early in the concept development process that the neutralization of the found mines, especially neutralization using UUVs, would be very difficult for a number of practical reasons that were documented in a neutralization issue paper <UUV NEUTRALIZATION>.

c. Identification. It also became clear in discussions that small UUVs had a significant advantage over larger systems: the ability to sense minelike objects at very close range. This advantage made possible the use of classification and identification techniques that had barely been considered. The possibilities were examined in a paper called UUV Identification <UUV IDENTIFICATION>.

d. Transport and Support Functions. Because of the limited range of the Minimalist UUV, a number of means were examined for how to transport the vehicle to the search area, to recharge it, and to provide communications for it back to the operators. Being a two-man portable system, the vehicle could be handled universally and easily and the tactical applications were limited only by the ingenuity of the designers and

operators. The most difficult application was transport to remote areas that had to be searched clandestinely. For this application, a larger transport UUV was envisioned, as were delivery by helicopters and small boats. Some of the more prevalent delivery methods are discussed in a paper called Tactically Flexible UUVs <TACTICALLY FLEXIBLE UUVS>.

e. Information-Based Functions. The last characteristic that seemed worthy of special note was the clear trend toward faster and cheaper processing that would enable future systems to take advantage of information-based functions that are currently too complex or too data-intensive to be practicable. Among the functions that could be greatly improved is underwater navigation, which is currently a weak link in UUV operations. The processing issues are described in <INFO BASED FUNCTIONS>.

The five issue papers that address aspects of the Minimalist UUV evolved with the project, so each paper has been revised in iterative fashion to help integrate the ideas.

6. Type II Vehicles: Sonobuoy UUVs. . One system concept that has been developed and analyzed is that of small UUVs dropped from an aircraft similar to a P3; the UUVs could be of typical sonobuoy size (4.875 inches in diameter and 36 inches long). Initial system concepts focussed entirely on this concept for rapidly seeding a forward area, well in advance of other forces. As the analysis phase progressed, and simulations of the concept were run, two trends developed: the UUVs had insufficient power to perform a mine hunting mission of a duration greater than 3 hours and that for most missions/scenarios, thousands of these UUVs would be required (each P3 can carry approximately 70-100 units; thus a considerable and unreasonable number of P3 sorties was necessary). Later development of the concept considered the option of more robust UUVs (larger than a standard sonobuoy), and based capability more on the load limit of an aircraft than on the number of sonobuoy tubes.

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8 March 1999
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STUDY OF FUTURE MCM SYSTEM ALTERNATIVES

PROBLEM DEFINITION, MISSIONS, THREATS, MOEs/MOPs, AND BASELINE CAPABILITIES

1. Purpose. This paper documents the problem definition, including agreed missions, threats, Measures of Effectiveness (MOEs)/Measures of Performance (MOPs), and treatment of baseline capabilities for Office of Naval Research (ONR) sponsored Study of Future Mine Countermeasures (MCM) System Alternatives. The problem statement referenced in this paper is that cited in the draft Task Assignment [*1*]. Participating research activities are The Applied Research Laboratory University of Texas (ARL:UT), the Coastal Systems Station, Panama City, FL (CSS), and The Johns Hopkins University Applied Physics Laboratory (JHU/APL). ONR Code 321TS will guide the project.

2. Contents. This paper describes the following program issues as agreed at meetings of 12 January 1999 [*2*] and 24-25 February 1999 [*3*]:

- Problem Definition
- Missions
- Threats
- MOEs/MOPs
- Baseline Capabilities

3. Problem Definition.

a. Task Statement. The problem is defined according to the following verbatim excerpt from the Task Assignment document [*1*]:

"2.2) Problem Definition: This task will define the scope of the project and determine what missions, operating guidelines, threats, Measures of Performance (MOPs)/Measures of Effectiveness (MOEs), data requirements, and costing will be required to define future Mine Countermeasures (MCM) systems. For background this task will review previous studies (e.g. ACI MCM Study, MCM Force 21 Study, and MCM in support of Operational Objectives Study [read 'Operational Maneuver' vice 'Operational Objectives']. The aim is to provide sufficient detail and sufficient credibility to the concepts, and to reach consensus among fleet and scientific community so that required technologies can be identified for development into the foreseeable future. This task will address the following issues:

"2.2.1 Types of Mine Countermeasures functions the project will address (mine search, mine neutralization, identification, influence minesweeping, mechanical minesweeping, navigation, brute force technique)

"2.2.2 Range of platform deliver [sic] and support (dedicated surface MCM, dedicated airborne MCM, diver, organic platforms, Unmanned Underwater Vehicles (UUVs), mother ship concept, air delivered munitions, etc.)

"2.2.3 Range of sensors (acoustic, laser, other optical, active electrical, NQR, olfactory, infrared, radar, chemical, tactile, luminescence, wave generation, GRADAR, etc.)

"2.2.4 Range of land and/or water depths (deep, shallow, Very Shallow Water (VSW), Surf Zone, Beach, landward of the beach)

"2.2.5 Range of threat mines to be countered. If the system is intended to operate in a hostile littoral environment, what other threats must be countered.

"2.2.6 MCM missions (CONUS port breakout, clearance of SLOCs and choke points, clearance of CVBG operation areas, amphibious assault, port break-in.)

"2.2.7 Operational Guidelines (dedicated platforms, organic, or platforms of opportunity; day and night operations; hostile or permissive environment; skill levels required for operation and maintenance; if organic, are other missions performed simultaneously)

"2.2.8 MOPs/MOEs (timeliness, thoroughness, and risk to operators. Confirm early in the study how performance will be estimated, e.g., detection probabilities, classification probabilities, actuation probabilities, etc. Determine whether validation requirements are needed.)

"2.2.9 Data requirements for modeling (environmental acoustics, magnetics, optics, etc. What source will be used as authoritative for threat mines and tactics?)

"2.2.10 Costing models (R&D, T&E, engineering, acquisition, storage and handling, maintenance, other life cycle)"

At the aforementioned meetings, there was discussion about emphasis and implementation of the task issues, but no suggestion that the task statement of reference [*1*] be modified.

b. Background Research. Several recent studies have been conducted that bear on the future approach to MCM. Three studies were cited in the Task Assignment [*1*] and others were discussed as important at the kickoff meeting. The ONR study should, as a minimum, articulate its relationship to these studies:

(1) The Accelerated Core Initiatives (ACI) Study, which analyzed the effectiveness of integrating underwater acoustic communications with static and mobile sensor nodes [*4*].

(2) The MCM Force 21 Study, which analyzes the issues surrounding the use of organic MCM systems and how that affects force level requirements for dedicated MCM forces. Phase I of the MCM Force 21 Study was briefed to the Flag Oversight Board on 27 January and to staffs on 28 January 1999. [*5*]

(3) MCM in Support of Operational Maneuver, a recently completed study of requirements to implement amphibious assault in a mine and obstacle environment using Ship to Objective Maneuver (STOM) type tactics [*6*].

(4) The Organic MCM Study conducted in 1997 by CSS and JHU/APL. [*7*]

(5) The Joint Countermine (JCM) Advanced Concept Technology Demonstration (ACTD) evaluations conducted for Demonstration I at Onslow Beach, NC [*8*] and

Demonstration II in Newfoundland. [*9*]

The ONR Study of Future MCM Systems Alternatives will analyze system concepts beyond the current Future Year Defense Plan (FYDP) and concepts already analyzed, but its approach should be consistent with the evolving concept of future MCM operations unless there is good reason to depart. The aim of performing the background research is to:

- Lend credibility to the concepts analyzed (beware of concepts which the operators will not use for stated reasons),
- Enable consensus building between the scientific and operational components of the MCM Community, and
- Identify key needed technologies early in the process so they can be researched in more depth during the study.

c. Issues in Defining the Task. The following are key components of the MCM task:

(1) MCM Functions. MCM functions are organized as shown in Figure 1. The three main categories are defined here:

- Offensive MCM - preventing or deterring the enemy from laying mines
- Defensive Passive MCM - reducing the threat from mines without physically removing them
- Defensive Active MCM - rendering mines incapable of threatening traffic

Offensive MCM is conducted by non-MCM forces and is considered beyond the scope of the current project. However, components of Offensive MCM within the control of the MCM forces would fall within the purview of this study, if future concepts would facilitate them. Examples of relevant components of Offensive MCM might include: the integration of Intelligence/ Surveillance/Reconnaissance (ISR) into MCM planning; the identification of mine storage, handling, and laying assets as targets to friendly strike forces; and advice to the chain of command regarding Rules of Engagement (ROE). All functions of Passive and Active MCM are within the purview of this study. See *Appendix D* of Reference [*6*] for an organization of MCM functional relationships and definitions of terms.

(2) Type of Delivery and Support. The type of delivery and support required for conceptual systems is unconstrained. There is no requirement to deploy conceptual systems from current MCM platforms. It is recognized that platform independence is a positive characteristic of conceptual systems to facilitate their use, not only from MCM vessels, but also from combatants (organic MCM) or mother ships (Catskill Concept). However, no options are excluded at the problem definition stage. For example, if a new type of platform must be built to accommodate a future concept, that option is not specifically excluded. Requirements to modify ships or submarines to accommodate future MCM systems should be minimized.

(3) Range of Sensors. The type sensor that can be used by conceptual systems is unconstrained.

(4) Water Depths. Required water depths range from deep (Over the Horizon (OTH)) to the 30-foot mark. Current MCM vehicles are generally effective to about 30 feet, although the risk to the vehicle tends to increase with decreasing water depth. Concepts do not have to be effective in every water depth within this region. Emphasis should be placed on 40 feet (the deeper limit for Very Shallow Water (VSW) systems) to about 240 feet (the maximum depth at which conventional bottom mines pose a substantial threat to surface traffic). It is noted

that conventional surface and airborne MCM sweeps and hunting systems operate as shallow as 30 feet and as deep as the current threat. VSW for amphibious purposes is defined as 40 feet to the surf zone, which for practical reasons is estimated to begin at 10 feet. Accordingly, it is recognized that there is an overlap in this requirement with the VSW region, and that some overlap (redundancy) is desirable. [*10*] Counters to land mines or mines designed specifically for the surf zone are beyond the scope of this study.

(5) Threat Mines to be Countered. The threat of greatest interest is the threat considered widely available to adversaries in the 2015 time frame for use in water depths of 30 feet and deeper. More discussion on mine types is given in a separate section below.

(6) MCM Missions. Emphasis will be placed on MCM in support of littoral operations, particularly power projection ashore. These operations include choke point clearance, Carrier Battlegroup (CVBG) operating areas, port break-ins, and clearance for amphibious assaults. There is more discussion in a separate section below.

(7) Operational Guidelines. Concept development is not constrained by current operating procedures and tactics; however, concepts that the operators say would not be employed for operational reasons should be avoided. Operational characteristics of individual systems that are favorable to the trade-off evaluation include:

- Effectiveness factors
  - Thoroughness (fraction of the mine population the system can counter)
  - Total mission time
    - Single system clearance time
    - Endurance
    - Ability to operate multiple systems simultaneously (force multiplication factor)
  - Reduction of risk, especially to manned craft
  - Compatibility with other MCM systems
  - Operations that are non-obtrusive to other Naval missions
- Supportability factors
  - Platform independence
  - Reliability and maintainability
  - Minimum skill requirements for operations and maintenance
  - Ability to store systems for indefinite periods
  - Availability when needed
- Transportability
  - Rapid deployability worldwide
  - Deployability within theater
  - Ability to cross-deck
- The operating environment
  - Operate in hostile environments
  - Performance of day and night operations
  - Clandestine or low-observable operations
- The physical environment
  - Operations in high sea states
  - Effectiveness in cluttered hunting environments
  - Effectiveness in difficult acoustic environments (e.g., thermoclines, salinity gradients)
  - Effectiveness in other difficult environments (e.g., high magnetic clutter)
  - Coping with high currents
  - Range of water depths countered by a single system

Other characteristics apply to packages of systems:

- Ability to reconnoiter mine defenses
- At least one effective counter against all threats in all environments
- Ability to report mines data and clearance data for use by following forces
- Ability to navigate within a common reference system (which can be tied to absolute)
- Resistance to navigation spoofing and jamming
- Planning and evaluation tools to include optimization techniques
- Systems should operate simultaneously without mutual interference

(8) MOEs/MOPs. The primary MOEs for assessing the effectiveness of MCM systems are timeliness (total mission time), thoroughness (residual threat to traffic), and risk to the MCM platforms and systems, especially as the MOEs affect amphibious operations. See the section below on MOEs/MOPs. MOE calculations shall be made using MCM tactical theory founded in the writings of Dr. R. K. Reber and as implemented in the national tactical publications (NDP 3-15 series) and NATO Tactical Publications (ATP-1(B), ATP-6(B), and ATP-24(B)(NAVY)). PEO-MIW NOTE 3370 contains the mathematics.

(9) Data Sources for Effectiveness Calculations. For the development of concepts and their assessment in this project, the inherent (as opposed to operational) capabilities will be judged based on data from laboratory experiments and controlled tests. See the section on Baseline Capabilities for a description of the difference between inherent and operational capabilities. The following sources are authoritative:

- NAVOCEANO environmental data
- ONI sea mine threat and shore threat data
- COMINEWARCOM tactical guidance and data (Primary Review Authority for MCM tactical publications)

(10) Cost Models. Cost trade-offs will be based on total life cycle costs of the systems being developed. However, affordability issues that become apparent from platform independence (no MCM vessel needed) or potential modifications to Navy infrastructure should be noted.

4. MCM Missions. MCM mission considerations comprise standard scenarios, mission priorities, and miscellaneous other issues.

a. Scenarios. The following sources were reviewed to identify standard MCM scenarios:

- Scenarios used in the MCM Force 21 Study (highest priority)
- JHU/APL standard scenarios
- Scenarios used in Joint Countermine (JCM) ACTD Demonstrations
- Scenarios used in the study "MCM in Support of Operational Maneuver" [6]
- The Littoral Warfare Handbook

This study will use generic, unclassified scenarios that are consistent with scenarios practices applied in recent Mine Warfare studies.

(1) Notional Scenarios. The notional scenario will use the assault lay down depicted in Figure C-2 of MCM in Support of Operational Maneuver. [6] This is the same lay

down that was developed and approved for Demonstration I of the JCM ACTD and was used subsequently in the CONTECH 00 Wargame.

(2) DPG Based Scenarios. Scenarios used for the ongoing MCM Force 21 Study will be used as the DPG based scenarios for this study to the extent that they are needed. Emphasis will be placed on the amphibious operations and other operations that enable them. It is noted that the N85 sponsorship of future MCM systems has articulated a strong need for systems which operate in the amphibious environment. Virtually all prior MCM system development was conducted to satisfy Cold War requirements. The expeditionary warfare sponsor has also stated the need for systems that can reconnoiter or clear large operating areas quickly to enable CVBG or Naval Fire Support operations.

b. Mission Priorities. During the Cold War, the NATO first scenario required urgent supply of European ports to replenish the land war. Accordingly, Continental United States (CONUS) ports received the highest priority and other missions were emphasized roughly in the order in which they were expected to occur after the commencement of hostilities:

(1) CONUS Port Breakouts
(2) Clearance of SLOCs and Chokepoints
(3) CVBG Operating Areas
(4) Amphibious Assault

There was a strong assumption during the Cold War that amphibious operations, if conducted at all, would be executed well after the commencement of hostilities and that US amphibious forces would have support from allied MCM vessels. Accordingly, MCM force level requirements assessed during the Cold War calculated requirements for CONUS Port Breakouts and key chokepoint clearances, and the CNO selected the force level option that assumed those forces would suffice for all subsequent operations. In the post-Cold War era, emphasis shifted to operations in the overseas littorals with Power Projection being a primary aim. [*11*][*12*] Operation DESERT SABER (the planned amphibious assault of Kuwait) demonstrated the allied support we could likely expect. Even with a strong combined force solidly unified against Iraq, only the UK provided MCM support to DESERT SABER. All other allied MCM stayed outside the Persian Gulf until the shooting had stopped. Accordingly, there are two salient differences between current mission priorities and those of the Cold War:

- Priorities are largely reversed, with amphibious assault being a high priority and other MCM operations (Chokepoints, CVBG Operating Areas, Port Break In) mainly supporting that mission,
- US forces should not rely on the availability of allied MCM support.

c. Other Mission Related Issues. Amphibious operations are the most difficult operations to support with MCM for a variety of reasons:

- MCM systems are threatened not only by the mines they attempt to clear, but also by shore fire and other coastal defenses, requiring those systems that operate within the horizon to be clandestine, unmanned, or otherwise imperious to non-mine threats. [*6*]
- Time available is very compressed, especially in the overt phase.
- Defensive fields, such as those protecting a potential landing beach, often contain counter-countermeasure (CCM) devices as well as mines. Examples of CCM include wire sweep obstructors, decoys, anti-sweep discrimination logic, control wires to turn mines on and off, and anti-detection techniques.

On the positive side, systems that are designed to operate in the amphibious environment should satisfy clearance requirements in other missions as well. N85 notes that virtually all MCM systems built to date have been designed for use in shallow and deep water where shore threats are either non-existent or suppressed. Thus, MCM clearance operations other than amphibious are basically administrative in nature. Exceptions include chokepoints like the Strait of Hormuz or Bab el Mandeb, which are under potential threat from shore fire, so requirements to clear these areas are similar to those for clearing amphibious areas.

Also on the positive side, the USN currently has the best deep water clearance capability it has ever had with the MCM 1 and MHC 51 Class ships (the earlier MSOs did not have a complete minehunting system). The availability of the AN/SQQ-32 Variable Depth Sonar (VDS), the AN/SLQ-48 Mine Neutralization System (MNS) (powered down the cable to make sortie time virtually unlimited), and the AN/SSN-2 Precise Integrated Navigation System (PINS) make the USN MCM vessels probably the best ship class in the world for worldwide clearance of deep water mines.

Influence sweeping by current MCM platforms is deficient: the MHC 51 Class has none; the MCM 1 Class pulses only 5000 amps (the MSOs pulsed 7500 amps) and there are serious maintainability problems; deployable MH-53E helicopters complement the MCM 1 Class sweeping, but are not expected to be operational in the timeframe of the study. (The MH-53E will be replaced by the CH-60 helicopter, which is capable of only nominal influence sweeping capability.)

5. Threats. MCM systems of the future should be designed to cope with mine threats and shore threats. If MCM systems become cheap and plentiful, the risk to MCM from mine threats would be largely obviated - one mine, one MCM system might not be a bad trade-off. However, the number of MCM systems available in theater can become a critical issue independent of its cost. If the MCM systems are few and hard to replace, they become strategic assets, as their attrition leaves friendly forces with a mobility deficiency that cannot be overcome by other capabilities. Accordingly from the threat/attrition standpoint, the ideal MCM system of the future would be cheap and plentiful. I.e., a wide distribution of inexpensive systems, even if each has a modest capability, would provide more strategic and operational utility than a few highly capable systems, keeping in mind that the suite of MCM systems must cover the entire range of mine threats.

a. Mine Threats. The conceptual systems for this study are required to operate against sea mines. Land mines are beyond the scope of this study.

(1) Water Depths. Conceptual systems must operate from deep water to 30 feet of water depth. Any shallower capability would be useful, but effort should not be expended to make the systems go shallower.

(2) Mine Types. Figure 2 lists sample mine types, some of which are exotic and not operational. This project will concentrate on clearing bottom and moored mines that stay in place for a reasonable period of time. It is required that all existing mines of a military type that are found routinely in water depths of 30 feet or more must be cleared. The requirement includes mines constructed of ferrous materials, non-ferrous metals, fiberglass, and plastics. The clearance of floating and drifting mines is within the scope of the study, although less emphasis should be placed on drifting mines than bottom and moored mines that stay in place. It is not required that mobile or migratory mines be cleared when the mines themselves are moving. It is highly

desirable to clear mines that are buried, including self-burying mines, but the inability to clear buried mines does not exclude a concept from further consideration.

(3) Mine Sensors. Mines of all sensor types, including those that may be presently unknown, must be cleared. See Figure 3 for sample mine sensor types. The study should assume that mines to be cleared are set for good localization on target ships. The mine's ability to localize the MCM system must be reviewed on a case by case basis.

b. Other Threats. MCM systems developed under this project must be capable of operating in the presence of both mine and non-mine threats. Shore threats that must be dealt with are assumed to be those described in the SECRET Addendum to "MCM in Support of Operational Maneuver." [*13*] During the study the Office of Naval Intelligence (ONI) should be consulted to update potential shore threats.

6. Measures of Effectiveness (MOEs)/Measures of Performance (MOPs).

a. Directing MOEs. Planning and evaluating MCM operations is based on three broad MOEs: timeliness, thoroughness, and risk to the MCM platform. The emphasis placed on each MOE depends on the MCM objectives of the operation. For amphibious operations, the highest emphasis is placed on timeliness, next is thoroughness, and last is risk to MCM vehicles. For Clean Up operations, such as those that followed DESERT STORM,/DESERT SABER, the highest emphasis was placed on MCMV risk, next was thoroughness, and last was timeliness. The Officer in Tactical Command (OTC) specifies the acceptable risk through promulgation of MCM Risk Directives, where Risk Directive Alfa accepts virtually no risk and Risk Directive Charlie puts strong emphasis on timeliness at the expense of risk. Experience has shown that Commanders are very reluctant to operate under any directive except Risk Directive Alfa during peacetime operations, even when time is of the essence. For example, during DESERT SABER, MCM forces went to a modified Risk Directive Bravo for a very short time and then reverted by OTC direction to Risk Directive Alfa, even though amphibious operations were being prepared.

b. Defining MOEs. The methodology for calculating these MOEs, which was derived and documented by Dr. R. K. Reber [*14*][*15*], is contained in the Navy's NDP 3-15 series and Allied Publications, ATP-1(B), ATP-6(B), and ATP-24(B)(NAVY). ATP-6(B) contains most of the methodology. The mathematics is also contained in standard approved Tactical Decision Aids (TDAs). The PEO-MIW Metrics Instruction [*16*] contains procedures for analyzing exercise data and calculating MOEs.

(1) Time to Clear. Time to clear can be calculated from various MOPs, which are routinely measured in MCM exercises. For minehunting, the time to clear using a "blow as you go" technique can be calculated from the equations given in a COMINEWARCOM report on Minehunting Effectiveness Modeling [*17*], which is consistent with the derivations of Dr. Reber and the PEO-MUW Metrics Instruction. USAGE factors are available from numerous Exercise Analysis reports, such as references [*18*] through [*50*]. Other potential sources of USAGE data include after-action reports for MCM operations during EARNEST WILL (the Tanker War) and the DESERT STORM clean-up operations. USAGE data from MCM exercises and real world clearance operations is the most representative of future MCM operations for reasons discussed in the Baseline Section below. However, usage data from TECHEVALs, OPEVALs, and other developmental testing can be used to estimate the inherent capabilities. When necessary, allowances should be made for the difference between inherent and operational capabilities. Calculated times must include the time required to perform all needed functions. For example, if clearance is applied by hunting techniques, the calculations must include the time needed to

detect, classify, localize, identify, and neutralize mines and minelike contacts (MILCs). If neutralized mines are to be destroyed or removed, time must also be calculated for the verification and clean up steps. Because of the various steps in the minehunting process, time required to clear or reconnoiter by search techniques is not proportional to the area search rates. Accordingly, comparisons of search rates tend to be misleading. For amphibious assaults, clearance of future assault areas is expected to occur in distinct phases: covert, overt pre-assault, assault, and post-assault. A different command philosophy is applied in each phase. Minehunting in other hostile areas may also require distinct covert and overt phases. Calculation of time to perform minesweeping is straightforward. When mechanical sweeping is applied, time must be allowed for the periodic re-arming of the explosive cutters. Time spent due to gear loss should be considered in both mechanical and influence sweeping, although it is most significant in the mechanical operations. It is noted that some of the authorized TDAs calculate time, but these are tow times only (no USAGE applied for required platform time) and are generally not calibrated with operational data.

(2) Thoroughness. MCM operations are planned and evaluated using percent clearance as the MOE. Procedures for calculating percent clearance are automated and available in tactically approved form in TDAs called Uniform Coverage Planning (UCPLAN) and Non-Uniform Coverage Evaluation (NUCEVAL). The authorized TDAs are distributed from COASTSYSTA with the approval of COMINEWARCOM, which is the Primary Review Authority (PRA) and Model Manager for MCM tactics. It is noted that, while the OTC may prefer to know the threat to his ships as opposed to percent clearance, threat is highly dependent on the number of mines in the transit area and that number is unknown to the MCM Planner. Hence, planners use percent clearance, which is independent of the number of mines. Percent clearance provides a consistent measure of how much of the job has been completed. Percent clearance is used in exploratory and reconnaissance operations as one of the entering arguments to those calculations. Furthermore, when an ongoing operation is evaluated with NUCEVAL or the MCM Commander's Tactical Decision Aid (MCM-CTDA), the percent clearance and number of mines cleared can be used to estimate the number of mines remaining and, hence, the expected Simple Initial Threat (SIT) to traffic. For this study, the standard MCM TDAs may be used for calculating percent clearance. It is noted that the UCPLAN procedure uses discreet numbers of tracks at specified track separations, and small changes in the desired percent clearance can make significant differences in the plan and the time to clear. Accordingly, it may be preferable to use the equations provided in reference [*17*], as these treat track separation as an independent variable and present solutions as relatively smooth values of desired percent clearance, as opposed to the discontinuous results that come from UCPLAN.

(3) Risk to the MCMV. Risk is the probability of an MCM vehicle or system receiving mission abort damage per mine cleared. Like percent clearance, it is independent of the number of mines present (always unknown) and can therefore be calculated for planning purposes. It differs from threat to traffic, which is calculated on a "per transit" basis and requires the planner/evaluator to know the number of mines present. Risk was originally derived by Dr. Reber and its calculation entered as a manual procedure into the old NWPs. Its re-derivation from first principals is found in reference [*51*]. The Cognitive Minesweep Model (COGNIT) program, which is part of the MCM TDA package, is the only authorized program that performs the calculation.

c. Calculating MOPs. The modeling of effectiveness for MCM planning and evaluation is a two-part process. The first step is to calculate the tactical parameters (MOPs) that describe the effectiveness of a single system against a single mine type on a single pass. The second step is to enter the MOPs into a statistical model to calculate the probable outcome of a planned

operation.

(1) Influence Sweeping MOPs. For influence sweeping, the tactical parameters are calculated from the physical interaction between the mine and the sweep or the mine and the ship as the sweep or ship passes the mine at a given Closest Point of Approach (CPA). The accepted model for calculating influence sweep parameters is the Total Mine Simulation System (TMSS), which is an international program shared by the UK, US, Canada, Australia, and New Zealand. (This is one of the few models that applies to mining as well as MCM.) The TMSS will be used in this project as the standard for calculating tactical parameters for influence sweeping.

(2) Mechanical Sweeping MOPs. Tactical parameters for mechanical sweeping are based mainly on the geometry of the sweep, with the probability being taken from field data. Example calculations are found in the NDP 3-15 series.

(3) Minehunting MOPs. Probability of mine detection and probability of classification depend on many variables: mine type, geometry of the lay, geometry of the encounter, ambient and operational environments, sonar characteristics, and skill of the operator. There are no authoritative or accepted algorithms for calculating mine detection probability or mine classification probability from fundamental inputs. In the tactical publications, the characteristic search probability (probability of detection times probability of classification) is tabulated as a function of sonar type, bottom type, and mine type (bottom or moored). The values in the table come mainly from the results of exercises and tests since the 1960s. The difficulty in calculating realistic probabilities results mainly from three factors: (1) the many variables that affect the outcome coupled with the inability to control the variables in tests, (2) sparse data sets from fleet exercises, which are most representative of real mine clearance operations, and (3) the widely disparate skill levels of the sonar operators. It is noted that signal excess is a necessary condition for mine detection, but because the entire bottom is insonified in the search area and virtually all objects on the bottom have signal excess, signal excess alone is not a sufficient condition for detection. A mine or minelike object is detected when the operator marks the contact for classification and many mines go unclassified even though they show as blips on the scope. It was agreed at the meeting of 12 January 1999 [2] that a technical process would be agreed early in the project to estimate detection and classification probabilities. For this project detection probabilities will be based on the following process:

(a) Use the Shallow Water Acoustic Toolset (SWAT), or other acoustic model such as MINERAY 3, to calculate detection ranges for the acoustic sensor in a variety of environmental conditions.

(b) Use the detection ranges, signal excesses, and COASTSYSTA "black box" to derive detection probability at various ranges.

(c) Construct a P(y) curve by the above step and extract characteristic search width (A) and characteristic search probability (B) from it using the methodology in the Metrics Instruction [16].

(d) Enter the A's and B's into statistical models to get probability outcomes.

In a subsequent meeting [52] it was agreed that the process for calculating both detection probability and classification probability would be documented in more detail for the record. Tabs A and B describe the processes used at ARL:UT and COASTSYSTA to calculate detection

and classification probabilities. It is noted that no procedures exist for the calculation of false alarm probabilities, except for those false alarms caused by noise, which is not the general source of false alarms for minehunting.

d. Modeling MOEs. Researchers can use the following types of models for the statistical analysis of conceptual systems: (1) Tactically approved TDAs, (2) Monte Carlo simulations, (3) virtual reality simulations, (4) other analytic models that are consistent with Reber's MCM tactical theory. Before performing extensive analysis with any statistical model, the researchers should consult with the other participants to discuss the ramifications the use of that model would have on the results.

(1) Tactically Approved TDAs. COASTSYSTA is custodian of the MCM Tactical Library and is authorized (with COMINEWARCOM approval) to distribute copies as required. The package contains statistical models such as UCPLN, NUCEVL, COGNIT, and MCM-CTDA, which provides bookkeeping for the NUCEVL algorithm to calculate clearance for various areas.

(2) Monte Carlo routines including Mined Channel Transit (MINCHANT), which resides in the standard MCM tactical package, and the Battle Force Engagement Model (BFEM) are acceptable statistical models.

(3) Virtual reality models, such as the Joint Countermine Operational Simulation and COASTSYSTA's Naval Mine Warfare Simulation (NMWS), are acceptable. (NMWS can be run iteratively in Monte Carlo fashion.)

(4) Analytic models, in addition to those in the approved tactical package, are acceptable so long as they are consistent with Reber's MCM theory. To perform parametric excursions, the Minehunting Effectiveness Model [17] can be a useful tool. Using the track separation (one run per track) as an independent variable, it would use an iterative technique to calculate search level, percent clearance, traffic casualties (for assumed number of mines laid), risk to MCMV, probability of mission success, effective time on task, and total mission time. Any one MOE can be specified and the others calculated. This type of model was programmed and available during the timeframe of the study. [53]

7. Baseline Capabilities. The baseline for this study will be the capability of current MCM systems, namely the minehunting sonars AN/SQQ-32 , AN/AQS-14, and AN/AQS-20. For influence sweeping the representative baseline should be the MK-105 magnetic sled with MK-104 acoustic device attached. (The combination of MK-105 and MK-104 is called the MK-106.) For mechanical sweeping, the A/N-37U is selected as the baseline because it is the most recently developed sweep and because surface MCM vessels are reluctant to sweep, especially in shallow water. Most of the operational data from Fleet exercises applies to systems that have been superseded. Accordingly, it will be necessary to use data collected in the field by the laboratories, which is more representative of inherent, vice operational, capability.

a. Inherent Capability. Inherent capability is that measured under controlled, near-ideal conditions. It is important to scientist, as it helps to define the physical relationships between systems and threat, and it brackets the upper limit of performance to be expected from a given system. Field data from controlled tests, which defines the inherent capabilities, is the purview of laboratories that evaluate developmental MCM systems. COASTSYSTA is the main repository for inherent MCM capability data, but ARL:UT and other laboratories have data too. Controlled tests tend to collect data under near-optimum conditions:

- Operators are well trained
- Operators are motivated to perform well
- Equipment is tweaked up
- The search area is relatively small, so the operators are always alert to the presence of mines when in the test area
- If the weather is not good, the ship does not leave the pier
- Operating periods are relatively short

b. Operational Capability. Operational capability is the effectiveness measured under operational conditions when the equipment has been maintained and operated by fleet operators. It should be measured under a harsher set of conditions:

- Operators may or may not be properly trained
- Operators may or may not be motivated
- Equipment is not necessarily tweaked up
- If equipment breaks, the crew may or may not be prepared to repair it
- Search and clearance are applied over large areas, only part of which is mined
- Operations continue for long periods even if weather conditions turn bad
- Operators are subject to sea sickness and fatigue more so than in controlled tests

Fleet exercises are considered representative of operational conditions. Clearance data taken from fleet exercises is used to determine tactical parameters for planning real world operations.

c. Inherent versus Operational Data. For this study, analyses should be performed using inherent capabilities to compare their relative performances. However, when projected capabilities are presented to fleet operators, caveats must be made to distinguish between the inherent and the operational capabilities. (Systems that operate without a man in the loop will be less susceptible to operational degradation than those that require operators.)

d. Baseline Source. For this study, projected capabilities will be compared with the corresponding baseline systems as itemized above by calculating the performance of both the baseline system and the operational system under the same circumstances and using the same methodology.

e. Other Systems. In the timeframe of the study (~2015), there will be some current systems that are still available plus systems that are now in development. If necessary to estimate the performance of developmental systems, they should be assessed in the same manner as the conceptual systems being proposed by this study, if the system parameters are known. If only the specified performance is available, the validity of comparisons would be questionable. A recent listing of current and budgeted MCM systems is given in Appendix D of reference [6].

Figure 2

SAMPLE MINE TYPES

Mines Types Required to be Cleared within the Scope of This Study

- Moored stationary mines (explode in place)
- Moored rising and homing mines (in their stationary state)
- Bottom Influence Mines, including:
  - Submarine Launched Mobile Mines (SLMM)
  - Migratory mines in their resting
  - Wide Area Munitions in their resting state
  - Other mobile mines in their resting state
- Floating and drifting mines *
- Buried mines*

* Desirable, but not mandatory for further consideration.

state

Mine Types Not Required to be Cleared within the Scope of This Study

- Roving mines
- Baggy mines (binary liquids with a DST-like TDD)
- Thermocline mines
- Obstructors, decoys, other CCM devices

Figure 3

MINE SENSOR TYPES

Mine Sensor Types Required to Be Cleared Within the Scope of This Study

- Magnetic
- Acoustic - both passive and active
- Seismic
- Pressure
- Electric Field (UEP)
- Total field magnetic
- Magnetic gradiometer (triangulating)
- Contact horns
- Antennae
- Distributed sensors

Mine Sensor Types Not Required to Be Cleared Within the Scope of This Study

- Gravity sensors
- Cosmic Ray
- Total field pressure
- Acoustic gradient
- Optical

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Tabs: A *Sonar Performance Assessment Process: Target Detection and Close-Tethered Target Discrimination*, ARL:UT paper, undated

B *Classification Sonar Modeling for COMID*, NSWC/CSS paper by Robert Manning, undated

TAB B

Classification Sonar Modeling for COMID

(Robert Manning NSWC/CSS)

Background:

The probability of detection (P_d) and probability classification (P_c) values were predicted using PCSWAT 6.0. There is a user manual that explains the operation of this model in more detail. The most recent version of PCSWAT has included a function that accounts for the pixel density in the prediction of the P_c. This function requires the operator to input the number and spatial orientation of the highlight and shadow pixels necessary to classify the target and then applies a smooth transition from 1 pixel to the number specified. This model has not been verified for the effects of pixel density versus P_c. However, it is well known that the larger the number of independent pixels that can be used to resolve the target, the greater the amount of target shape information that can be gained. This results in a higher confidence of correctly classifying the targets and a greater ability to accurately discriminate between targets and clutter. Even though the model has not been verified, it does allow us to make reasonable estimates of imaging sonar performance.

Methodology:

<u>Calculation of Probability of Detection:</u>

PCSWAT 6.0 is an energy sonar prediction model that calculates the signal-to-reverberation ratios (SRR) as a function of range for a number of user specified sonar operational parameters. These SRR values are then used to predict the corresponding P_d and P_{fa} values over the same range values. A comprehensive set of system specific sonar operating parameters were provided in the COMID Modeling Inputs document. The relevant P_d and P_{fa} related sonar parameters that were selected for this modeling effort are as follows:

Center Frequency
Transmitter Pulselength
Transmitter Source Level
Transmitter Bandwidth
Transmitter Horizontal Beamwidth
Transmitter Horizontal Sidelobe Level
Transmitter Vertical Beamwidth
Transmitter Vertical Sidelobe Level
Transmitter Depression/Elevation (D/E) Angle
Receiver Horizontal Beamwidth
Receiver Horizontal Sidelobe Level
Receiver Vertical Beamwidth
Receiver Vertical Sidelobe Level

Receiver Depression/Elevation (D/E) Angle
Maximum Operating Range
Typical Operating Altitude

A nominal processing gain was used in order to more accurately reflect the advanced internal processing capabilities of the sonars. The individual nominal processing gains were calculated as 5 Log (BT) where the transmit bandwidths and transmit pulselengths were used as the B and T values respectively. The nominal processing gains were used to increase the target strength values. Initial target strength values of -20 and -30 dB were used. The detection threshold was set at a standard of 12 dB.

<u>Calculation of Probability of Classification:</u>

There is no generally accepted quantitative requirement for what is necessary to achieve classification. Target classification involves a number of variables. Those include, SNR of the target highlights and the shadow contrast of the target, uniqueness of the target shape, target size relative to sonar resolution in both along track and in range, the classifier (human or machine). For bottom targets the P_c changes based upon bottom type (sand, gravel or rocks) and the bathymetry. For both man and machine (neural nets) it depends upon the training received and how comprehensively the training was against various environments and targets expected to be encountered. In the SW/VSW environment the target amplitude also varies. In the SW/VSW environment the temporal and spatial coherence is an unknown variable. Sonar theory has not advanced to the stage that all these parameters can be quantified in a model and make accurate predictions of Pc and Pfa.

PCSWAT 6.0 calculates P_c via a generalization of the Swerling Type II single look pulse detection probability function, which is given by:

$$P_d = \Gamma(s_H, y/x)/\Gamma(s_H)$$

$$x = 1+10^{SIR/10}$$

$$y = 10^{S_{fa}/10}$$

SIR = signal-to-interference ratio, dB
S_{fa} = detection threshold, dB
s_H = order parameter for the incomplete gamma function, where

$$\Gamma(s,x) = \int_x^{\infty} t^{s-1} e^{-t}\, dt$$

is the incomplete gamma function. A Gaussian distribution corresponds to s_H = .5; an exponential distribution to s_H = 1; and, a Rayleigh corresponds to s_H = 2.

The equations given above are reduced to the following for a high-resolution system with signal and clutter values distributed according to a Rayleigh distribution ($s_H = 1$):

$Pc = 1-[1-Pfa^{(1/\eta)}]^{\xi} \qquad \xi \geq 1$

Pfa = the false alarm per look

ξ = image resolution which equals At/A (At = area of target, A = pixel area)

η = average signal to clutter ratio in the image

The resolution dependence is given by a 2D Gaussian distribution of the resolution of the sonar in range and cross range. The probability of classification due to highlights is given by

$$P_H = \Gamma(s_H, y/x)\tanh(L/N_{HL}L_{pix})\tanh(W/N_{HW}W_{pix})/\Gamma(s_H)$$

$$x = 1+10^{SIR/10}$$

$$y = 10^{S_{fa}/10}$$

where L is the length of the target. W is the width of the target. L_{pix} is the length of a pixel. W_{pix} is the width of a pixel. N_{HL} and N_{HW} are the number of pixels along the length and width of the target necessary for classification due to highlights.

The probability of classification due to shadows is given by.

$$P_L = (\Gamma(s_L, 2/x) - b)/(\Gamma(s_L) - b)\tanh(L_S/N_{LS}L_{pix})\tanh(W_S/(N_{WS}W_{pix})$$

$$x = 10^{CONTRAST/10}$$

$$b = \Gamma(s_L, 2)$$

where CONTRAST is the shadow contrast in decibels. L_S is the length of the shadow. W_S is the width of the shadow. L_{pix} and W_{pix} are the length and width of a pixel. N_{LS} and N_{WS} are the number of pixels along the length and width of the shadow necessary to classify the target by its shadow. The number '2' in the above expressions represents the shadow contrast threshold. Experience has shown that a contrast of 3 dB is easily discernible for a large shadow. Therefore, the contrast threshold was set to 2.

The tanh functions in the above equations approximate a 2-dimensional Gaussian probability function and account for the resolution dependence on performance. The tanh function was chosen because its general shape matches the observed classification performance at the extremes. In the limit of a poor resolution system, the probability of classification is proportional to the ratio of the area of the target (shadow) and the pixel

area, as expected. For a high-resolution system, the probability function for resolution approaches 1, as expected.

As N_{HL} and N_{HW} increase, agreement between predicted values and measured values of Pc improves. In fact, experience has also shown that agreement is strong when 80 percent or more of the pixels are illuminated.

The probability of classification by highlights and shadows are combined to obtain the following expression for the probability of classification.

$$P_C = P_H + P_L - P_H P_L$$

The method used in SWAT 6.0 was one of four methods previously developed to predict Pd and Pc. This particular method gave the most realistic results. Plus, the parameters of the Gamma function can be adjusted to give the best fit between theory and experiment. Assumptions inherent in the expressions include 1) The number of pixels available is greater than 10 and 2) The single pixel probability is given by the order of the Gamma function.

The sonars of interest in this modeling effort had equal range and cross-range resolutions. Based upon the specified target type and the corresponding ray geometry produced by the specified nominal operating altitudes an appropriate number of highlight and shadow pixels were determined selected. For the systems with 3-inch resolution, 12 highlight pixels were used configured as 6 pixels in the along the track direction and 2 pixels in the across track direction of the sonar. For this case, a total of 36 shadow pixels were used configured as 6 pixels in the along track direction and 6 pixels in the across track direction of the sonar. . For the systems with 6.25-inch resolution, 6 highlight pixels were used configured as 6 pixels in the along the track direction and 1 pixel in the across track direction of the sonar. For this case, a total of 9 shadow pixels were used configured as 3 pixels in the along track direction and 3 pixels in the across track direction of the sonar. These number of highlight and shadow pixels represent a conservative estimate of the number of actual target pixels that would be characteristic of the sonars for an end-on (zero aspect) look at the specified target. A broadside (quarter aspect) look would produce a large increase in the displayed target pixels.

Scenario Descriptions

Modeling was completed for three distinctly different environments. These environments were titled Shallow Water SLOC (SSLOC), CVBG Operating Area (OA), and Deep Water SLOC (DSLOC). The associated environmental parameters (i.e., bottom types, water depths, sound velocity profiles, salinity, etc.) required for modeling were provided in either the COMID Scenario Descriptions document or directly from Rick Bailey (ARL/UT). Performance modeling was completed for a single specified target type.

Calculation of A and B values

The A and B values were calculated using WAB3 . WAB2 is a computer program written by Richard Nelson (NSWC/CSS) that automates the Navy authorized method for calculating A and B values. WAB3 is a modified version that can read PCSWAT 6.0 output files. The P_d and P_c values calculated by PCSWAT 6.0 were used to calculate A and B values for both P_d and P_dP_c. In those cases where a pair of sonars are normally operated simultaneously, such as is in the case of side-scan and gap-filler sonars, the P_d and P_c values for the two sonars were combined, based upon the information provided in the COMID Modeling Inputs document, to form the joint P_d and P_c prior to the calculation of the A and B values.

Results:

The results are shown in the Table below. The systems are defined by a sensor pseudonym in order keep this document unclassified. It should be noted that the results shown do not reflect any degree of optimization in terms of how these sensors would actually be deployed within these various environments and therefore they do not necessarily reflect the best performance that could be achieved for these various sensors. It should also be pointed out the A values given in meters maybe greater than the actual maximum ranges (i.e., as dictated by the pulse repetition interval) of the sonars and should therefore be adjusted to represent fundamental system limitations that are not necessarily performance driven.

			A_U_USL				S_A_VSL				A_SA_VSL & A_SA_VGF			
			Pd(y)		PdPc(y)		Pd(y)		PdPc(y)		Pd(y)		PdPc(y)	
SC	TS	BT	A(m)	B	A(m)	B	A(m)	B	A(m)	B	A(m)	B	A(m)	B
SSLOC	-20	4	151	.8377	152	.8149	173	.6999	171	.6145	232	.9054	234	.8854
SSLOC	-20	9	151	.8443	151	.8222	172	.7186	169	.6345	232	.9110	233	.8946
SSLOC	-30	4	154	.7481	155	.7129	166	.3375	151	.2451	244	.7480	247	.7154
SSLOC	-30	9	155	.7291	156	.6927	160	.3752	145	.2799	243	.7657	246	.7349
OA	-20	4	151	.8375	152	.8141	169	.6920	166	.6038	237	.7373	240	.6993
OA	-20	9	151	.8441	151	.8214	168	.7113	164	.6261	228	.9092	230	.8891
OA	-30	4	155	.7282	156	.6908	159	.3248	141	.2330	237	.7373	240	.6990
OA	-30	9	154	.7474	155	.7111	154	.3637	136	.2696	236	.7592	238	.7222
DSLOC	-20	7	158	.6709	160	.6366	203	.3374	207	.2811	253	.6991	254	.6850
DSLOC	-20	14	159	.6448	161	.6100	208	.3020	212	.2508	253	.6746	258	.6421
DSLOC	-30	7	174	.3585	176	.3360	212	.0052	224	.0030	279	.4346	280	.4216
DSLOC	-30	14	177	.3191	178	.3010	219	.0040	227	.0025	282	.4104	283	.4002

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STUDY OF FUTURE MCM SYSTEM ALTERNATIVES

SCENARIO DESCRIPTIONS

1. Introduction.

a. Background and Purpose. At the project review meeting of 24-25 February 1999 [1], the problem definition, missions, threats, Measures of Effectiveness (MOEs)/Measures of Performance (MOPs), and baseline capabilities were discussed in detail and the approach to each was agreed. Descriptions of these issues are recorded in the problem description document, revision a, which was distributed to team members on 9 March 1999. [2] As part of the mission definition, it was agreed that the notional system concept development phase should use generic (unclassified) scenarios and that final system comparisons should use a standard Defense Planning Guidance (DPG) scenario. This paper describes the unclassified scenarios for the notional phase of the project.

b. Scope of Scenarios and Sources. Scenario descriptions to follow include threat geometries, clearance geometries, bottom types, depths, sound velocity profiles, water currents, and water clarity. Detailed environmental characterization was provided by ARL:UT. [3] A strategic Sea Line of Communication (SLOC), a strategic debarkation port, and a CVBG Operating Area were developed using unclassified scenario information from the SC-21 Cost and Operational Effectiveness Analysis (COEA) briefing [4] and Long-term Mine Reconnaissance System (LMRS) COEA [5] documents. An anti-amphibious assault minefield was developed based on Figure C-2 of the report on MCM in Support of Operational Maneuver [6] and the mine and obstacle lay-down from the Joint Countermine Advanced Concept Technology Demonstration (JCM ACTD) Demonstration I. [7]

c. Scenario Relationship. For convenience of dealing with the components of the full scenario, notional clearance areas are arranged from left to right in the order in which each operation would be performed, specifically:

(1) Sea Line of Communication (SLOC) on the left
(2) Debarkation port in the upper center
(3) Carrier Battlegroup (CVBG) Operating Area in the lower center
(4) Amphibious Assault area and other near shore components of the Amphibious Objective Area (AOA), such as the Sea Echelon Area (SEA), on the right.

See Figure 1 for the relationship among the scenario areas.

2. Threat Mines. To minimize the development and tabulation of new threat definitions, mine threats have been defined consistent with their use in the LMRS COEA, Appendix E. [5] As agreed at the Project Review of 6 April 1999, the bottom mine type has been expanded to three separate types and drifting mines have been added for a possible excursion.

Table 1. Mine Types

Designation	Mine Type
T1	Moored Contact
T2	Moored Influence
T3	Rocket-Propelled Rising
T4	Torpedo-Propelled
T5A	Large Bottom Influence
T5B	Small Bottom Influence
T5C	Medium Bottom Influence
T6	Drifting Influence

Section 2 of the LMRS COEA provided background on threat types T1 through T5A. The most difficult mines to detect acoustically are usually bottom influence mines and antenna or contact mines moored close to the surface. Near surface mines are hard to detect because of ray spreading near the surface and because the surface reflects mine-sized echoes. Bottom mines are hard to classify because of bottom reverberation, proximity to other minelike clutter, and partial or full burial, which diminished the acoustic reflectance, alters the geometry of the exposed case, and shortens the shadows. Bottom mines come in a variety of shapes, sizes, and materials, making it difficult for the operator to distinguish minecases from clutter of various types.

3. Operating Environments.

Acoustic environmentals are taken from ARL:UT's environmental summary for the N87 Winter Study 2K. [3] Maximum currents are assumed to be three knots. For confined areas (choke points and port approaches), systems are required to work with and against a 3-knot current. For open water operating areas (CVBG Operating Areas, SEAs, etc.) systems must work with and against a 3-knot current and against a 3-knot current perpendicular to the track. For calculation of search times, a one-knot current is assumed. Water clarity is defined for each area.

4. Strategic Sea Line of Communication (SLOC).

a. Source. The SLOC Scenario is based on the Strategic SLOC Tactical Situation (TACSIT) found on page 61 of the SC-21 COEA briefing, "TACSIT 1: Strategic SLOC" [4] and in the main body of that briefing.

b. Relevance. Maintaining strategic SLOCs is key to joint force missions across the spectrum of scenarios - from naval presence to crisis response to open conflict. Potential adversaries may attempt to use mining to close strategic SLOCs.

c. Tactical Situation. This scenario requires surface combatants and submarines to operate in potentially mined waters in a strategic SLOC. It is assumed that the SLOC is adjacent to hostile territory, so the surface combatants must provide protection for any dedicated MCM forces during their MCM operations. If MCM systems are operated from surface combatants, the mission must be conducted in such a way that the combatant is protected from both mine and nonmine threats. If the MCM systems are operated from other surface ships (auxiliaries, amphibious ships, work boats, etc.) protection must be provided to those vessels.

d. Operational Characteristics.

(1) Threat Geometries. The potential mine threat area is shown in Figure 2. Conceptual systems must counter mine threats T1, T3, T4, and T5A in this area. T3 and T4 are the predominant threats in the deeper parts of the potential mine threat area. T1 and T5A are the predominant threats in the shallower parts of the threat area.

(2) Clearance Geometries. MCM forces are required to clear a central channel 0.5 nmi wide and 120 nmi long through the potential mine threat area. Combatants will move through the channel when the central 600 yards has been cleared to 95 percent and the number of mines cleared indicates that the Simple Initial Threat (SIT) to surface combatant traffic is no more than 5 percent. All traffic will begin moving through the channel when the entire 0.5 nmi has been cleared to 95 percent and the number of mines cleared indicates that SIT is no more than 5 percent. Eventually, the entire box (5 nm x 120 nm) must be cleared, but no time requirement is levied for this operation. It is required that the same systems perform the clearance after completing other required missions.

(3) Physical Environment. Water depth through the SLOC varies from 150 feet to 300 feet deep. For analysis purposes a depth of 250 feet is to be used. The bottom is APL_UW 4 [13] (APL_UW 9 as an excursion) and clutter density (non-mine bottom objects (NOMBOs) prior to classification) is estimated to be 28 minelike objects per square nautical mile. Water currents are less than 3 knots at all times; wind speed is 8.3 knots. A medium level of volume scattering strength is assumed. The sound velocity profile (SVP) for this winter environment is shown in Figure 3. Average salinity for the area is used. The water clarity at this location and season translates to one optical depth of 6.7 m at the specified wavelength.

5. Strategic Port.

a. Source. The Strategic Port Scenario is based on "TACSIT 2: Strategic Port" from page 62 of the SC-21 COEA. [4]

b. Relevance. Keeping strategic ports open is a key to deterrence of aggressive action against peaceful nations and, in the event hostilities commence, the availability of strategic ports is critical for joint force build-up. Friendly forces must ensure port accessibility for build-up ashore. The intent is to prevent damage from mines to friendly shipping and to encourage the host nation to allow continued access to the port.

c. Tactical Situation. This scenario requires friendly shipping to enter port in a timely fashion for debarkation of military supplies to support allied forces in the area.

d. Operational Characteristics.

(1) Threat Geometries. The potential mine threat area is shown in Figure 4. Mine types are T1 and T5A from the sea buoy to the jetties (which are mid-way between the sea buoy and the off-load area) and T5A inside the jetties.

(2) Clearance Geometries. A channel 0.5 nmi wide must be cleared in 48 hours to enable shipping to enter port and off-load military materiel. The length of channel is 20 nm from the sea buoy to the offload area. The entire channel must be cleared to 95 percent in the 48-hour period. At a later time (no time requirement) the remainder of the port must be cleared to 95 percent by the same conceptual systems. Assume that the remaining area to be cleared is the same dimensions as the original channel, but shallower.

(3) Physical Environment. The bottom is APL_UW 4 (APL_UW 9 as an excursion) from the sea buoy to the offload area. Assume 20 percent mine burial inside the jetties. Channel centerline depths vary from 200 feet at the sea buoy to 40 feet at the offload area. A depth of 65 feet is used for planning. For later clean up operations, the same systems will be required to clear to the 20-foot mark. A medium level of volume scattering strength is assumed. The sound velocity profile for this summer environment is shown in Figure 5. An average salinity for this area is used. Wind speeds are 7.2 knots. Water currents are three knots or less and conceptual systems are required to work both against and with the maximum current. No crosscurrents are assumed for port clearance operations. Calculation of search time is based on a one-knot current along the channel being cleared. The density of minelike contacts is 8 pre-classification NOMBOs per square nautical mile. The water clarity at this location and season translates to one optical depth of 3 m at the specified wavelength.

6. Fleet Operating Area.

a. Source. The Fleet Operating Scenario is based on the CVBG Operating Areas shown on page 63 of the SC-21 COEA "TACSIT 3: Fleet Operating Area" [4], adjusted for similar operations in the MCM Force 21 study, as provided in reference [8].

b. Relevance. Adversaries may mine potential fleet operating areas. Because most regional adversaries have little or limited naval capabilities, they may use mines as an alternative approach to sea battlespace control. Adversaries will not know with certainty which areas have been selected for battlegroup operations, but will plant harassment fields in bands or clusters that are likely to intersect areas selected for carrier and other types of operations.

c. Tactical Situation. This scenario requires surface combatants to operate in potentially mined waters to support other operations. The types of operations expected include carrier flight operations, missile firing operations, and naval interdiction. The most stressing case is the CVBG Operating Area because of its size and importance.

d. Operational Characteristics.

(1) Threat Geometries. There is a potential threat for all parts of the Fleet Operating Area shallower than 2000 feet. Locations of the mines and mined areas are unknown to friendly forces at commencement of the operations. Figure 6 shows where mines are assumed laid. Potential mine types include all types shown in Table 1.

(2) Clearance Geometries. Fleet combatants must operate in all parts of the operating area. The operating area is a rectangular box 40 nmi by 60 nmi.

(3) Physical Environment. The environmental description is taken from the MCM Force 21 Study as provided in reference [8]. Water depths vary between 125 feet and 200 feet in the shallow half of the Operating Area. They vary from 2000 feet to 200 feet in the deep half. For purposes of this study, a water depth of 175 feet is assumed for planning. The bottom is APL_UW 4 (APL_UW 9 as an excursion). A medium level of volume scattering strength is assumed. The sound velocity profile for this winter environment is shown in Figure 7. An average salinity for this area is used. Wind speeds are 9.9 knots. Systems are required to work against maximum water currents of 3 knots, including with and against the system travel and perpendicular to search tracks. For calculation of search times, use a one-knot current. The density of minelike objects is 8 pre-classification

NOMBOs per square nautical mile. Water clarity at this location and season translates to one optical depth of 10 m at the specified wavelength.

7. Anti-Amphibious Assault Minefields.

a. Defensive Minefields. Intelligence estimates state that adversaries in the foreseeable future will use the effective and widely disseminated minefield philosophy of the former Soviet Union for planning defensive minefields. These minefields are comprised of several elements that include perimeter, main, very shallow water (VSW), surf zone (SZ), and beach minefields. The level of threat posed by a minefield is dependent on the density of mines and the types of mines used. The mines themselves have varying levels of explosive power, fuzing/firing logic, and counter-countermeasure capability.

b. Covering Fires. Minefields will typically be covered with shore fires (to varying degrees) to defend the minefields as part of an Integrated Anti-Amphibious Assault (IA3) plan. Placement of covering defenses is based in large part on a briefing [9] provided by the Marine Corps Intelligence Activity (MCIA) to the review panel for the study on MCM in Support of Operational Maneuver [10].

c. Lay-downs. For the study of alternative counter-mine systems to enable future assaults, a nominal threat lay-down has been prepared. The composition of the minefield to counter an amphibious assault (see Table 2), is the same as that used in the Joint Countermine Advanced Concept Technology Demonstration (JCM ACTD) Demonstration I. [7] Field locations and mine types are depicted in Figure 8.

(1) Perimeter Field. The perimeter minefield is located approximately 40 km (21.6 nm) from the shoreline in depths of 40 to 200 ft, and is 25 nm x 0.5 nm. The minefield consists of one row of 500 MKB moored contact mines and two rows of 200 KMD-II-1000 bottom influence mines with 150- to 200-meter spacing. The perimeter minefield is laid across anticipated approaches to potential amphibious landing areas.

(2) Main Minefield. There are five belts comprising the main minefield each 1 nm x 5 nm: two are comprised of two rows (150 mines total) of MKB-moored contact mines spaced 125 meters apart and one row (50 mines) of KMD-II-500 bottom influence mines spaced 150-200 meters apart; two others are comprised of two rows (80 mines total) of MYAM-moored contact mines and one row (40 mines) of KMD-II-500 bottom influence mines all spaced 250 meters apart; the remaining belt is composed of three rows (250 mines total) of MKB-moored contact mines spaced 120 meters apart. The main minefield is located between 12 and 16 km (6.5 and 8.6 nm) from the shoreline in 40 to 200 ft of water.

(3) VSW Field. The VSW minefield is 12 nm x 0.3 nm and contains two rows (1000 mines total) of Al Muthena/35 and PDM-3Ya moored contact mines spaced 45 meters apart and 20 meters apart, respectively, and one row (200 mines) of Manta bottom influence mines spaced 110 meters apart. This minefield is located approximately 1 km (0.5 nm) from shore in 20 to 40 foot water depths.

(4) Surf Zone Field. The SZ minefield is approximately 3.2 nm in total length, but comprised of 3 clusters of mine belts 1000-2000 meters in length. This minefield contains 1000 PDM-1 tilt rod mines spaced 6 meters apart and 750 PDM-2 tilt rod mines spaced 8 meters apart, emplaced in 3 -10 ft of water. TM-46/TM-57 or equivalent AT mines and PMN/POMZ or equivalent AP mines (3000), spaced 6 meters apart, are interspersed with obstacles (100) at the water's edge (1.5 ft).

(5) Beach Minefield. The beach minefield is comprised of one row of AP mines (PMN/POMZ), three rows of AP/AT (TM-46/TM-57 and PMN/POMZ) mines, and a

mixture of obstacles (500). There are a total of 6000 AP mines and 3000 AT mines in the beach minefield.

(6) Covering Fire Positions. The covering fires will consist of howitzers from one-half an artillery brigade and tanks from a mechanized brigade. The tanks are capable of providing covering fires for the VSW and SZ regions. The howitzers can cover the main minefield but have insufficient range to protect the perimeter minefields. The coverage of the howitzers is depicted in Figure 9. While not depicted in the figure, patrol boats and land-based aircraft also threaten MCM operations.

d. Assumptions and Assault Geometry. It is assumed that covering fires will be partially suppressed prior to clearance operations. The assault lane geometry is shown in Figure 9 in the proper scale. The assault lanes are 165 yards wide by 23.5 nmi long ingress lanes that stretch from the shallow water region into the 10-foot depth of the VSW/SZ demarcation. Each assault lane then generates two 50-yard wide lanes through the SZ, each SZ lane culminating in an 80-yard diameter Initial Craft Landing Site (ICLS). (The assault lane geometry is compatible with the OPNAV N852 recommended changes to the Shallow Water Mine Countermeasures (SWMCM) Operational Requirements Document (ORD) [11] and MCCDC's concurrence with that recommendation. [12]) A blow-up of the assault lane geometry is shown in Figure 10.

Table 2. Nominal Anti-Landing Minefield

MINE LOCATION	MINE TYPE & NUMBER
PERIMETER	· 500 MKB moored contact mines · 400 KMD-II-1000 bottom influence mines
MAIN	· 400 MKB moored contact mines · 80 MYAM moored contact mines · 90 KMD-II-500 bottom influence mines
VSW	· 1000 A1 Muthena/35 and PDM-3Ya moored contact mines · 200 Manta bottom influence mines
SZ	· 1000 PDM-1 tilt rod mines · 750 PDM-2 tilt rod mines · 3000 AT/AP mines (TM-46/TM-57 and PMN/POMZ) · 100 Obstacles
BEACH	· 6000 AP mines (PMN and POMZ) · 3000 AT mines (TM-46 and TM-57) · 500 Obstacles

e. Physical Environment. The physical environment is based on similar fields used in the MCM Force 21 Study as defined by reference [8]. Water depths range from 100 feet at the line of departure to the shore. For purposes of this study, a water depth of 40 feet is

assumed for this area. The bottom is APL_UW 4 (APL_UW 9 and 17 as excursions). A low level of volume scattering strength is assumed. The sound velocity profile for this summer environment is shown in Figure 11. For representation of this environment the SVP is truncated at 40 feet. An average salinity for this area is used. Wind speeds are 6.7 knots. There are estimated to be 8 pre-classification NOMBOs per square nautical mile. Currents run less than or equal to 3 knots both along and athwart the lane direction. The water clarity at this location and season translates to one optical depth of 9 m at the specified wavelength.

8. Near Shore Operating Areas.

a. Source. The Sea Echelon Area (SEA) description is based on amphibious geometries applied to the Marine Corps Warfighting Laboratory's Operational Maneuver from the Sea (OMFTS) Scrimmage Wargame series. This scenario is discussed from the MCM perspective in Section 19 of the STOM Report. [6] The mine and obstacle lay-down is taken from the JCM ACTD Demonstration I, nominal threat lay-down, [7] which is also used in the STOM Report.

b. Relevance. The SEA encompasses the area in which amphibious and other friendly ships operate at the commencement of assault operations. It is located over the radar horizon from land to help protect our forces from direct fire weapons. Once the assault is underway and the threat from shore fire diminishes due to friendly suppression, it is highly desirable to move the Sea Echelon Area as close as possible to the shore to minimize the transit times for vehicles moving between the Amphibious Task Force (ATF) and the shore.

c. Tactical Situation. Ships of the ATF are required to operate 20 to 25 nm from the shore during the pre-assault phase of the operation and to move to an area approximately 12 nm off shore once the threat from shore fire and other land based threats has been suppressed. It assumes that fire suppression will not occur until friendly forces are placed on the shore. The initial SEA will be selected in an area that is deep enough (or inaccessible enough to the enemy) so that mining is not expected. After the initial assault, the SEA will be moved closer to the shore where the main minefield is expected. Ships must move through the perimeter minefield to get to the SEA in both cases. (The outer SEA will be referred to as the Over-the-Horizon (OTH) SEA; the near-shore SEA will be referred to as the Inner Transport Area (ITA). The ITA is intended to be placed a safe distance outside the main minefield, so that only the assault vehicles penetrate the main minefield, VSW field, SZ field, and beach field. MCM systems must determine where the minefields are with sufficient confidence to position the ITA safely.

d. Operational Characteristics.

(1) Threat Geometries. The minefields, including composition, are laid relative to the shore as defined in Figures 8 and 9 and Table 2.

(2) Clearance Geometries. The near shore (ITA) position of the SEA is shown in Figure 12. Figure 12 also shows the assault lanes drawn nearly to scale. A blow up of the beach ends of the assault lanes is shown in Figure 10. The OTH SEA is 15 nmi by 25 nmi. [8]

(3) Physical Environment. The physical environment is based on similar fields used in the MCM Force 21 Study as defined by reference [8]. Water depths range from 100 feet at the line of departure to 200 feet at the seaward edge. For purposes of this study, a water depth of 164 feet is assumed for this area. The bottom is APL_UW 4

(APL_UW 9 and 17 as excursions). A low level of volume scattering strength is assumed. The sound velocity profile for this summer environment is shown in Figure 11. An average salinity for this area is used. Wind speeds are 6.7 knots. There are estimated to be 8 pre-classification NOMBOs per square nautical mile. Currents run less than 3 knots. The water clarity at this location and season translates to one optical depth of 9 m at the specified wavelength.

LIST OF REFERENCES

1. JHU/APL memo JMA3:gwp of 8 March 1999; Subj: "AAR; ONR Future MCM Systems Review Meeting; 24-25 Feb 99"

2. JHU/APL paper JMA3:gwp of 8 March 1999, revision a, "Study of Future MCM System Alternatives; Problem Definition, Missions, Threats, MOEs/MOPs, and Baseline Capabilities"

3. "Winter Study Mineray Analysis", email from Rick Bailey including summary by Mimi Lawrence, ARL:UT, 28 April 2000.

4. CNA Annotated Briefing, CAB 96-71.09 of 24 September 1996, entitled, "SC-21 COEA Part I Results: Sea Battlespace Dominance/Mine Warfare," by Sabrina Edlow

5. JHU/APL NWA-96-009 of September 1996, Final Report entitled, "Long-term Mine Reconnaissance System (LMRS) Cost and Operational Effectiveness Analysis (COEA) (U)"

6. JHU/APL Final Report, JWR-98-016-1, of December 1998, "MCM in Support of Operational Maneuver; long title: Analysis of Mine Countermeasures (MCM) Capabilities in Support of Operational Maneuver from the Sea (OMFTS) and Ship to Objective Maneuver (STOM)"

7. Joint Countermine (JCM) Advanced Concept Technology Demonstration (ACTD) Demonstration I, Minefield Annex, Version 2.0, 25 June 1997

8. "MCM Future Systems Study Concept Assessment Process," briefing of 6 April 1999 by Richard E. Nelson, CSS

9. MCIA briefing entitled, "IA3 and MCM," by Mr. Mike Howard, MCIA, given to the Review Panel for MCM in Support of Operational Maneuver on 9 March 1998.

10. JHU/APL memo JMA-3:gwp of 12 March 1998; Subj: "AAR; MCM ISO Op'l Maneuver Project Review; 9 March 1998"

11. CNO ltr 3900 Ser N852D/8U652865 of 19 May 1998; Subj: "Shallow Water Mine Countermeasures (SWMCM) Operational Requirements Documents (ORD) Revision"

12. MCCDC ltr 3900 Ser C443 of 10 September 1998; Subj: "Shallow Water Mine Countermeasures (SWMCM) Operational Requirements Documents (ORD) Revisions"

13. "APL-UW High Frequency Ocean Environmental Guides," Applied Physics Laboratory University of Washington, APL-UW TR 9407, October 1994.

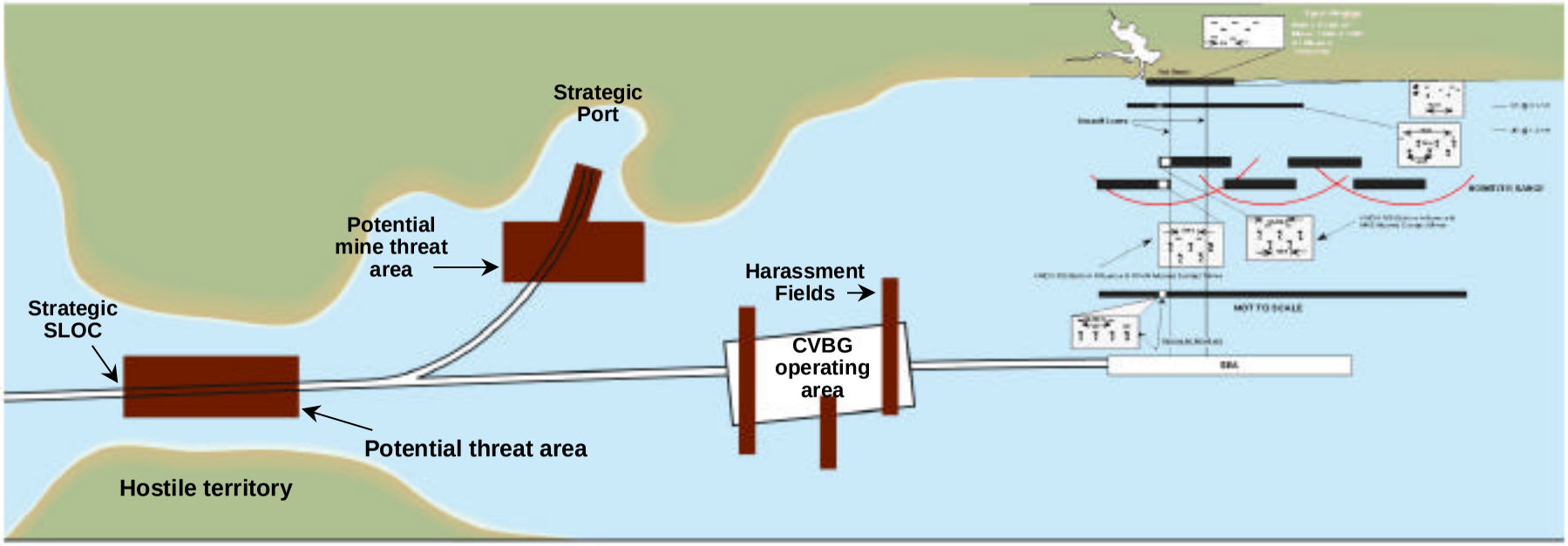

Figure 1. Scenario Areas

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TACSIT 1: Strategic SLOC

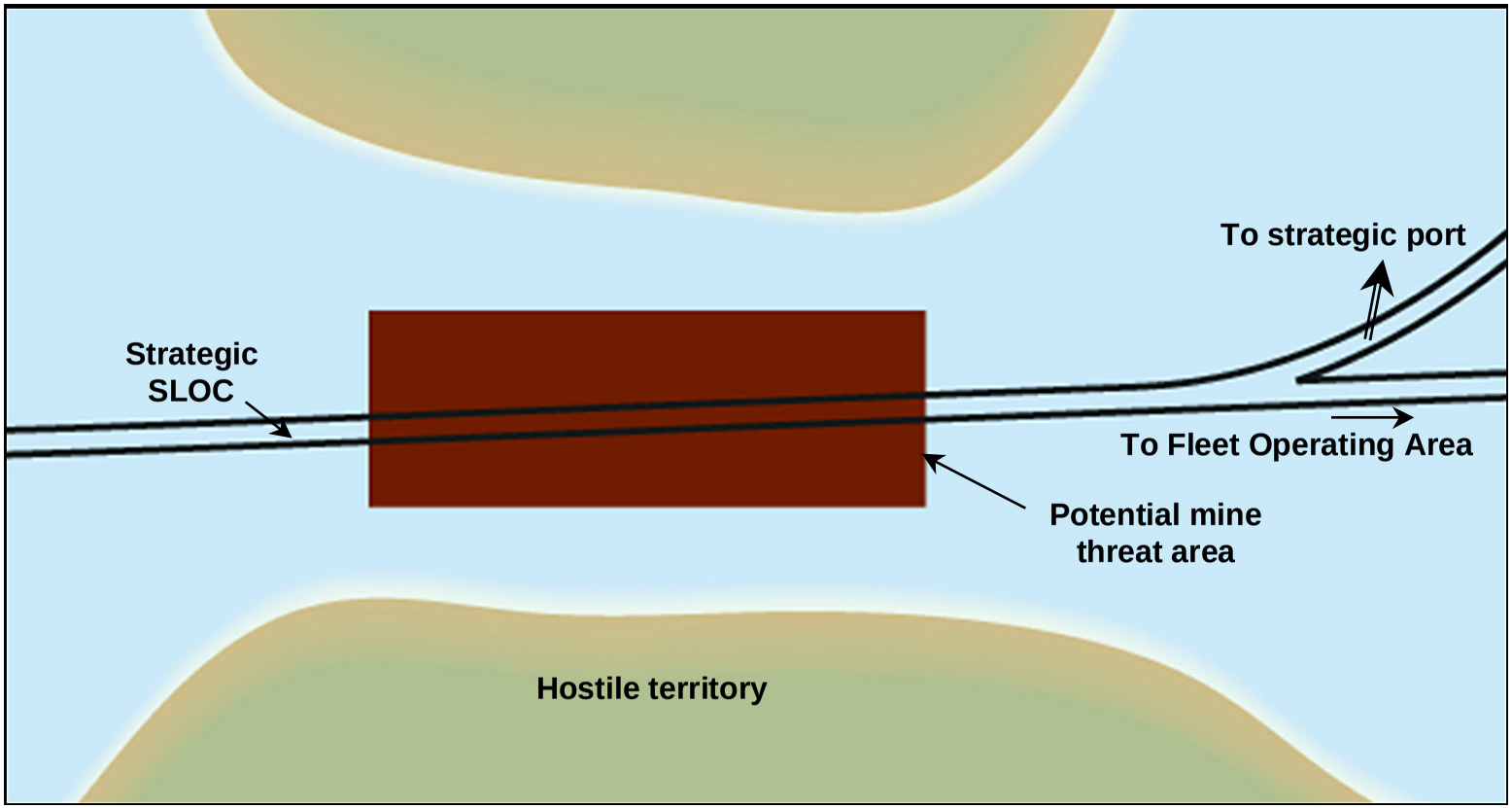
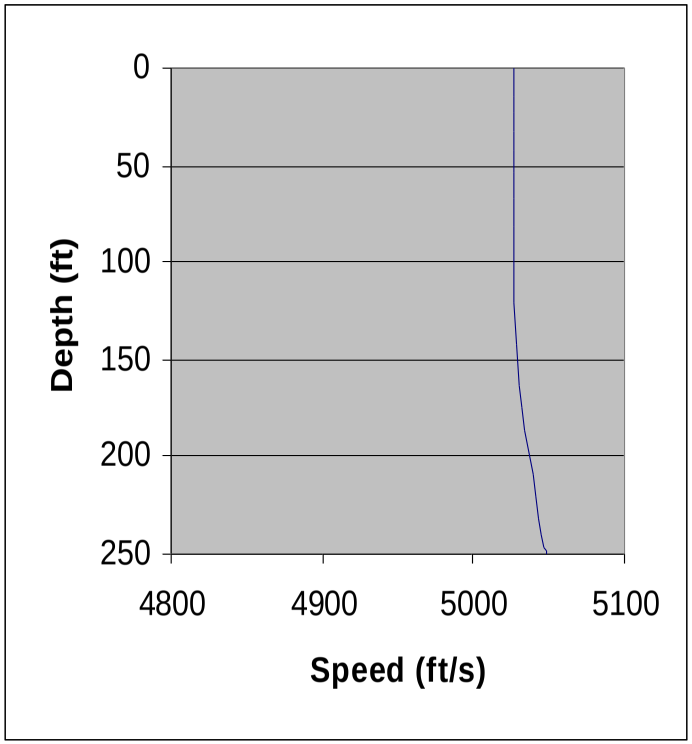


Figure 2. Strategic SLOC



Depth (ft)	Speed (ft/s)	Salinity (ppt)
0.00	5026.45	37.07
32.81	5026.62	37.07
82.02	5027.39	37.07
164.04	5031.29	37.07
246.06	5047.28	37.07
250.00	5048.00	37.07

Figure 3. SLOC Sound Velocity Profile (SVP)

TACSIT 2: Strategic Port

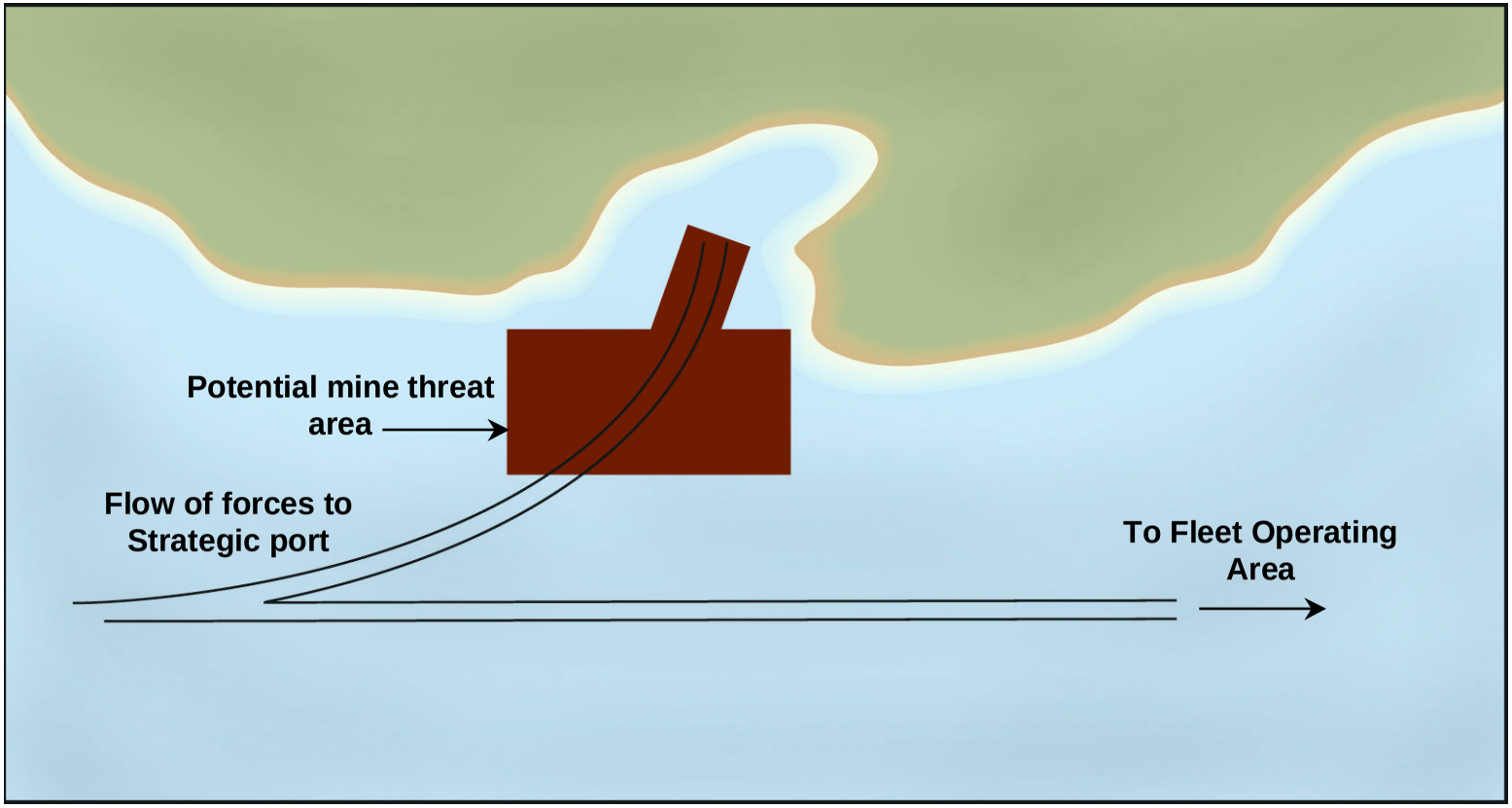
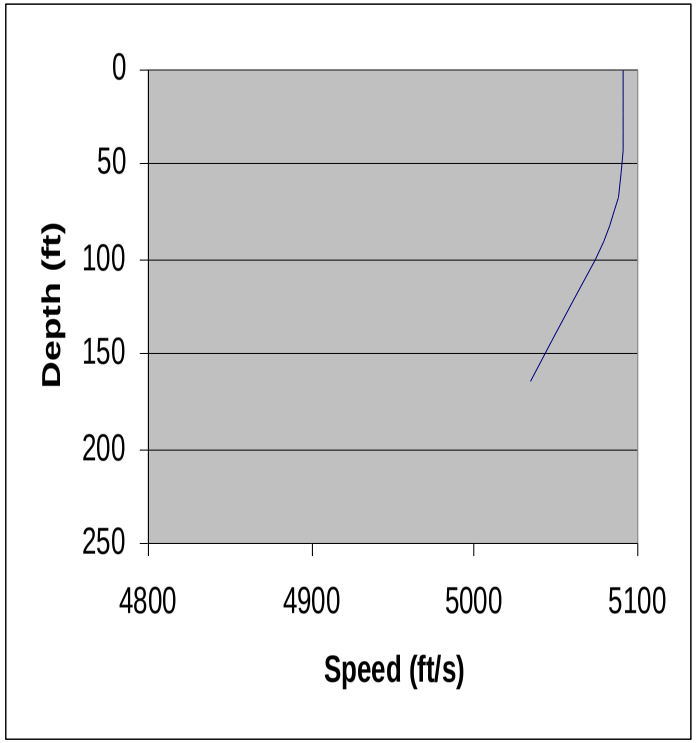


Figure 4. Strategic Port



Depth (ft)	Speed (ft/s)	Salinity (ppt)
0.00	5091.07	40.18
32.81	5090.32	40.18
82.02	5082.33	40.18
164.04	5033.64	40.18

Figure 5. Strategic Port SVP

TACSIT 3: Fleet Operating Area

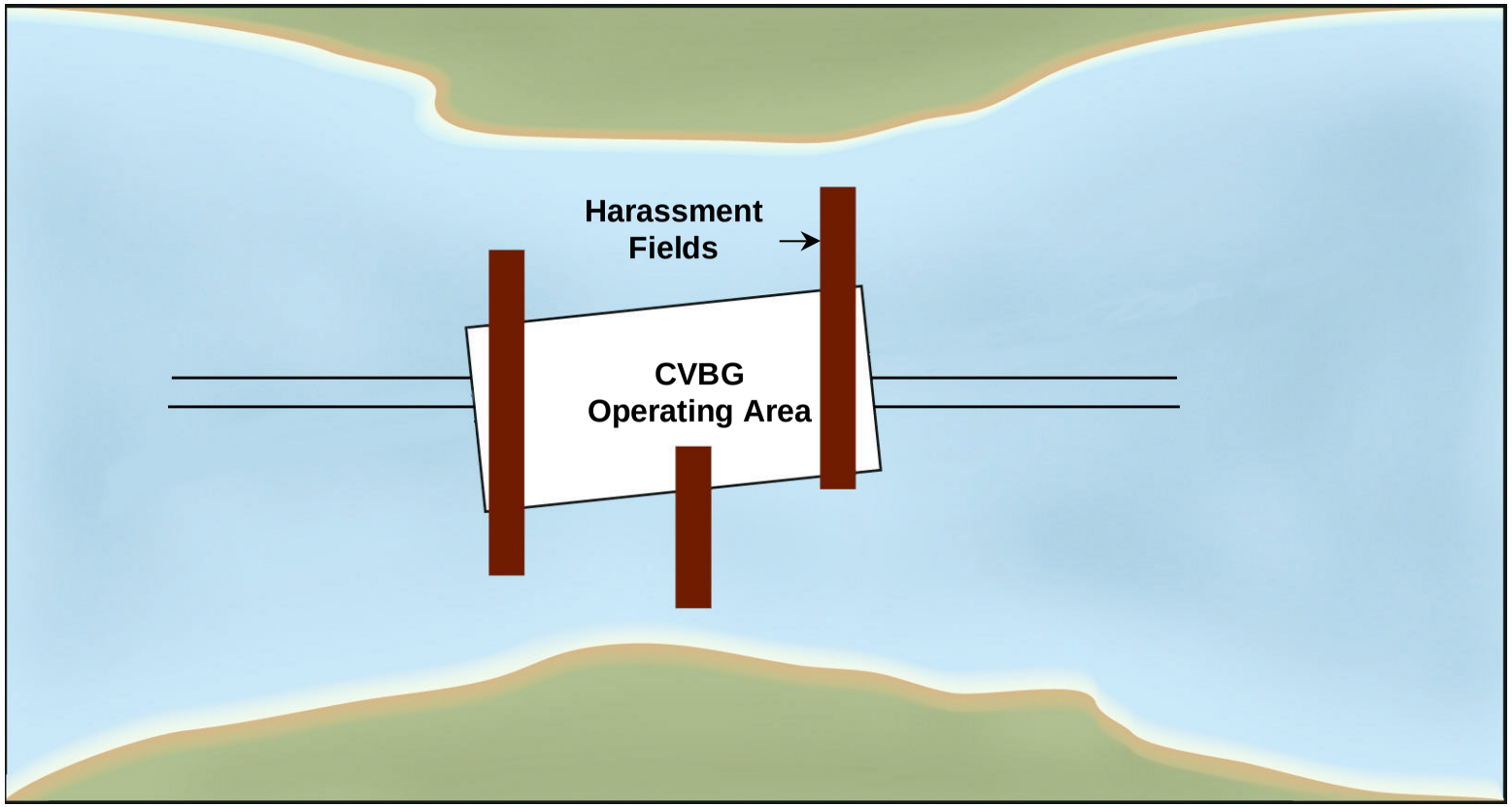
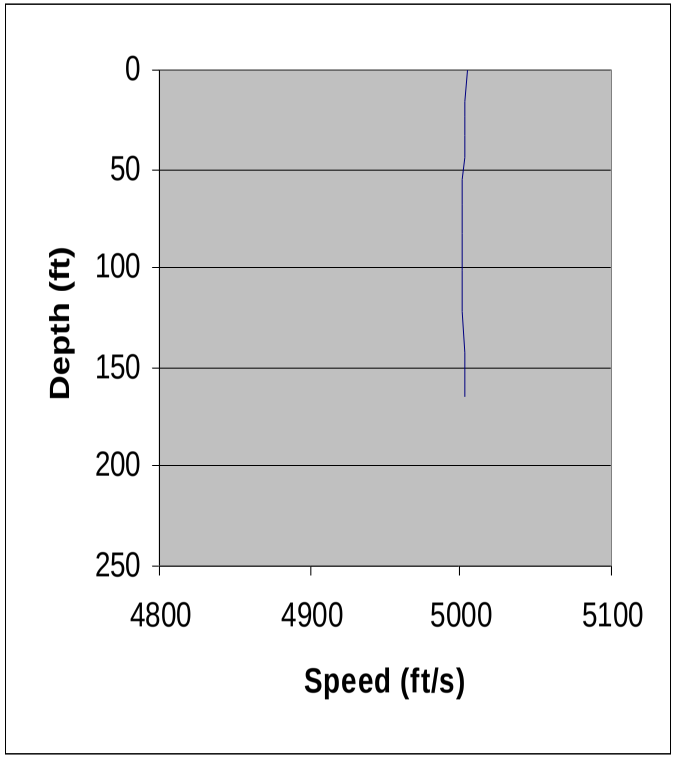


Figure 6. Fleet Operating Area



Depth (ft)	Speed (ft/s)	Salinity (ppt)
0.00	5004.76	40.35
32.81	5002.95	40.35
82.02	5001.45	40.35
164.04	5002.70	40.35
175.00	5002.90	40.35

Figure 7. Fleet Operating Area SVP

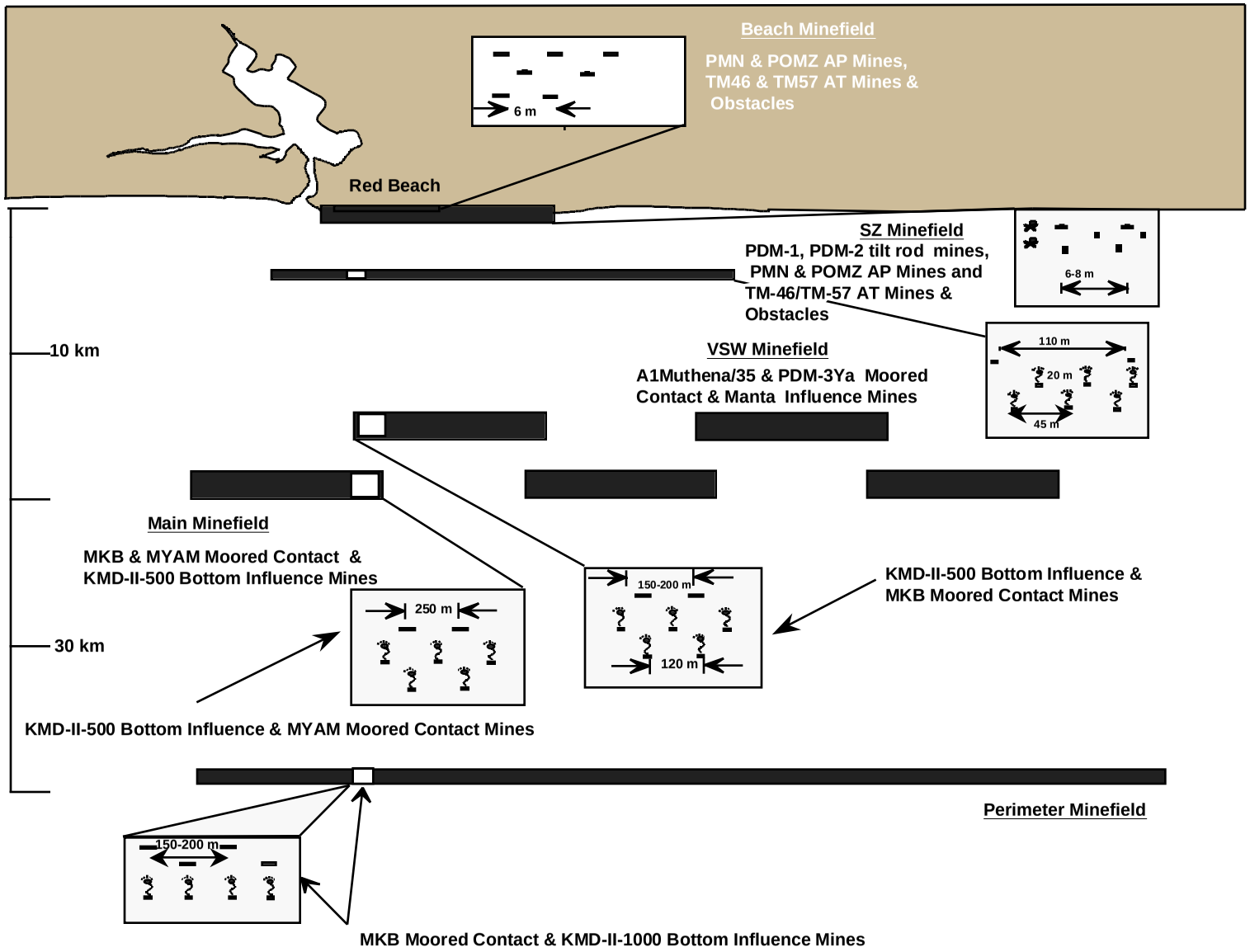


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Figure 8. Anti-Amphibious Assault Mine Threat

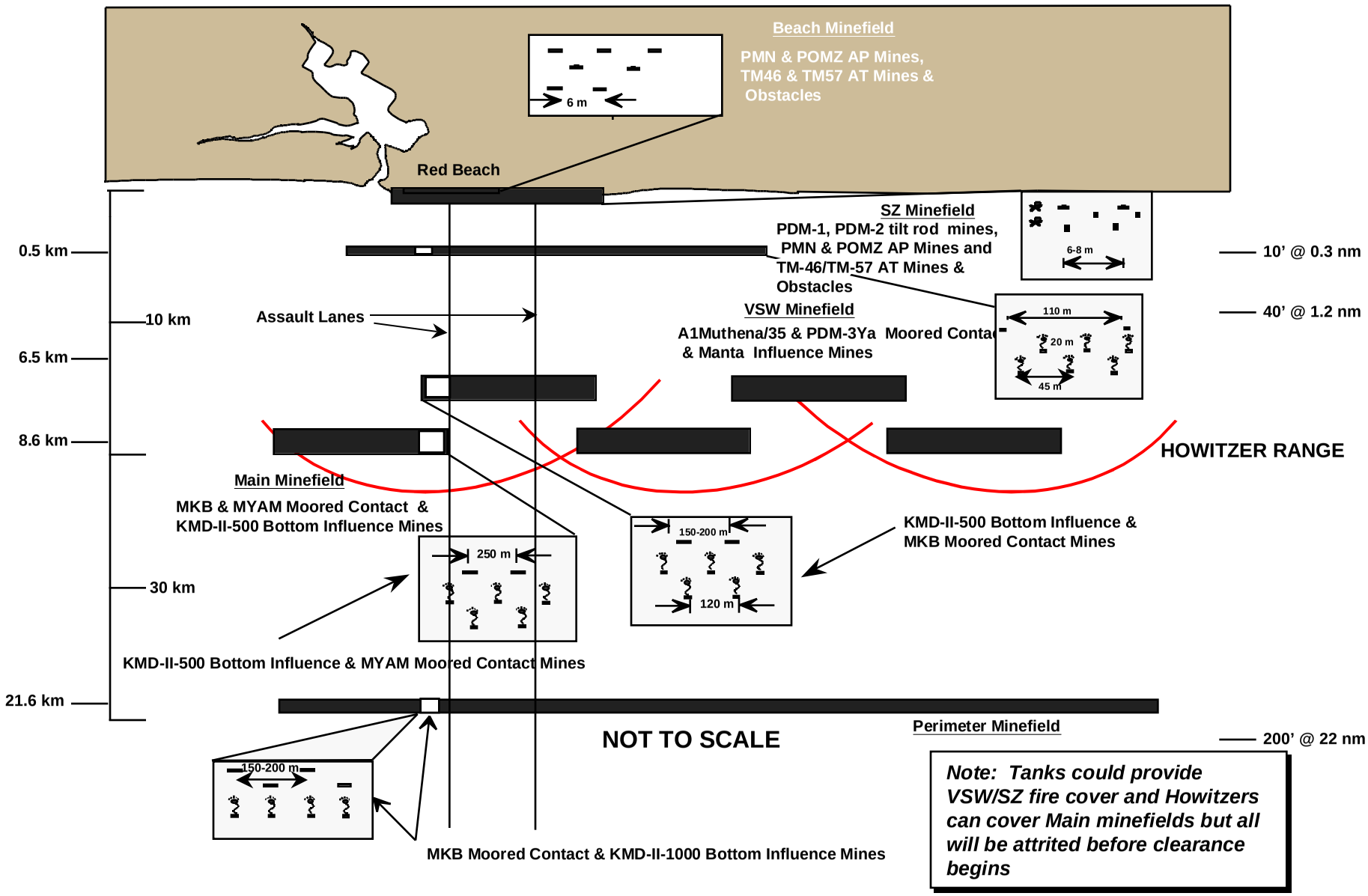

Figure 9. Nominal Mine Threat

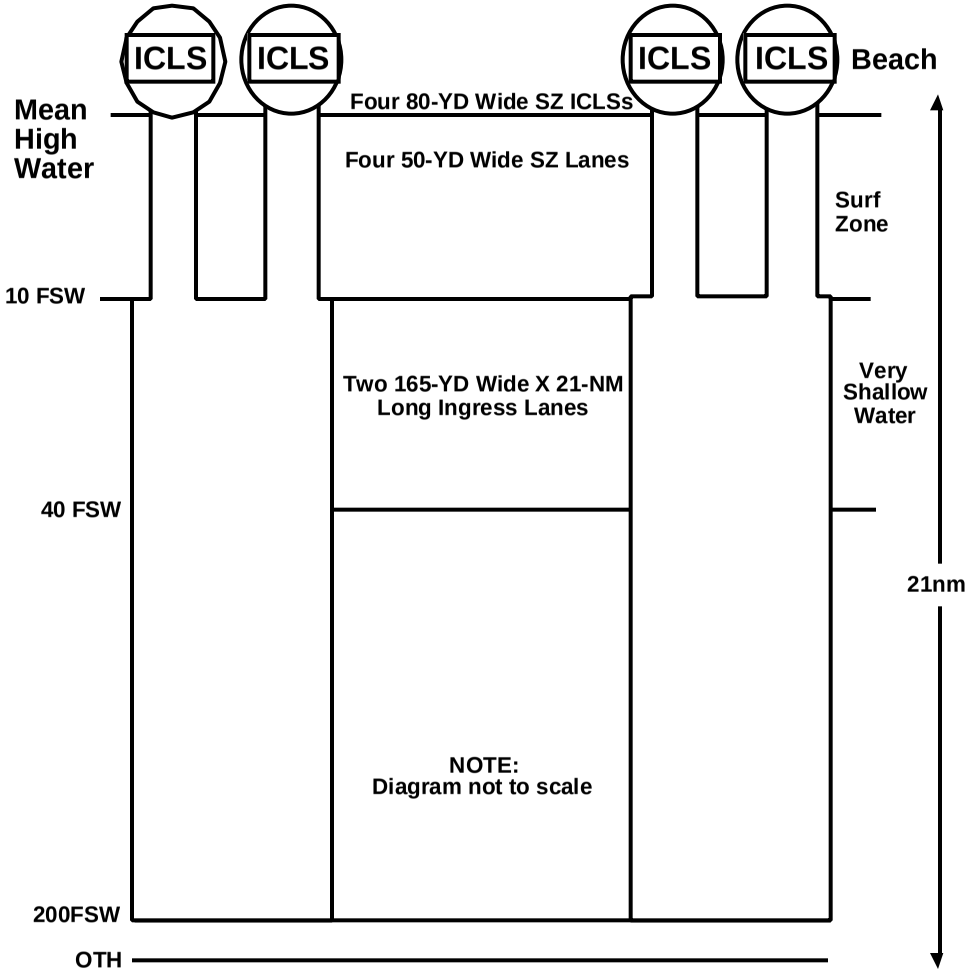

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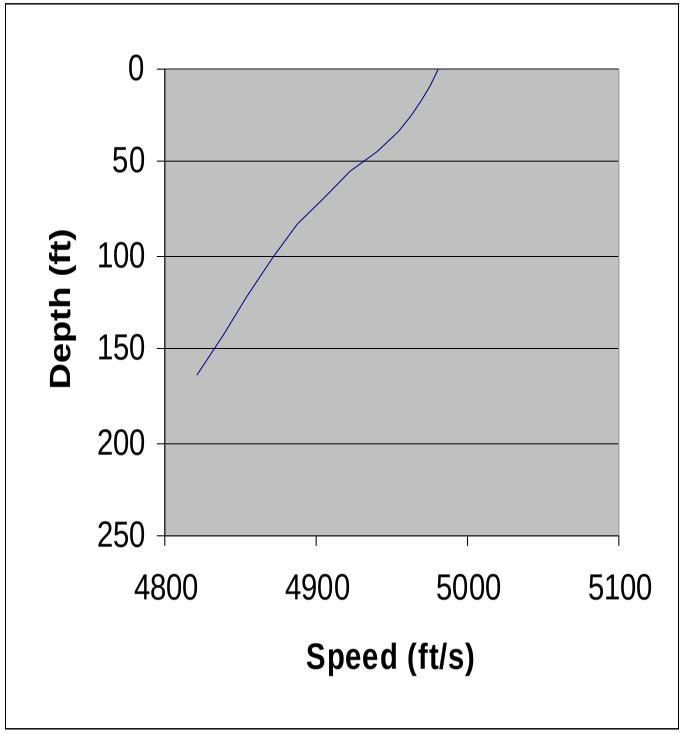
Figure 10. Assault Lane Geometry



Depth (ft)	Speed (ft/s)	Salinity (ppt)
0.00	4979.89	33.25
32.81	4954.01	33.25
82.02	4886.94	33.25
164.04	4820.69	33.25

Figure 11. Anti-Amphibious Assault SVP

Assault Beach

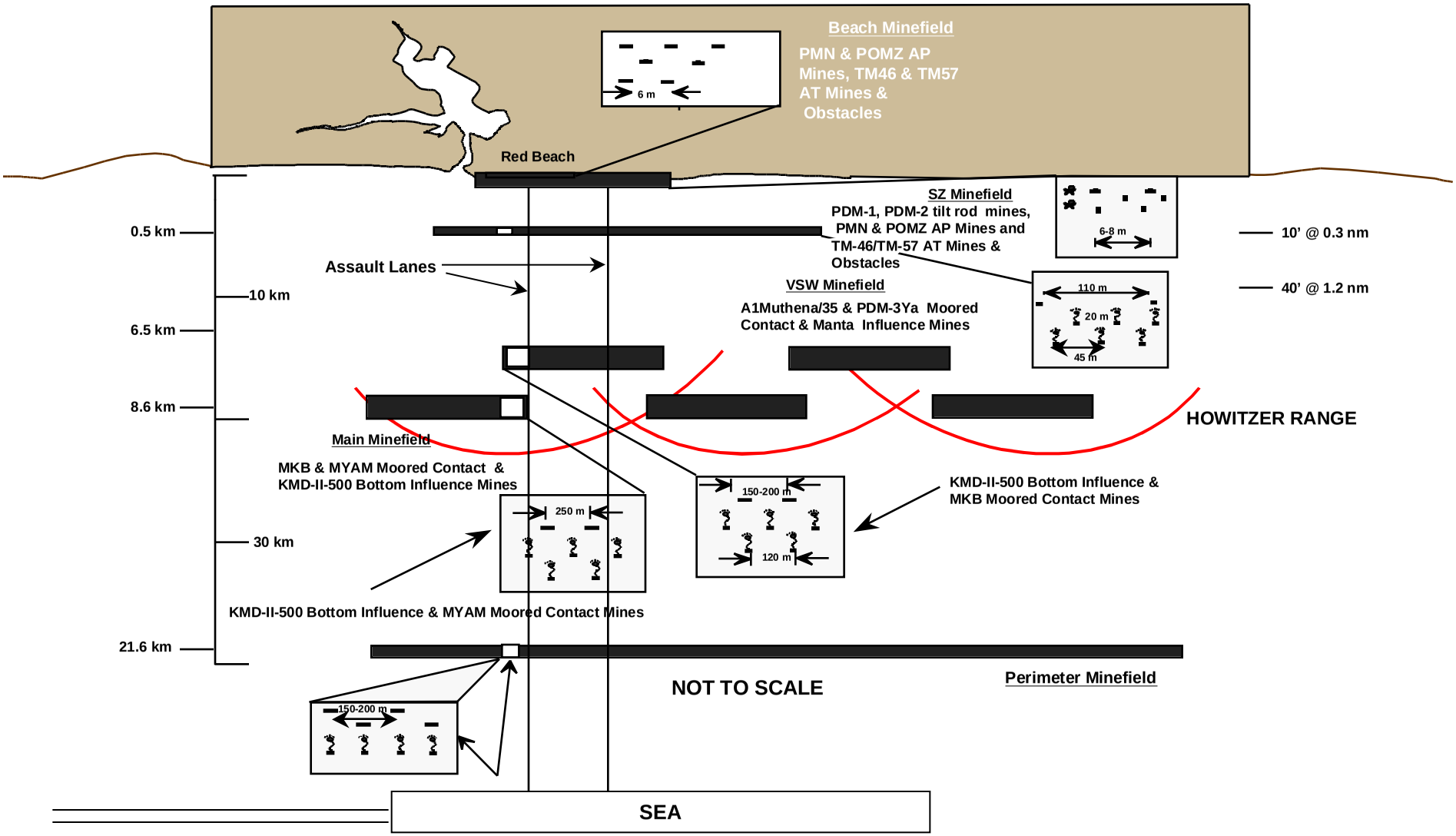


Figure 12. Assault Beach with Off-shore Operating Areas

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ROVING MINE

1. Concept. Given that an Unmanned Underwater Vehicle (UUV) could have a very long endurance, UUVs could be designed to search for enemy ships (or facilities) and to attack them. Solar power has been demonstrated feasible for long term UUV propulsion. Vehicle behaviors would be highly information based.

2. Delivery. Air, surface, or submarine delivery would be feasible. Since the vehicles should have virtually unlimited endurance, the need for exotic (air, submarine) deliveries is diminished. The roving mines could be launched from any surface ship or even piers or offshore platforms to transit to the intended minefield. The roving mine would be unarmed until it reached the designated minefield perimeter. Since the vehicles must surface periodically to recharge, it would be possible to communicate with the mines by RF or satellite (RECO). Communications should be primarily from command post to mine to conserve power. However, occasional status reports (location, systems status) from the mines should be feasible. Arming commands may be reserved until the UUV reports its presence in the assigned minefield. Because the mines are delivering themselves from a remote location, the delivery does not have to be accomplished all at once - the roving mines could be delivered on controlled, but continuous, basis so the enemy could never be assured that the field was clear.

3. Search Behavior. The mine's behavior should be highly information based. Each mine will be programmed to rove an assigned area until a target vessel is detected and identified. The identification library should contain descriptions of all enemy vessels and all allied and friendly vessels. The mine can be directed to seek a single vessel, a single class of vessels, or multiple classes. In some instances it may be directed to attack any vessels in the area (e.g., a blockade). Search patterns can be defined by track coordinates, depth contours, or specified behavior within designated areas. The mine library should contain as much detail as possible on the bathymetry of the area, currents, tidal cycles, prevailing weather conditions, and environmental characteristics (SVPs, water clarity, bottom types, etc.), and the mine should be trained to take advantage of conditions to find targets and to avoid capture by the enemy. For example, the vehicle may lie on the bottom at night (alert or dormant as directed), rove in the mornings and afternoons, and bask to recharge its batteries at mid-day. (Probability of mine detection by aerial visual search is a strong function of sun altitude. At mid-day in most climates of interest, aerial detection probability is near zero due to sun glint. It is also near zero in the early morning and late afternoon because insufficient sunlight enters the water to illuminate the minecase. Depending on the latitude and time of year, the mine can take advantage of these search limitations to maximize battery recharge opportunities while minimizing the likelihood of detection by the enemy.)

a. Mobile Target Detection. Sensors for detection of mobile targets, such as ships and submarines, should be passive, whenever possible. Good candidates would include passive acoustic, magnetic, electrical, optical, and chemical. Targets might be localized from a distance by sniffing and tracking fuel residue or exhaust. Passive acoustic could be used to discriminate among targets at a distance. Localization for attack might use the virtual telescope. This technique has potential for imaging a ship's profile (an excellent identification clue) at

depths down to 150 feet. Depending on the target draft, the virtual periscope might allow the vehicle to ride at the proper depth for maximum damage while it is localizing. Stereoscopic optics would allow the mine to image the target in three dimensions for comparison with library data and to optimize vehicle placement for final attack. To seek submarines, the mines might rove the thermoclines.

b. Static Target Detection. The same roving mine design might be used to attack static targets, such as piers, offshore platforms, dry docks, etc. The main difference in programming would be that coordinates would designate the target to the mine. If the mine had difficulty reaching the target because of nets and other obstructions, the mine might have to practice patience and await lapses in the defenses, such as determining when the gates would be opened in the nets and attempting penetration at those times.

c. Self-protection. The mine should be programmed to protect itself against a variety of threats: entanglements in ambient materials, entanglements in nets and traps, capture by alerted enemy, entrapment in tidal basins, etc. Some sort of obstacle avoidance sensor is required. The selection is important, as this is likely to be the only active sensor, other than a Fathometer or Doppler sonar, and the most power consuming system onboard. Sensors should alert the mine when it is being detected by the enemy. For example, a virtual periscope may be able to detect laser energy and alert the vehicle that it has been illuminated by an ALMDS-type system. Passive sensors might detect active ASW or MCM sonars that are insonifying the mine. In these cases, the mine should initiate an escape behavior. An active obstacle avoidance system is needed to avoid nets or stationary obstacles.

d. Navigation. Navigation can use a combination of Dead Reckoning (DR) techniques, map reading, and updates with GPS or other electronic means.

4. Attack. The roving mine would normally rove at best endurance speed and take advantage of tidal currents to move around its assigned area. Its slow cruising speed would not allow it to close on a target unless the target steamed very close to the mine's position. Accordingly, it may be necessary to provide a rocket for final closure to the target. An alternative might be to attack the target at its berthing or anchorage location, but an alerted enemy could protect its ships with booms and nets, preventing the mine from reaching its target. Because of the various sensors, batteries, processing, etc. required, there may be limited space and weight for an explosive payload. Accordingly, a shaped charge might be an appropriate warhead.

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CATSKILL CONCEPT AND ISSUES

1. Purpose.

Current surface and airborne MCM platforms were designed for Cold War applications. While they perform administrative clearance in deep and shallow water well, they are not well suited for MCM in hostile environments, which are the prevalent environments for littoral warfare. Organic MCM provides forward-deployed combatants a "punch-through" capability, but MCM is only one of their many missions, so MCM platform alternatives should be considered. Consider the following:

- Dedicated MCM platforms are slow, vulnerable, expensive, and most of all slow to arrive in theater
- Organic MCM will have mainly deep water clearance requirements to protect the battle force to which it is attached
- Organic host platforms will have competing missions to perform during amphibious assault operations and during other clearance operations in hostile littoral regions.

2. The Catskill (Mother Ship) Concept

Organic MCM systems consist of small, unmanned vehicles or CH-60 helicopters residing as a squadron (with other duties) aboard a Carrier or assigned as single assets to small combatants in the group. To make best use of future organic systems capabilities in an amphibious environment, a mother platform could tend many small vehicles that were remotely controlled, autonomous, or manned by small crews. This concept was used in the 1960s when USS OZARK and USS CATSKILL were converted to MCM Command and Support ships (MCSs). [*1*] The concept was abandoned for two reasons: (1) because the small open craft they employed, the remotely controlled minesweeping launches (LSMs), were limited to Sea State 2 and (2) because the MCS design was top heavy. An MCM 1 Class is manned with a crew of 83 officers and men, yet only a fraction of these are engaged in operating the sonar and mine neutralization vehicle which are the main battery of the platform. The advantages that large ships provide over small platforms are these:

- Stability,
- Endurance,
- Drawbar pull, and
- Lift for deep ocean systems.

Tending small vehicles with a mother ship obviates the endurance aspect. UUVs and semi-submersible vehicles like the AN/WLD-1 Remote Minehunting System (RMS) have good sea-keeping capability. The 20-ton SWATH has demonstrated stability comparable to that of the MCM 1 class. [*2*][*3*] It can transit at 18 knots and tow small bodies as slow as 1.5 knots with good steerage control. Its draft is 4.5 feet and it has demonstrated searching in water as shallow as ten feet. The LSD 41 Class is capable of carrying ten 20-ton SWATH hunter/neutralizers and ten fully hangered CH-60 helicopters. RMSs, platform-independent UUVs, or remotely controlled Advanced Lightweight Influence Sweep System (ALISS) vehicles could also be

carried, as the mission required. Thus, for minehunting operations, which do not require strong towing capabilities, the multiplication potential provided by many small hunters is clear. Add to this the lower signature, lower observability (especially if the SWATH is designed for stealth), and shallower draft of the small craft, and there appears to be pay off all around. Small stealthy craft could also be used to tend Marine Mammal Systems (MMS) in addition to those used by the VSW MCM Detachment.

3. Catskill Advantages.

- Concept operates multiple MCM sensors or sweeps instead a single sensor
- SWATH has a crew of 5 (can even go to 3 or be remotely controlled) while the MCM 1 Class has a crew of 83.
- Provides force multiplication through multiple sensors employed simultaneously.
- Provides endurance and support for craft which otherwise have limited endurance.
- Drastically reduces the number of people who enter the minefields.
- Can accompany the Fleet.
- Can stand back from shore defenses while its small vehicles sweep and hunt in the dangerous areas
- A single casualty is not catastrophic to the MCM operation.
- As a standard Navy hull, the mother ship does not suffer from the materiel problems associated with low magnetic MCM hulls.
- Can mix and match vehicles carried aboard the mother ship to fit the mission.
- Can support other missions (e.g., ASW) by swapping out vehicles.

4. Disadvantages.

- Requires a dedicated large platform, such as an LSD.
- Does not handle the deep hunting as well as MCM 1 or MHC 51 Classes.
- Does not provide the high current influence sweeping that MCM 1 Class or MH-53Es provide.
- Does not provide heavy mechanical sweeping; (small, remotely controlled craft have demonstrated a capability of towing light mechanical gear).

5. Scope of Application.

- Deep water (for mines moored to threaten surface traffic)
- Shallow water
- VSW
- Potentially into the surf (can design small vehicles to drive all the way to the beach)

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A MINIMALIST APPROACH TO UUV MINEHUNTING

1. Purpose. This paper describes in brief terms an approach to minehunting with Unmanned Underwater Vehicles (UUVs) that provides the tactical commander with confirmed mine search data with minimal complexity and cost to the individual vehicle. The concept helps define the Type II UUV analyzed by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) for the ONR sponsored project on Future Mine Countermeasures (FMCM) Systems Concepts analysis. The process below forms a baseline to which more technologically complex capabilities can be added and analyzed as excursions.

2. UUV Search. The most basic approach to minehunting with UUVs is to provide torpedo-shaped vehicles with minehunting sonars (either ahead-looking or side-scan or both) that can detect minelike contacts with sufficient resolution to classify them, using internally computed Computer Automated Detection (CAD) and Computer Automated Classification (CAC) algorithms. The vehicle transits from a staging area to an assigned area for searching on preprogrammed or autonomously planned tracks. When an object is detected and classified as minelike, the vehicle makes a procedure turn in the direction of the object and passes over the object for identification using optics or other sensors of comparable resolution. An ahead-looking sensor may be necessary to ensure that the vehicle passes directly over the object to be identified. A marker may be dropped in the vicinity of the object. After the identification data has been collected, the vehicle makes another procedure turn in the same direction (racetrack fashion) and resumes searching on the original track. Another detection of the object is made as the UUV passes abeam the object for the second time, and the second measured position of the object is combined with the calculated position from the original detection and compared to the position measured when the UUV passed directly over the object. If a marker was dropped, the relative positions of the object and marker are measured during the second pass from the search track. Search resumes until another object is detected and classified as minelike, and the turn procedure is repeated. The vehicle continues to search as long as endurance permits, or until the assigned sortie objectives are complete, at which time the UUV transits to its rendezvous point for recharging and/or recovery.

3. Data Recovery and Training the CAD/CAC. When the UUV is recovered, the optical data is retrieved directly from the UUV and viewed as soon as possible by an operator. Operators will take the data directly from the vehicle; if the vehicle is docking, the docking station should pass the essential data to the operators. (If optical systems are working properly and water clarity permits positive identification, the acoustic search data is of little immediate interest to the operator. Acoustic search data should be archived for bottom mapping and reconstruction. If acoustic snippets are used to help calibrate CAD/CAC routes, they should be reported along with the optical data. Otherwise, acoustic search data is not needed in the minehunting operation.) When viewing the optical data for identification purposes, the operator enters the appropriate responses to record which objects are mines and what kind of mines they are. Special keys should be available for denoting mine types (bottom cylindrical, moored, Manta, Rockan, etc.) and depending on the CAC routines in use at the time, non-mine types (55 gallon drum, rock, coral head, metallic debris, etc.) may also need to be identified with special function keys. These data are fed back into the CAD/CAC algorithms, which are presumably neural networks or other

learning based routines, to train the algorithms to discriminate better in the local minehunting environment. (Every minehunting environment is different, so training feedback is always needed.) Hence, for subsequent sorties of the UUVs in the local area, CAC/CAD will be improved. The coordinates of mines and non-mine minelike contacts (MILCs) are recorded automatically in a tactical database where they are available to be transferred directly to a neutralization system, which may or may not be a different class of UUV. The process of UUV search, data extraction, algorithm training, and subsequent search continues until mission objectives are met.

4. Nice to Have Capabilities. The above process should provide high quality identification data to the operators in a reasonable time and with a reasonably affordable vehicle system. It makes use of existing, near-term, and information-based technologies that can be engineered with state of the art computers and algorithms, acknowledging technological challenges like underwater navigation. Additional functions may provide improvements, but none are essential to the minehunting mission. The most commonly discussed additional functions are discussed in context below.

a. Communications. Note that the above search process is conducted without real time or even periodic reporting of the vehicles. Data can be extracted at the end of each sortie to go directly into the tactical database (through a node, if the vehicle is docking) without human participation other than the identification function. Mine clearance operations typically take days to complete. So long as the search plan is sound, data reported by MCM units seldom result in urgent modifications to the plan. Exploratory and breakthrough objectives can make communications more urgent and should be planned accordingly. If periodic updates of critical information are required, underwater acoustic communications might be used to transmit critical data or charging garages might be designed to extract UUV data during the recharging process. When recharging nodes are used, they should also function as the communications hub to transmit critical data to the tactical commander.

b. Platform Independence. Small, general purpose UUVs, like the Remus vehicles built by Woods Hole Oceanographic Institute (WHOI), can be launched and recovered from a variety of support platforms, including combat ships, support ships, MCM ships, fishing vessels, submarines, and even aircraft. Their size is referred to as "two-man portable." If the vehicles are kept small and easy to handle, they can be operated in large numbers to increase the combined search rate. The best vehicle size should be the largest (for endurance sake) that can be launched easily and safely by deck hands without specialized handling gear. A separate issue paper discusses tactical delivery options.

c. Range. So long as there are multiple tactical options for delivering and recovering the UUVs, vehicle range is not critical. For example the Remus UUV, which is state of the art, has demonstrated 15 hours at about 3 knots with lithium ion batteries. In other configurations an underwater docking mechanism and recharging garage has been used to recharge the Remus without human control. Delivery and recovery of this sized vehicle should be feasible with rotary wing aircraft or small surface vessels like fishing boats or by mixing the two methods. If the search area is significantly remote from the UUV support platform, an underwater recharging garage should be considered as part of the delivery to extend vehicle search time.

d. Ahead-looking Sonar. Some sensor is needed to guide the UUV over the Minelike Contact (MILC) during the identification maneuver. Since the object's position is known with precision at that time, the guidance sensor could be very simple. If a high-resolution ahead-

looking sonar is selected, it could provide the entire search capability or it could complement a side-scan sonar in the following ways:

- Fill the hole in the middle of a typical side-scan trace
- Alert the side-looker to the MILC position so it can focus on that spot as the vehicle goes by
- Provide better localization and guidance to the vehicle during the racetrack maneuver
- Provide a separate and independent image of the object that can be fused with the others to extract features
- Avoid obstacles during search and transit
- Help navigate by map reading bathymetry

These above functions, and others that were not described as part of the baseline process, are considered beyond the minimal requirements. The ahead-looking sensor and the recharging communications node provide obvious benefits to mission completion.

5. Neutralization with UUVs. The approach above assumes that MILCs identified as mines will have their coordinates automatically transferred to a neutralization system for reacquisition and neutralization. With the MILCs having been positively identified and accurate positions having being recorded, neutralization with divers, mammals, ships, or airborne neutralization systems should be expeditious. UUVs might be used for neutralization, but their application is not straightforward. The different approaches and issues are recorded in a separate paper entitled, "Mine Neutralization Using Unmanned Underwater Vehicles (UUVs)."

6. Search Variations. A "mow the lawn," identify-as-you-go, search technique, as described above, should be considered the baseline. There are variations on the minimalist approach to minehunting that could be employed without sacrificing too much simplicity.

a. Bumper Pool Search. The minimal UUV could search the entire assigned area first without performing the racetrack patterns for identification. At the end of the search, the same UUV could identify all classified MILCs, one at a time, before proceeding back to the rendezvous point. This variation in technique is sometimes called "bumper pool" tactics. It may be theoretically faster to cover the whole area this way, but the price paid is threefold: (1) the tactic requires that the UUV reliably reacquire MILCs (not a trivial task), (2) mean sound speed will not be calculated to adjust search positions, and (3) if the UUV is unable to complete its search due to some failure, no MILCs will have been identified. In the last case, the tactical commander will be deprived of positive confirmation of minefield presence and the CAD/CAC will not be updated to upgrade sonar performance for the next round of searching. Experience with dedicated minehunting systems indicates that positive identification is needed as early as possible in the operation in order to expedite high-level tactical decision-making. Note that the difference in approach described here is procedural; i.e., the same UUV could be programmed to conduct either type of mission without hardware modification.

b. Early Reports. Other variations that could be applied would include different ways of communicating information from the vehicle back to the commander without returning for recovery. Especially if an automated identification function is available, the vehicle may be programmed for some missions to report immediately when it finds a high probability mine.

7. Cost Drivers. Historically, three requirements have tended to drive the cost of remotely operating minehunting systems: (1) the requirement to be deployed from and recovered by specialized platforms, such as submarines, (2) the requirement to report back to the operators on a

continuous or frequent basis, and (3) the requirement for long reach, which drives the size of the vehicle, its handling, and all complementary support. The minimalist approach to UUV search and neutralization attempts to avoid these cost drivers while still providing to the commander the information he needs the most, namely positive identification of mines and nonmines at precise positions in the field.

8. Selection of Subsystems. Considering that this paper describes a future system concept, as opposed a current design, there are criteria in the selection of its subsystems that should help keep the basic vehicle simple and affordable. As a minimum, the following capabilities should be designed in:

- Mine search sensor(s)
- Ability to discriminate to some degree between mines and nonmines
- Guidance and control
- Precise and accurate underwater navigation
- Propulsion that optimizes search speed and maximizes endurance
- Mine identification
- Storage and processing for large amounts of data
- Ability to transfer data as directed and in an operationally effective and efficient manner
- Ahead-looking sensor for obstacle avoidance and reacquisition*

* A UUV can operate without an ahead-looking sensor, but vehicle safety and reacquisition of MILCs would be very questionable.

As much of the above capability as possible should be information based to enable system growth without major hardware modifications. This design approach encourages cost-effective upgrades. An example might be advanced real-time processing of various kinds to make sonar images sharper and turn decisions faster. Navigation might be made more accurate through map reading techniques not currently available - if the sensors can recognize and match previously detected features, navigation drift can be kept within limits.

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rev b

MINE NEUTRALIZATION
USING UNMANNED UNDERWATER VEHICLES (UUVs)

1. General. When small UUVs search for mines, the neutralization is generally performed as a part of a separate phase in the minehunting process. Minehunting functions are usually approached in phases with the two most common divisions of functionality as follows:

- Search-Classify-Mark and Reacquire-Identify-Neutralize (S-C-M & R-I-N) or
- Search-Classify-Identify-Mark and Reacquire-Neutralize (S-C-I-M & R-N)

These are the phasing combinations that the ONR Semi-Autonomous Hydrographic and Reconnaissance Vehicle (SAHRV) and the EOD Very Shallow Water (VSW) UUV Programs are researching. With any minehunting phasing arrangement, searching UUVs must pass coordinates of mines automatically to the systems performing the second phase of the hunting operation. If the minelike contacts (MILCs) have been positively identified as mines and their positions have been reported accurately and precisely, neutralization with divers, mammals, ships, or airborne systems should be relatively expeditious, though not clandestine. UUVs could be used for either clandestine or administrative neutralization, but there are several issues that require examination.

2. Clandestine Operations. The employment of UUVs to perform clandestine mine search is easily understood. Basically, UUVs are released close enough to the search area that they can transit to the area, run parallel search tracks, and return to a pre-designated rendezvous point with the search data. Clandestine neutralization, on the other hand, is not so easily applied. Traditional neutralization techniques would alert the enemy to the presence of mine hunting systems. The obvious remedy is to delay actuation of the neutralization charge to keep from alerting enemy surveillance. The discussion that follows examines ways of neutralizing with UUVs and assumes that clandestine neutralization is highly desirable.

3. Neutralization versus Sympathetic Detonation. Current US Navy MCM policy requires neutralization, as opposed to the sympathetic detonation of mines. Mine neutralization requires only that the mine is rendered incapable of operating against passing traffic. A neutralized mine remains on the bottom, providing a minelike echo that subsequent mine search operations will detect. A separate "clean up" operation is normally performed after the shooting phase of an operation to remove or dispose of neutralized mine bodies. If mines require disposal (sympathetic detonation) during the initial hunting operation, the most commonly researched approach for UUV disposal would be to attack the mines' explosive materials with shaped charges. (See the discussion of methods below.) If the disposing UUV is non-expendable, it must vacate the area before the disposal package actuates, leaving the disposal package to attack the mine by itself. Considering the complicated nature of attacking mine explosives, which are distributed non-uniformly within the minecase, disposing of a mine with a shaped charge is a non-trivial operation. The requirement to delay the disposal further complicates the operation. Delayed neutralization with a bulk charge is more straightforward, but requires greater weight. The discussion to follow assumes that sympathetic detonation is desirable, but not required.

4. Neutralization Requirements. An ideal neutralization system would have the following characteristics:

- Unmanned
- Cheap
- Reliable
- Insensitive
- Easily handled
- Easily transported
- Good range of operations
- Effective against a variety of mine types
- Confirmation that the neutralization had been achieved
- Effective in numerous environments, including against buried mines
- Capable of either delayed detonation or undetectable neutralization to preserve the clandestine nature of certain operations

5. Neutralization Methods. The following are some of the more common approaches to neutralization and/or disposal:

a. Bulk Charge. It is relatively easy to place bulk explosives in close proximity to bottom mines. Delaying the detonation would be relatively easy, although the package must be designed with low acoustic and magnetic signatures to prevent actuating influence mines. The penalty paid for neutralizing with bulk charges is weight.

b. Shaped Charges. A high order explosion caused by a shaped charge detonating a mine's explosives would confirm disposal, assuming the clearing forces were equipped to monitor and localize explosions. However, the ability to strike the mine's explosives requires precision control of the shaped charge at the moment of disposal. There are several mine design issues that would affect the performance of a shaped charge neutralizer:

- Some modern mines will be manufactured with insensitive munitions, which might not detonate even if the shaped charge penetrated the explosives,
- For shaped charges to penetrate to and detonate the explosive, they must strike the minecase at near-orthogonal angles,
- Building in delay activation for a shaped charge is difficult. Consider the following:
  - Currently available underwater adhesives are unsuitable for attachment of shaped charges to minecases.
  - Magnets are inappropriate for attachment to influence mines and will not work on many modern mines.
  - A canister of submunitions with shaped charges could be designed to moor above a bottom mine to release a large number of submunitions at the programmed time.
    - However, the canister and submunitions would likely weigh as much as a bulk charge designed to neutralize.
    - This concept, called Shaped Charge Anti-Mine Projectile (SCAMP), was researched in the 1970s.
    - SCAMP had a higher estimated probability of sympathetic detonation, but a lower estimated probability of neutralization than bulk charge.

c. Influence Sweeping/Jamming. If a small device could generate magnetic and acoustic signatures, it could be laid in proximity to a mine. Pros and cons of using influence signatures for neutralization are listed here:

Advantages:

- Potentially lighter and smaller than bulk charge explosives
- Could delay actuation until commencement of overt operations
- When successful, would cause sympathetic detonation, as opposed to neutralization
- Could potentially provide masking and jamming in the channel that might confuse mines and help protect traffic
- Could provide emulation effects; i.e., if the mine doesn't actuate against the influence generated, it would not likely actuate against the traffic being emulated
- Target vehicle signatures might be more easily emulated with low level signatures than with magnetic/acoustic sweeps; i.e., it might be possible to control small signatures more precisely

Disadvantages:

- Ship counters and probability actuator circuits might delay detonation into the traffic transit period
- Mines with arming delays are unsweepable until activated
- Pressure influence is not easily emulated
- Other actuation influences (e.g., UEP, ELFE) might also be difficult to emulate
- Control mines would be turned off until needed
- Mines that could measure mine-to-target distance would not be fooled

If the influence device were strong enough to be heard by other mines in the area, it could provide a jamming or emulation effect. Sometimes mines can be kept in the active state (more power consumed) long enough to run down their batteries.

d. Supercavitating Projectiles. To circumvent the difficulty of attaching a shaped charge, it might be possible to design a gun that fires a superconducting projectile, such as those being developed for RAMICS. These projectiles contain reactive materials intended to make the mine detonate (or burn) when they contact the explosives. The advantage of this approach over shaped charges is that contact between the device and the minecase is not required while the device is awaiting actuation. Also, if the projectile reliably caused deflagration of the mine charge, as opposed to detonation, the neutralization would be less conspicuous than bulk charges to enemy surveillance systems. The disadvantages are the requirement for precision aiming at the right time and the total system weight, which might approach that of a bulk charge.

e. Crawlers. Tracked or legged vehicles could be designed to crawl up to minecases and apply one or more neutralization techniques at the assigned time. For example, they might continue firing shaped charges or projectiles at the mines until detonation occurred or there was a high probability that the mines had been neutralized. One advantage of crawlers is that they can move into position as soon as they are deployed and reposition themselves before applying the neutralization devices, in case currents or migrating sediments have separated the vehicle from the minecase during the waiting period. Disadvantages include complexity and the possibility that the vehicles and neutralization packages might weigh as much as bulk charge neutralizers. Unless a UUV can deposit multiple crawlers during a sortie, there is no clear advantage over the bulk charge approach.

f. Other Methods. Other neutralization methods might include:

- Corrosive slurries

- Explosive slurries
- Encasement of the mine in concrete
- Bio-engineered organisms that eat the O-rings.
- Comma shaped devices that can be wedged down beside the mine with a shaped charge flush against the minecase
- Grabbers that grasp the minecase for a variety of potential neutralization techniques:
  - Apply shaped charge against the minecase
  - Apply the barrel of an underwater gun against the minecase
  - Inflate a buoyancy bag to float away with the mine
- High pressure water jet to cut the mine in two
- Jammers that blanket mines with so much noise that they cannot detect and localize targets
- Serpentine robots that crawl astride the minecases and wait for the time to detonate. (Cal Tech is building serpentine robots to search earthquake rubble.) Such vehicles might be equipped with shaped charges or Waterhammer tubes to reduce weight and increase the probability of sympathetic detonation.
- Cluster of very small UUVs, each containing a shaped charge and little else, that swarm in a localized area and neutralize whatever they strike.

6. Expendable Neutralizer UUVs. The simplest concept for neutralizing with UUVs would be to program expendable neutralizer UUVs to reacquire designated mines and attack them. Since the UUVs are expendable, they should be designed as cheaply as possible, while still providing a high degree of reliability and assurance that the mine has, indeed, been neutralized. To provide delayed detonation, it would most likely have to employ bulk explosives, although other neutralization approaches might be feasible and should not be ruled out without researching the options. Perhaps the most difficult task for expendable neutralizers would be for them to provide the tactical commander positive assurance that the neutralization placement had been achieved. Reporting systems could be added to expendable UUVs, but these would drive up the cost, would be difficult to effect without breaching covertness, and their reliability would always be questioned. Even if expendable UUVs were able to report their precise and accurate positions covertly, there would be questions about their proximities to the minecases when they detonated. To provide accurate distances to the minecases, expendable UUVs would require their own detection sensors to measure proximity and would then have to report proximities to the tactical commander. Given all the above, the "cheap" UUVs now must have accurate and precise navigation systems to reacquire the mine and know their positions for reporting, detection sensors to home in on and measure proximity to the mines, and reliable communications systems to report that information covertly. There is an added complication of the tactical commander's reluctant to have explosively loaded vehicles operating autonomously in his water space without his having positive control over them. He may accept that risk and responsibility after mine searching UUVs have proven their reliability, but there will be a probationary period while autonomous search UUVs prove themselves.

7. Master/Slave UUV Concepts.

a. Reacquisition Concepts. It should be possible for a large master UUV to reacquire identified mines and to place slave UUV charges near them for delayed neutralization. If the master UUV contains sensors that can see both the mine and the slave, it can guide the slave to the mine with a wire or fiberglass tether and possibly get confirmation with an optical sensor onboard the slave that the slave had found the mine and positioned itself within the neutralization locus of the mine. Upon recovery or reporting, the master UUV could provide confirmation data for all the mines it was assigned to neutralize. Under this concept, only the slave UUVs would be expendable, and they could be rather small and simple. A variation on this concept would have

the master UUV illuminate the mine to enable the slave to home in. This concept is not likely to be small or cheap and the master vehicle would be at risk from approaching active mines, as the illuminating distance would be limited. Its main advantage over the other concepts is its ability to confirm where the charges had been placed.

b. Hunter/Killer Concepts. A variation on the master/slave concept is to perform all the functions in a single minehunting phase. This process is similar to the Reacquisition Concept above, but has the problem of distinguishing mines from nonmines in real time. These are the options:

- The Master vehicle would communicate identification images to the operators for confirmation as the operation progressed.
- The Master vehicle would employ Computer Automated Identification (CAI) and make its own decisions, or
- The Master vehicle would neutralize without identifying, in which case a large number of neutralization devices would be wasted.

(1) Communicate Identification. A reliable, real-time, clandestine, underwater communications system would make the first option very attractive, but considering the large number of identifications and the high data volume required for each, this capability represents a difficult technological challenge. If there were a delay getting the image to the operators and the operators' classification decision back to the vehicle, these delays would be added to the identification/neutralization time for each minelike object.

(2) CAI. Computer Aided Detection (CAD) and Computer Aided Classification (CAC) technologies have been researched for over thirty years with limited success. CAD is finally mature enough to provide utility on the AN/SQQ-32 sonar, but CAC is generally not as good as operator classification. CAI will be even harder than CAD/CAC and will require the operators to have confidence in its effectiveness. CAI too is a difficult technological challenge.

(3) Omit Identification. The penalty paid for omitting neutralization is a dramatic increase in the number of objects requiring neutralization. This requirement translates to large stores of charges and smaller areas searched before the Master vehicle requires replenishment. There may also be objects on the bottom that should not be neutralized, such as pipelines. (Protruding portions of buried pipelines can resemble mines.) Such objects might be neutralized inadvertently in any case, but are more likely when identification is bypassed.

8. Proposed Baseline Neutralization Vehicle. The simplest concept, and one that seems to have a reasonable expectation of succeeding, is to design expendable UUVs containing a bulk charges. The expendable neutralization vehicles should match the minehunting UUVs in size, weight, and other characteristics for expediency of employment. When the minehunting UUVs returned to the underwater garage or staging area and reported their identification images to the operators, the operators would assign a neutralization vehicle to each mine that required neutralization. The Baseline Neutralization Vehicle would be feed the coordinates of the mine to be neutralized and any other information needed to find its way to that location and confirm that it had located the right object. The Baseline Neutralization Vehicle would swim to the location and come to rest on the bottom close to the mine it had been assigned. It should report its location and proximity to its assigned mine and then go dormant. It would remain dormant until the assigned neutralization time, at which time it would detonate. A difficulty might be in confirming that the neutralization vehicle had come to rest sufficiently close to the object (and to the right object) to assure neutralization. If the searching UUVs lay bottom transponders or other navigation aids, the

Baseline Neutralization Vehicles should use those same aids to return to the detected mine positions. A number of reporting schemes could be employed:

- Release of a reporting buoy
- Underwater modem
- Fiber optic connection to home base
- Confirmation by independent UUVs after the neutralization vehicles had come to rest
- Triangulation on the detonations (If the neutralization times were staggered, a network of transducers on the bottom, on buoys, on UUVs, and on ship's hulls could triangulate the position of each as the charges detonated.)

The Baseline Neutralization Vehicle itself could be relatively simple. There would be a need for some sensor capability for the reacquisition, but it would not need the large field of view and range that a searching vehicle would need. If the mine were marked with a pinger/transponder by the searching UUV, the neutralizer could home on the pinger and position itself relative to the marker. It would need to make only a one-way trip, so the power requirement would be considerably less than that for searching vehicles. The weight and volume saved (assuming same size vehicle) could be used for bulk explosive warhead. It might be possible to make the neutralizing vehicles smaller than the Remus sized UUVs so that more could be stacked in a given volume, however considering that the Remus vehicle weighs about the same as the Mine Neutralization Vehicle's neutralization charge, the Baseline Neutralization Vehicle should probably weigh the same as the Minimalist Minehunting Vehicle. If a pod or recharging garage were used to support the minehunting UUVs, that same pod or recharging garage could house some neutralization vehicles for the operators to assign. It is proposed that this concept be refined and used as a baseline neutralization capability to enable excursions based on other assumed technologies.

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MINE IDENTIFICATION
USING UNMANNED UNDERWATER VEHICLES (UUVs)

1. General. Because of the large number of physical objects in the water that look acoustically minelike, Mine Countermeasures (MCM) operators traditionally require positive identification of mines before execution of the neutralization function or declaration of a Mine Danger Area (MDA). The requirement to identify mines applies to both the exploratory reconnaissance of potentially mined areas and mine clearance operations.

2. Definitions. The traditional steps in minehunting are these:

- Detection
- Classification
- Localization
- Identification
- Neutralization

Since neutralization does not necessarily cause sypathetic detonation of the mines, verification and clean-up steps are sometimes added. The PEO-MIW Metrics document of 30 December 1997 defines the sensing functions this way: [1]

- Detection determines the presence of an object.
- Classification determines if the object is minelike.
- Identification determines if the minelike object is a mine.

3. Identification in Exploratory Reconnaissance. The exploratory reconnaissance objective is to determine the presence of a minefield or to infer its absence. To confirm the presence of a minefield it is necessary to identify a mine positively. The central identification issue is this: If acoustic reconnaissance is applied without identification, the search will detect and classify minelike contacts in virtually every case. Hence, the reconnaissance system will always report the presence of minelike contacts (MILCs), a circumstance that the Commander knew before ordering the search. Except for route planning, acoustic-only reconnaissance data provides little tactical advantage. To achieve either the affirmative or negative hypothesis of the exploratory objective, positive identification is required.

4. Identification in Mine Clearance Operations. The central identification issue for clearance operations is that, if mines are neutralized on the basis of classification alone, the false contacts will overwhelm the operation. For example, in the operator review of the Joint Countermeasure Advanced Concept Technology Demonstration (ACTD) Demonstration II [2], the MCM Commander stated that more than 500 MILCs had been reported for each of his last three major MCM exercises. Accordingly, mine identification is required to make the neutralization job manageable from the explosives availability standpoint.

5. Other Benefits. In addition to the enabling benefits for achieving the exploratory and clearance objectives above, there are other benefits provided by the identification process:

- Identification feedback improves the search sonar operator's proficiency. Operators cannot improve their sonar skills if they never learn whether they are performing their jobs correctly. Analysis of exercises has shown that the AN/SQQ-32 performance is considerably better than that of the AN/SQQ-14 sonars on the old MSOs, even though the sonar characteristics are not very different. One reason sometimes attributed to the improvement is the availability of identification information to the AN/SQQ-32 operators through the AN/SLQ-32 Mine Neutralization System (MNS). Identification information was unavailable to the MSOs, which had neither remotely controlled vehicles (ROVs) nor divers indigenous to the ships.
- Identification provides intelligence data on the mine types that are being countered. If the mines were being destroyed without identification or swept with influence sweeps, that intelligence information would not be available. The data is needed for further MCM planning and optimization of tactics.

6. Current Identification. Currently accepted ways of identifying mines are optical identification or tactile identification. Optical identification can be achieved through the use of divers or ROVs. Tactile, of course, is diver only.

7. Future Identification. It has been proposed many times by the technical community that very high-resolution acoustics be developed for mine identification. Other technical approaches have also been proposed. To date, no alternate ways of identifying have been accepted by the operational community. The operational criterion for identification is now, and is likely to remain, "... whatever provides certainty that the found object is indeed a mine." Accordingly, the criterion will change when and only when the operators are convinced that the sensor call is nearly perfect. Since the requirement to identify is dictated by the operators, as opposed to being an acquisition requirement, any candidate identification sensor must be built, tested, and exercised to build up the operators' confidence.

8. Other Issues. The identification function is becoming more difficult. Consider the following:

- Modern bottom mine designs are more amorphous and harder to recognize than the old cylindrical mines. Examples include the Manta (truncated cone), Rockan (glider), and Bunny (coffin-shaped) mines.
- Mine construction materials have broadened to include non-ferrous metals, such as aluminum, and non-metallic materials, such as fiberglass.
- The U.S. Navy is concerned about improvised explosive devices. This class of weapons, which may look like common objects, includes mines.
- Modern acoustics can provide near-optical images at short ranges.
- Computer technology has the potential to generate 3-D images from acoustic and other sensor inputs.
- Data fusion can provide a more complete picture of an object's attributes than optics alone.
- The miner can lay decoys to fool and confound the countermeasures practitioner.
- Inoperable mines were used during Desert Storm as decoys.
- There are important coastal regions where turbidity makes optical sensors ineffective for identification.

9. Opportunities. UUVs are being developed to help remove the human from the minefield. Some developmental swimming UUVs are relatively inexpensive and can be designed to approach minelike objects at close range. Crawlers and walking vehicles are other options. The closer proximity to the minelike object provides opportunities to collect sensor data that could not

easily be collected by divers or even ROVs. As a minimum, alternative sensors might be employed initially as cross-checks to current methods of identification to help distinguish, for example, between explosive devices and non-explosive devices, regardless of their appearance. If the alternative sensors work reliably, the operators may come to trust them for identification. Consider these issues:

- Mines have three common characteristics that might be used to distinguish them from other objects on the bottom:
  - Batteries
  - Active electronic circuitry
  - Explosive materials
- Data fusion technology makes multi-sensor identification more practicable.
- Neural networking and other learning algorithms have the potential to train systems in the field based on what has already been learned about found mines.
- Very short ranges between the vehicle and the object (inches) might enable electromagnetic techniques that historically have been defeated by seawater.

10. Alternatives. The close proximity to minelike objects afforded by the use of small, relatively cheap UUVs makes viable the use of sensors that would be impractical at longer standoff ranges. The closeness relaxes the sensor's requirement for sensitivity, power, size, and volume.

a. Sensors. Below are listed some of the sensors that might be employed in the future to enable or supplement identification:

- Advanced optical:
  - Multi-spectral
  - Near ultraviolet (may help distinguish newly laid objects from those that have been in the water for a long period)
  - Florescence
  - STIL and other laser based technologies that can build 3-D images
- Other electro-magnetic:
  - Electric field sensors (emulating those on sharks and rays)
  - Active electrical sensors
  - Underwater Electrical Potential (UEP)
  - Magnetometers (including magnetic gradiometers)
  - Radio and other frequencies that are normally defeated by sea water
  - Scan for the presence of transistors
- Acoustic:
  - Very high frequency/resolution acoustics
  - Low ka
  - Lambda wave
  - Ultrasonic imaging of the internal construction
- Chemical/physical sensors
  - Sniffing
  - Tasting with chemically sensitive feelers
  - Nuclear Quadra-pole Resonance (NQR)

b. Processing. Below are listed some advanced processing techniques that might become viable with advances in computer and processing technology:

- Data fusion techniques

    - Standard anding, oring, and averaging
    - Neural networking and other adaptive learning algorithms
- Display techniques
    - 3-D images that can be rotated
    - Images comprised of data from disparate sensor types
    - Comparison with templates of known mine types

LIST OF REFERENCES

1. *Mine Warfare (MIW) Measures of Effectiveness*, PEO(MIW) NOTE 3370, Ser MIW/311 of 30 December 1997

2. Joint Countermine (JCM) Advanced Concept Technology Demonstration (ACTD) II Warfare Analysis Laboratory Exercise (WALEX) conducted by JHU/APL for USACOM on 4-5 August 1998

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TACTICALLY FLEXIBLE MINEHUNTING UUVs

1. Purpose. An issue paper on a Type II, Minimalist Minehunting UUV [1] describes an approach to minehunting with Unmanned Underwater Vehicles (UUVs) that provides the tactical commander with confirmed mine search data with minimal complexity and cost in the searching UUVs. This paper describes ways that the Minimalist Minehunting UUVs might be employed, while retaining the tactical utility afforded by their small size.

2. Pros and Cons of Small UUVs. Among the advantages provided by small minehunting UUVs (about 7.5 inches in diameter) over their larger counterparts (typically 12.75 inches or 21 inches) are these:

- Larger combined area search rates, while on station, than larger vehicles of the same total size and weight
- Potential to engineer a low vehicle signature, enabling vehicles to approach mines closely for identification and other functions
- Potentially low procurement and mission costs
- Graceful degradation in that the loss of one or more UUVs does not negate the entire mission
- Relative ease of moving vehicles into and within theater
- Full platform independence, enabling multiple tactical employment schemes

The primary disadvantages of smaller vehicles, when compared to larger, are these:

- Short reach, making them difficult to apply in remote or hostile areas
- Low endurance, requiring a larger fraction of their operating time to be consumed in transit
- Size and power limitations that restrict the types of sensors and other payloads that might be employed

3. Baseline Assumption. It is assumed for reference purposes that the Minimalist Minehunting UUVs are the size of the Remus vehicles developed and demonstrated by Woods Hole Oceanographic Institute (WHOI). These vehicles are 7.5 inches in diameter by 52 inches long in their unmodified configuration, [2] and a substantial amount of performance data is available for performance model calibration. At least eleven vehicles have been built for a variety of applications, and the Office of Naval Research (ONR) has experience with Remus search operations in their Semi-Autonomous Hydrographic and Reconnaissance Vehicle (SAHRV) Program. For future concept applications, the vehicles can be modified as needed, including their size and propulsion systems. However, the rationale to follow envisions a Remus sized vehicle that performs with

energy packages, hotel loads, guidance and control, etc. similar to the current Remus but enhanced by careful selection of new sensors and information-based subsystems. The demonstrated ability to recharge Remus vehicle batteries underwater will also be assumed for the small vehicles discussed below.

4. Elements of Tactical Utility. The advantages and disadvantages of small minehunting UUVs are discussed below. This paper addresses only the search functions of detection, classification, localization, identification, and reporting of the same back to the operators. Neutralization of mines has been examined in a separate paper entitled, *Mine Neutralization Using Unmanned Underwater Vehicles (UUVs).* [3]

a. Area Search Rates. Modeling performed by laboratories both inside and outside of the ONR Future MCM (FMCM) System Alternatives project has confirmed that the combined area search rate for the smaller vehicles is greater than the area search rate of larger vehicles of the same total weight when the vehicles have enough size to carry tactically useful payloads. This statement applies only to the search phase. Launch, recovery, and transit times must be considered when planning specific missions and the transit distance, in particular, degrades the utility of small vehicles more than that of large vehicles.

b. Vehicle Signatures. So long as small vehicles can operate below cavitation speeds, they can be engineered to be quiet in the frequencies which mines use to localize ships. Small signatures permit vehicles to approach mines closely with an acceptable probability of actuating a mine unintentionally. Close proximity to the mine can be exploited for optical identification and independent sensing techniques like chemical sniffing. If a small vehicle inadvertently detonates a mine and is destroyed, the trade off may not be too bad in the sense that one vehicle was sacrificed for one mine. (It has been suggested for some applications that small vehicles be intentionally engineered with large signatures for the express purpose of actuating mines. However, the need for some MCM missions to be clandestine outweighs the utility of actuating mines with UUVs.) For large, expensive vehicles, signatures should be reduced to prevent loss, as one mine one vehicle is a poor trade-off.

c. Mission Costs. Analysis has shown that, on the basis of coverage rates, small vehicles are more efficient than larger vehicles when on station. The difficulty is in delivering them on station when the search area is remote from the staging area or defended by hostile forces and without using up an inordinate amount of their endurance with transits to and from the staging area. System costs for large UUVs are driven up by three debatable requirements: (1) long reach, (2) vehicle compatibility with specific host platforms, such as specified classes of surface combatants or submarines, and (3) direct and continuous communications with the operators. For small UUVs, ways should be sought to eliminate or substantially reduce these requirements. Mines are very popular weapons for small countries, especially for those that lack strong navies, because mines cost much less than the MCM systems required to counter them. They also help deny the U.S. Navy access to littoral waters, and restrict their movements when there, regardless of whether any ships are damaged. Most of the expense of MCM systems is invested in

the special purpose platforms that employ them, such as large nonmagnetic hulls, large towing helicopters, command and support vessels to support the hunting and sweeping platforms, and submarines that will take UUVs close enough to reach the area of interest.

d. Mission Degradation. When system capability is designed into a few large vehicles, the loss of a single vehicle represents significant fractional loss of theater capability. For example, MCM 1 ships are treated like strategic assets because loss of one can represent a 50 percent loss of MCM capability in theater. The smaller and cheaper an MCM asset can be made, the smaller the investment needed to keep the systems safe from mines and other threats, and in particular, the smaller the fraction of total capability that is at risk. Some risk must always be accepted when countering mines. With small vehicles, the risk should be acceptable.

e. Transport into Theater. Systems that are so large they require specialized handling and support subsystems are typically designed for use from specific platforms. Except for dedicated MCM vessels, host platforms have other high priority missions and the MCM systems must compete for space and support with non-Mine Warfare capabilities. Platform dependence necessarily limits the number of systems in theater at a given time and precludes a rapid build up without bringing other platforms into theater. Systems designed for use aboard dedicated MCM platforms will be slow to arrive in theater. For example, it takes about 45 days to get surface MCM vessels to the Persian Gulf from CONUS. If effective search systems can be designed to be platform-independent, multiple systems can be transported rapidly into theater when needed and employed on platforms of opportunity. Platform-independence enables rapid response worldwide. (Airborne MCM was designed in the 1960s to provide a rapid worldwide MCM capability, so the Navy could bring back to CONUS the MSOs that were being stationed in strategic areas; i.e., the original impetus for AMCM was cost-effectiveness while retaining worldwide response. Minehunting UUVs might provide some of the same functions currently provided by MH-53E helicopters.) Platform-independent minehunting UUVs could be used as organic systems, stored as part of the Military Pre-positioned Force (MPF), or flown into theater in quantity when needed. The Remus vehicle, which serves as a template for the Type II vehicle, weighs 148 lb. as a total package and can be shipped worldwide by FEDEX. [4]

f. Employment Schemes. Maximum tactical flexibility is gained when systems are totally platform-independent, including potential use from surface, air, and subsurface platforms as available. For surface platforms, maximum flexibility occurs when the vehicle can be picked up by deck hands and launched without special handling gear. This enables use not only from Navy combatants, but also from support vessels, workboats, tugs, and even small craft of opportunity like fishing vessels. (The SAHRV Field Test Report of December 1999 shows a Remus vehicle being recovered by a runabout. [5]) If the systems can be employed inconspicuously from vessels indigenous to the area, then covertness (low observability) is enhanced. For air employment, tactical flexibility occurs when the vehicles can be handled like normal ordnance, sonobuoys, flares, or other systems employed by the aircraft. An easily handled vehicle or package could also be laid by helicopters or tilt-rotor aircraft. For submarine use, it is harder to design

flexibility into the system due to the limited ways that systems can be employed through the pressure hull. This is unfortunate, as submarines offer the best opportunity to deliver minehunting UUVs to areas where covertness is required or hostile forces are patrolling. Submarine employment options include use of torpedo tubes, countermeasure tubes, and swimmer vehicle handling facilities.

g. Reach. When long reach is required for a clandestine operation, the large vehicle has an advantage over the small, as small vehicles may use up their entire endurance transiting to and from the search area. There is a long-standing requirement to employ minehunting UUVs in remote areas - LMRS is being designed to satisfy that requirement. Future cost-effectiveness will be enhanced if we can transport multiple small vehicles into and out of the search area efficiently. Even disposable vehicles might be cost-effective if large quantities can be delivered to the area with sufficient power remaining. However, with disposable vehicles difficulties arise from the requirement to inform the operators of what the vehicles are finding. Unless the vehicles perform neutralization along with their search functions and unless the Officer in Tactical Command is willing to accept that clearance has been applied without confirmation, then reporting is an absolute requirement. The reporting requirement complicates the use of otherwise simple search systems.

h. Endurance. The time and energy required for a given vehicle to launch, recover, and transit to and from a given search area is fixed. Any increase in vehicle energy, given a fixed distance to the minefield, can be applied directly to the search part of the mission. Large vehicles have longer endurances and can stay on station longer than their Remus sized counterparts. There is a crossover transit distance where either small or large vehicles are more efficient, with the larger vehicles performing better at longer distances. An ability to transport small vehicles closer to the area should extend the reach at which small vehicles are more efficient than large.

i. Sensor Limitations. Current sensor designs have minimum sizes associated with their ability to scale. For example, a laser line scan (LLS) device requires, as a minimum, a cylinder approximately 4 inches in diameter by 8 inches long for its optical paths plus the volume needed for the electronics. The electronics can be miniaturized, but the optical pathways do not scale well. Other sensors have their own practical weight and volume limits. Accordingly, the type of sensors selected dictates the lower limit for how small a search vehicle can be.

5. Enhancements to Tactical Employment. As discussed above, maximum tactical utility of a minehunting UUV system results when the system becomes totally platform independent. Total platform independence is unlikely, especially for the important submarine employment case; however, there are design considerations that can enhance tactical utility.

a. Support Subsystems. Subsystems to support minehunting UUVs include handling gear, stowage, test gear, power replenishment equipment, planning and evaluation aids, and communications gear. Small vehicles may not require special

handling gear at all. Containers in which the vehicles are transported can serve as stowage. Test gear might also be designed into those containers. If the power source is battery, it can be designed for compatibility with shipboard power plants and other electrical power sources that are typically available and standard battery types can be used. Mission planning and evaluation is computer based and should be compatible with other tactical decision aids used routinely by naval forces. Communications can be handled at the simplest level by writing search data on a tactical computer medium, such as the mission data loader used by AMCM, and extracting that medium for analysis by computer. It may be more efficient to design ports to download data directly into shipboard computer equipment.

b. Universal Delivery. Even if not fully achievable, universal delivery of minehunting UUVs is a worthy design goal. This paper will address commonly available delivery means (air, surface, subsurface), but will exclude specialized delivery such as gun launched or missile launched UUVs that require major modifications to the UUVs to enable a specific type of delivery. (It is apparent that gun launched vehicles must have structural characteristics that are sub-optimum for other delivery methods.) Vehicles that can be picked up and launched by deck hands require no specialized handling equipment. Retrieval gear may be needed to fish the vehicle out of the water, but most vessels, including small boats, are equipped with deck gear for recovering objects from the water. A long-handled net can be used from a runabout to recover a Remus vehicle. [5, Appendix B] Remus sized UUVs are about the largest UUVs that can be easily manhandled without special gear. Accordingly, smaller UUVs need not be analyzed for handling ease. Conversely, larger UUVs will require special handling equipment and the universality of their use diminishes as size increases beyond that of the Remus. Transportation systems might help solve the reach problem without sacrificing the universality of the vehicles themselves.

c. Recharging. Remus vehicles have demonstrated their ability to return to a docking station to dock and recharge without human assistance. [6]

d. Centralized Command and Reporting. One of the drawbacks of UUVs of all sizes is the difficulty of communicating search data as the vehicles search. Tethers have been used, but they are expensive and impose operating limitations, including restrictions on reach, which is needed for clandestine operations. Applying communications gear to individual UUVs for continuous reporting would require an unacceptable power load and would reduce other capabilities. Accordingly periodic, perhaps burst, communications are more feasible for the vehicle to communicate one on one with the operators, but even then the communications would be unreliable and would require weight and volume that could be used for power and search subsystems. Small vehicles like the Remus are designed to recharge periodically to extend their endurance, so the communication function can be designed to take place while the vehicle is recharging. The power package could contain a system for communicating periodically, or on command, with the operators. Thus each vehicle would pass its tactical information to the power pack during the recharging process and the power pack would report for all the vehicles at the same time. Under this scheme, the data transmitted to the operators should be primarily

the positions of minelike contacts and the optical images of those contacts. This data would allow operators to make identification decisions and pass them back to the power pack to update the vehicles' computer aided detection (CAD) and computer aided classification (CAC), assuming CAD/CAC is neural based. (Mines look different to acoustic sensors in different environments; hence, there is always a learning curve for the operators when searching in a new area. Neural networks or other adaptive learning networks could be trained with feedback data to improve their performance.) The acoustic search data could also be passed to the power pack for retention, but the acoustic data is of secondary importance to the operators if optical data is available for the same minelike contacts. An exception is when acoustic attributes of mines are being collected for data fusion applications during the operation, in which case acoustic snippets of the same mines that have been identified become important for CAC feedback. Broad area acoustic search data should be stored for later retrieval and use in bottom mapping.

e. Centralized Processing. Processing functions that are not needed for the individual vehicles to perform their tasks of detection, classification, localization, and identification should be processed external to the vehicles in order to conserve space, weight, and power. An example might be cross-correlation of minelike contacts reported by multiple vehicles to consolidate the number of objects reported to the operators. Another example might be the queuing of vehicles returning to the power pack to assign docking and recovery stations. There is valuable tactical data that the power pack might want to pass to all vehicles, such as METOC or underwater obstruction data or optical images obtained by other vehicles using the same pack. If all vehicles receive all the optical and positional information on minelike contacts, then recovery of any vehicle or the power pack would provide the operators with all the vital tactical data collected by the whole colony. This redundancy could be very valuable in a clandestine or hostile operating area.

f. Information Based Subsystems. It is expected that computing speed and memory will continue to expand to provide whatever future capabilities are needed. Capabilities based on computing power and memory may require significant nonrecurring development costs, but should be easy and inexpensive to produce in quantity once the design is validated. Individual vehicles may carry libraries of tactical information to enhance their CAD/CAC process. Vehicles will need CAD/CAC to know when to maneuver to identify a found object. Information based sensor will be more efficient in the long run than current sensors. See the issue paper on information-based functions for minehunting UUVs. [7]

g. Selection of Sensors. To achieve maximum performance for a given size, UUV sensors should extract all possible information from the returning signal. Examples of high performance sonar sensors include synthetic aperture sonar (SAS) and mammal-based sonar technology. Broadband techniques, chirping, and lambda wave analysis are examples of other techniques that might provide higher performance for a given sensor size and power consumption rate. As technological opportunities permit, nonacoustic sensors might provide independent crosschecks to the classification and identification functions. An example would be a chemical sniffer.

h. Selection of Navigation and Guidance. Underwater navigation will continue to provide a challenge, not as much for own navigation as for the ability to relocate minelike objects with other vehicles for neutralization. For maximum simplicity, navigation should rely as much as possible on computing power and, where possible, should also cross-reference multiple sensors. If the submarine community begins mapping the bottom of tactically interesting areas, some form of map reading of bottom maps would provide accuracy independent of external aids. As UUVs search, they may update existing bottom maps or generate their own bottom maps that they can read precisely enough to return to previously searched areas and contacts. Among the information-based navigation techniques that would be useful to minehunting UUVs are bottom map making and reading, integrated tactical data sharing among fixed and mobile nodes, calibration techniques for known markers, and multi-source navigation to improve accuracy, precision, navigation management, and localization of minelike contacts. A separate paper on information-based UUV functions [7] provides more detail.

6. Delivery Systems. The major advantage of the Minimalist Minehunting UUV concept is that the vehicles are affordable and easily handled, opening the door for tactical innovation in their application. This paper will describe some air, surface, and subsurface means of delivering meaningful numbers of small UUVs to the search area. The delivery means discussed below are not intended to be exhaustive. Subsurface delivery is addressed first, as being the most difficult to implement and the method most desired when the operation requires covertness.

a. Subsurface Delivery. Using the Remus/power pack approach to UUV mine search, [1] it will be necessary, when the search area is remote, to deliver a power pack of some sort to the vicinity of the area being searched. A straightforward and non-intrusive means of delivering the power package would be to design a transport vehicle that would be compatible with submarine handling gear and could carry multiple small UUVs. The transport vehicle would be released from the deckhouse of a submarine using divers (if necessary), and would navigate as an unmanned and autonomous vehicle to a predetermined location near the search area. The transport vehicle should be designed to be compatible with the handling equipment already available to support SDVs. It will be referred to as the 54" transport vehicle.

(1) Characteristics. A 54" transport and recharging vehicle could be designed with the following characteristics:

(a) Unmanned
(b) Large power source (rack of batteries) held internally
(c) Retractable/extendable antennas for external communications and GPS fixing
(d) Storage and docking gear for multiple (eight) search UUVs 7.5 inches in diameter
(e) Ahead-looking obstacle avoidance sonar plus other guidance and control features as needed.

See attached schematic for configuration.

(2) Employment. As an example of possible employment, the 54" transport vehicle would drive to a pre-determined location, discharge its minehunting UUVs, extend its antenna, and report: (1) GPS location, (2) engineering status, and (3) number and status of UUVs successfully launched. The UUVs would proceed to search their assigned areas and return on a staggered schedule to dock and provide their detection, classification, localization, and identification data to the 54" vehicle while recharging. After recharging its batteries, each small UUV would resume searching as programmed. (While the 54" vehicle would normally anchor to the bottom to conserve energy, it could be programmed or commanded to move to different locations for better employment of the small vehicles. In some scenarios, it might be directed to drop off vehicles at different locations and to come back at pre-set times to recover them. The operators would develop tactical options, which would be virtually unlimited.) The 54" vehicle would report to the operational commander at a predetermined time (or as otherwise programmed), using the extendable antenna to transmit the identification and localization data for all minelike contacts found. The operational planning staff would use the identification data to plan transit routes, plan the neutralization phase of minehunting, and to re-task individual UUVs to search areas of interest in greater detail. The mine identification decisions (moored mine, bottom mine, 55-gallon drum, etc.) would be fed back to the 54" transport vehicle, which would update the CAD/CAC settings for all minehunting UUVs as they returned for recharging.

(3) Docking Mechanism. The basic design for the docking mechanisms would be based on the Remus experience, which uses a conical drogue type dock for the UUV to drive directly into. A pinger transponder system is used for the vehicle to home on the dock. [6] After the vehicle has driven into the cone, it is captured by the dock and pulled snugly into the 54" transport vehicle for recharging and data transfer. The current Remus dock is static and designed for peacetime use. To optimize vehicle space, it is proposed that the 54" vehicle use similar docks that can deploy and retract as necessary. The stowage unit for each vehicle would be a cylinder of the minimum diameter to store, launch, and retrieve a 7.5-inch vehicle reliably. It is assumed for conceptual purposes that the internal tube would be 14 inches in diameter and 72 inches long. (The minehunting Remus tested at Coronado in August 1998 was 70 inches long, but the length can be modified to accommodate mission payload.) This cylinder would be constructed to slide within a slightly larger cylinder of about 16-inch diameter and 75 inches in length. During transport and recharging, the inner cylinder would be retracted completely into the larger cylinder. During launch, the smaller tube would be pushed outward, allowing the specially constructed inner cylinder to blossom into a docking cone at the exposed end. A spring would eject the vehicle from the inner cylinder and the vehicle motor would activate the propeller in reverse to complete the extraction. After the vehicle clears, the inner cylinder would retract again, pulling the flexible cone in with it. Thus the cone would not stay outside the 54" transport vehicle to obstruct other launches and retrievals. When the vehicle returned from its search mission, the inner cylinder would move outward, deploying the cone to capture the vehicle. A pinging

transponder system would guide the vehicle into the cone, where it would be captured and pulled inside the 54" vehicle for charging and data transfer. (It might be advantageous to use neural networking techniques or evolutionary programming to train the vehicles to perform the docking task.) The cycle would be repeated as needed for mission accomplishment. This type of deployment and capture will be referred to as the "tube worm" docking design. With each minehunting vehicle having a storage tube and docking mechanism, redundant capabilities can be programmed. If one docking mechanism fails, a returning vehicle can be assigned another empty tube, and so forth. Various queuing schemes can be devised to optimize reliability among the vehicle system and docking subsystems. See the attached schematic for a tubeworm dock in the deployed position.

(4) Recovery of the Transport Vehicle. When the search mission is complete or the battery power is nearly exhausted, the power package would capture and retain the UUVs as they returned. After the last UUV has been captured, the power package would return to the rendezvous point, where divers would help stow it in the SDV shelter. (Minehunting UUVs that could not be captured would be left behind or directed to a predetermined rendezvous point.) Acoustic and other secondary data would be extracted from the 54" transport vehicle and archived for the route survey and bottom-mapping database. For redundancy purposes, the system should be designed to share all identification data with all the minehunting vehicles in the system. This way, so long as a single small vehicle or the transport vehicle was recovered, all data collected and reported to the 54" vehicle would be recovered.

b. Air Delivery. Still considering the 7.5 inch vehicle as the standard component of a universal delivery system, two primary air delivery schemes should be considered: laying individual vehicles and laying pods of vehicles.

(1) Individually Laid Vehicles. 7.5-inch vehicles could be laid from most standard aircraft and helicopters. An engineering trade-off study should determine whether retardation fins or parachutes are needed and, since they probably are, what type would be best suited for air laying. The air-laid 7.5-inch vehicles would require the same functionality as those delivered by the 54" transport vehicle with three notable additions:

(a) Communications, Command, and Control. Since individually laid vehicles will not automatically have a power source for recharging and data reporting, some method would be required to enable the vehicles to report their findings back to the operators. One scheme would be to have the vehicles float to the surface at the end of their programmed missions and report like sonobuoys. Another might be for the vehicles to rendezvous at a pre-determined location for recovery and data retrieval (perhaps more covert).

(b) Navigation. In the subsurface case, navigation accuracy would be provided by the 54" transport vehicle, which would take GPS positions with its antenna before reporting to the operators. The small vehicles would require only relative navigation sensors. In the air-laid case, some method would be needed to calibrate the

vehicles' navigation to GPS or other known references. Since GPS receivers are already very small and require low power budgets, equipping all individual UUVs with GPS receivers is probably warranted. Vehicles not recovered by 54" transport vehicles or pods (described below) would be able to fix themselves on the surface so their detection data could be calibrated geodetically.

(c) Recovery. Since the vehicles do not return to a transport vehicle for recharging and eventual recovery, different recovery techniques would be employed. Options include recovery by helicopter, small boat, divers, or whatever vehicle of opportunity is available on scene.

(2) Pod-laid Vehicles. Aircraft or helicopters could lay vehicle pods with functions similar to those provide by the 54" vehicle.

(a) Functions and Employment. Functions provided by the pod should include tubeworm recharging and recapture capability and an extendable antenna for periodic reporting and GPS fixing. The sequence of vehicle deployment, docking for recharging, data downloading, and eventual recapture should be similar to that provided by the 54" transport vehicle.

(b) Recovery. Instead of driving the small vehicles home, the pod would recapture them and retain them until its own recovery, which would be aided by popping a buoy to the surface. The recovery could be made by a number of standard means, such as EOD, salvage vessel, workboat, utility boat, or helicopter. If the pod were laid in hostile waters, the recovery might be delayed for a significant period. For ease of both laying and recovering, it would be prudent to limit the number of vehicles in a single pod.

(c) Pod Design. A three-vehicle pod seems reasonable for initial design and analysis purposes. Since multiple pods could be laid by air, there is less need to have a large number of the small vehicles operating from the same geographic position. I.e., three pods of three vehicles each would provide more tactical search flexibility than a single pod with nine vehicles, and the handling job would be easier. The pods might be cylindrical in shape and moored several feet above the bottom to facilitate the docking function. It might be worth considering single vehicle modules that could be stacked on top of one another so the operators could choose the right number of vehicles for each part of the mission. Pod laying seems to lend itself best to helicopter delivery, although tilt rotorcraft or cargo aircraft like the C-130 could also lay the pods. The pods might also be recovered by helicopter or tilt rotor, probably with the assistance of EOD divers.

(d) Example. Consider a pod constructed of modules. Three types of modules would be needed: (1) a communications module that would fit on top, containing an extendable antenna for communications and GPS fixing and a recovery buoy, (2) one or more vehicle modules, each containing a single small minehunting vehicle in a tube-worm deployment and docking canister, and (3) an anchor module.

The communications module would contain the same functionality as the 54" transport vehicle: communications, navigation, and processing. The vehicle modules could be designed in the shape of a hockey puck, with the tube embedded like a diameter through the puck. The remainder of the puck would contain battery pack for recharging. As additional pucks are stacked on top of one another, each canister would be rotated 120 degrees relative to the one below, so the tubeworm docking mechanisms, when they bloom, would not interfere with one another. This configuration would also prevent a situation where all the vehicles are prevented from docking because the approaches to one side of the pod were blocked by kelp or another obstruction. If the pucks are interconnected, the battery power of all could be used to charge all the vehicles, i.e., if one vehicle fails to return, its residual battery power would not be wasted. This connectivity among the modules would be needed for data sharing, communications with the operators, and other community functions. The bottom module provides an anchor to place the pod at an appropriate height above the bottom for easy deployment and docking of the vehicles. (This may be as simple as attaching a clump to the bottom module.) The anchor may be designed to drop off during the recovery phase. The pod could be designed so that, when the anchor released, the rest of the pod would float to the surface for easy recovery. The attached figure illustrates the modular pod concept. (Note: For reliability and maintenance reasons, a single 3-vehicle pod would probably be a better engineering trade-off than stackable units.)

c. Surface Delivery. Three types of surface delivery follow from the above: individually laid (launched) vehicles, vehicles delivered by 54" vehicle, or pod delivered vehicles.

(1) Individually Launched Vehicles. For surface craft, especially in waters controlled by friendly forces, the launching and recovery of individual vehicles is the most straightforward. If a large ship does not wish to approach too close to the minefield, it can send utility boats (RHIBs, Zeebirds, Captains' gigs, 41-foot SWATH boats) into the search area for the launching and subsequent recovery. Small vessels of opportunity might be employed, especially where Navy ships are not present or are otherwise employed.

(2) Transport Vehicle. When a measure of covertness is desired, the 54" transport vehicle designed for subsurface delivery could be employed from a surface vessel. The surface vessel need not be a combatant. The 54" vehicle might also be a good option when a long standoff is desired for mine safety reasons.

(3) Pod-laid Vehicles. If a pod system were developed for air delivery, the same pods could be used from surface ships with the same characteristics designed in and using the same general schedule of events.

7. Postscript. The list of delivery means described above is not meant to be exhaustive. Since the minehunting UUVs are two-man portable, methods of launch and recovery can be invented, as necessary, to suit the occasion.

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rev b

INFORMATION-BASED FUNCTIONS FOR MINEHUNTING WITH UNMANNED UNDERWATER VEHICLES (UUVs)

1. Purpose. In a series of issue papers on the following topics, numerous information-based functions were mentioned as UUV needs:

- Minimalist Approach to UUV Minehunting,
- Mine Neutralization Using UUVs
- Mine Identification Using UUVs
- Tactically Flexible Minehunting UUVs

Automated data processing continues to evolve under free market forces. Accordingly, it is assumed that computational power will become ever faster, cheaper, smaller, and less power hungry without special investment by DoD. Opportunities for increased speed, complexity, data assimilation, and redundancy are virtually unlimited. This paper compiles information-based functions that minehunting UUVs can expect to perform in the future and describes how they might be employed.

2. Organization. The functions most important to minehunting UUVs fall under these major headings:

- Navigation
- Communications
- Computer Automated Detection, Classification, and Identification (CAD, CAC, CAI)
- Route survey and bottom mapping
- Planning and tactical decision aids
- Autonomous control

3. Navigation. Navigation, as a computationally intensive discipline, was one of the first military functions to become highly automated. Yet major improvements in general navigation have resulted more from improved navigation sensors, such as the Global Positioning System (GPS), than from the ability to compute faster and more precisely. Improvements in underwater navigation lag those in general navigation because underwater vehicles have infrequent access to external sensors. Still, there are significant improvements that could be realized from the amalgamation of multi-source navigation data and inferences from numerous underwater sources. Potential sources of improvement are discussed below.

a. Map Reading. Aircraft use terrain maps to navigate at low altitude, where radio-navigation aids are inaccessible, but the presence of cloud cover is unlikely to obscure ground features. At higher altitudes, radar is used to measure range and bearing from known features like towns and lakes. From the planning standpoint, the map-reading process consists mainly of starting at a known point, calculating dead reckoning (DR) positions near identifiable features, and updating the DR positions to fixes when the known features are observed. As each identifiable feature is observed, the aircraft's position is updated and the process continues. Terrain contours are observed and sometimes followed to assure the navigator that he is in the right area. If routes are to be repeated, then objects not on the historic map can be fixed and

added to the local map to confirm later orientation. The map reading process improves when better estimates of ground speed and drift are available. A major difference between map reading in the air and underwater is that precise and accurate terrain maps are routinely available for air navigation, whereas underwater maps are not nearly so complete or accurate. This deficiency can be mitigated in the future by these techniques:

- Compiling historic maps (contours and identifiable objects) of the ocean bottoms through route survey and bottom mapping with commercial side-scan sonars (the Klein project)
- Enabling UUVs to build local maps as they swim
- Improving DR through better estimates of speed over the bottom and drift, using techniques like those in the PUMA system

b. Integrated Tactical Data Sharing Systems. Some air and surface systems improve tactical navigation through a series of transmissions that share information. Each vehicle transmits its own most probable position and other tactical information at a given time within a continuing transmission cycle. Each vehicle (or node) receives information from the other vehicles on the network and, because it knows when the other vehicles are supposed to transmit, it can calculate the range to each. Within each vehicle, external navigation data can be combined with locally measured data to provide a most probable position (MPP), which updates continuously. Triangulation with other vehicles provides good relative navigation; since one or more of the vehicles will have access to external navigation aids, geodetic accuracy is also provided.

Similar techniques can be employed by UUVs. Integrated Tactical data sharing among UUVs would resemble what the Accelerated Core Initiative (ACI) proposed in the early 1990s. That project advocated the use of underwater modems to transmit continuously among fixed and mobile nodes to build a tactical picture of the underwater environment. Each transmission contained tactical, navigational, and environmental information that would be assimilated in a fashion similar to that of the Integrated Tactical Navigation System (ITNS).

c. Calibration. An obvious way to fix vehicle positions underwater is to drop acoustic responders that the vehicles can interrogate for range. This system has been used in a number of precise underwater systems, including the AN/SSN-2 Precise Integrated Navigation System (PINS), which is the main navigation suite aboard our Surface MCM 1 Class vessels. Drawbacks with transponder systems are that (1) they are relatively large compared to small minehunting UUVs and (2) they require position calibration, which for the traditional case takes search time away from the minehunters. These problems can be mitigated in part by making the responders smaller and requiring responses only when vehicles are in close proximity to them. If the vehicles have good DR capabilities (including map reading) and drop the responders when they are themselves close to the bottom, the network of vehicles can calculate and continually update its own calibration of the responders without taking time out to make calibration maneuvers. Because the vehicle has a good DR position and knows where the marking responders are located relative to itself, the vehicle can refrain from interrogating the responders until it is close enough to receive direct path transmission and response. This technique would serve several purposes:

- It would conserve vehicle power
- It would conserve responder power
- It would fix using direct path ranges, which are more accurate
- The running calibration of the responder positions should be more accurate
- It makes the interrogation less subject to intercept by the enemy in clandestine operations

d. Multi-source Navigation. Minehunting functions require more accuracy and precision than almost any other function performed by the Naval forces. MCM navigation applications are discussed in NWP 3-15.41. [1]

(1) Accuracy. Accuracy is the ability to determine positions relative to an absolute reference. For MCM, the accepted absolute reference is the WPS-84 spheroid as measured by Precision (P-Coded) GPS. Areas searched by UUVs will often be long, narrow channels intended for transit by ships. The ability of a ship to stay within a channel is predicated on accurate knowledge of the channel boundaries. Thus, accuracy is required for UUV minehunting and reporting of its result if the areas hunted are to be used in this fashion, which they will be for amphibious assault operations. (Amphibious approach lanes are only 165 m wide. [2][3]) Accuracy must come from the GPS reference, so some means is needed to calibrate the UUV navigation reference periodically to GPS. NAWCWD has proposed to ONR the development of a Precision Strike Navigator that combines GPS and inertial functions into a circuit that measures about 1.6" on a side. [4] This type of technology would facilitate the GPS calibration process for UUVs.

(2) Precision. Precision is the ability to relocate positions repeatedly, regardless of where the position is said to be on the geodetic reference. Minelike Contact (MILC) positions are normally expressed in degrees, minutes, and decimal minutes of latitude and longitude to at least three places after the decimal. [1] The return to MILC positions for neutralization requires precision navigation. Precision can be provided by a number of underwater sensors and techniques, so long as they do not precess more than a few meters within the mission time.

(3) Navigation Management. Although air navigation was automated early due to its computational intensity, the human has been retained in the system because of the many unforeseeable events that can happen. Domestic flights generally fly without human navigators, but navigators are still required for overseas flights and other missions requiring particularly demanding navigation. Kalman filtering was introduced into navigation systems to calculate weighted averages of navigation inputs and to produce MPPs from measured sensor data. In the case of UUVs, external sensor data can disappear altogether or can be meckoned into showing systematic false positions. For aircraft, the human remains the arbiter of conflicting navigation clues. For autonomous operations with UUVs, a broad-reaching management of all navigation information must evolve to provide a similar crosscheck of navigation data and make high-level system decisions. The implication is that multiple sensor sources will be needed to enable UUVs to navigate successfully under all circumstances. See the section below on Autonomous Controller.

e. MILC Localization. The UUV has a great advantage over other minehunting platforms in its ability to approach MILCs very closely. Not only does the close approach enable the use of sensors that are useless at longer ranges, it enables precise localization of the objects classified as minelike. For example, when the UUV detects an object with its side-scan sonar and classifies it as minelike, it can make a 180-degree turn in the direction of the object (or similar procedure turn) and pass over the object for identification. An ahead-looking sensor may be needed to assure the vehicle passes directly over the object, but by passing directly over, the vehicle can record a very precise position of the object within the relative navigation framework. Also, it provides an opportunity for the vehicle to drop a small marker near the object as it passes over. After the object has been identified, the vehicle turns another 180 degrees in the same direction (racetrack style) and resumes searching on the original track. Another detection of the object is made as the UUV passes abeam the object for the second time. Now the vehicle has three separate positions on the same object with one being taken directly over the object. It has also

measured the position of the marker on the bottom near the object and reports the relative positions of marker and object to facilitate relocation for neutralization. This technique is similar to the blow-as-you-go technique used by SMCM platforms to clear as they search, but in the UUV's case, it is ID-as-you-go. It should be noted that other approaches can be used, such as bumper pool, but the ID-as-you-go approach provides optical pictures of the object early in the process and the operators badly need this kind of information. Exercises with manned systems indicate that it is wise to start the identification process as early as possible in the minehunting process because of the feedback it provides and because equipment failure and weather may preclude its later collection. Similarly, it is considered wise to collect identification as early as possible in the UUV minehunting operations too.

4. Communications. The specific communications fields used for UUV minehunting will depend on the objectives of the mission. The data that are critical to the MCM Commander and other operators are these:

- Precise and accurate MILC positions
- Optical or other identification level pictures of individual MILCs
- Tracks searched

With the above information, the MCM Commander can evaluate search operations and make virtually all his tactical decisions. Other information, while useful, is not critical to the tactical process. The MCM Commander must be able to re-task his assets as the tactical situation warrants.

a. Acoustic Communications. As described above, the ACI project proposed adding acoustic modems to fixed and mobile nodes to exchange information continuously. Data passed would have navigational, environmental, and tactical content, although the tactical data would normally be modest for power conservation reasons. Track status and MILC positions could be passed this way routinely, but optical data files are much larger and probably would not be passed acoustically unless specifically requested by the operators.

b. Dump to Node. For the small vehicles that are expected to dock periodically to recharge, the dock provides a good facility to dump all information of tactical value. The node contains the power supply and can be designed to hold a large amount of data. As a minimum, the vehicle should dump to the fixed node the tracks searched, positions of minelike and non-minelike contacts, optical or ID data on contacts classified as minelike, acoustic search snippets on those same objects (to glean acoustic attributes of mines and nonmines for CAD/CAC update), environmental data, and status of systems.

c. Data Distribution. If the UUV search system contains a recharging node, the node should function as the central repository for tactical data among small UUVs. Because it is not power limited like the small UUVs it services, it should also serve as a communications hub for reporting to the operators. If the node is submerged (the usual case), it could report periodically by popping a buoy to the surface and transmitting tactical data from all the vehicles assigned to it. The data transmitted to the MCM Commander should include precise and accurate MILC positions, optical and/or other ID information on those objects, acoustic snippets for the same objects, and the tracks searched and system status for each vehicle. It should receive from the MCM Commander tasking assignments for itself and its vehicles and should pass the re-tasking instructions to the vehicles as they dock. As a matter of redundancy, the fixed node should dump to each vehicle the critical tactical data from all other vehicles. This would enable the operators to learn virtually all the information about the operation by recovering a single vehicle or the

fixed node. Other than the snippets of the MILCs, acoustic search data collected by the vehicles is not of immediate interest to the MCM Commander, but would be useful for later bottom mapping or reconstruction of the operation. Because it is not of immediate interest, it should either be kept within the individual vehicles or dumped to the fixed node, if that dumping can be accomplished without interfering with other tactical functions.

5. Computer Automated Hunting.

a. Sensing. Minehunting UUVs will use acoustic, optical, and other sensors to detect mines and to discriminate between mines and non-mines. Because of increased processing power in the future, any sensing functions that can be enhanced by processing should be stressed in the design of future systems. Among the options are use of synthetic aperture sonar (SAS), fusion of sensors at the raw sensor data level, use of diverse sensors to key one other, and correlation of sensor data over time to build three dimensional images. Early minehunting sonars employed only the time and amplitude of single frequency signals to build an image. Current sonars employ broadband techniques, synthetic aperture sonar (SAS) techniques, and other clues in the returning signal to infer more about the object being insonified. There is still information in the signals that is not being exploited, and an effort should be made to glean as much information as possible from all the sensor sources to contribute to the composite picture.

b. Detection and Classification Decisions. CAD/CAC software aboard the individual vehicles would be used to decide which objects require classification. Since the process is "automated," as opposed to merely "aided," as it is aboard ship, its threshold affects mission time and thoroughness. For UUVs, CAD and CAC can be considered two stages of a single function because the computer performs both in rapid succession without human intervention. The CAD determines which objects will be submitted to classification, and as long as the vehicle has adequate processing capacity, a low detection threshold has no bearing on the mission outcome. For maximum detection probability, the CAD threshold should be adjusted to provide as many objects for classification as the CAC routine can handle. The CAC result determines when the vehicle will maneuver to identify objects. The identification maneuver is time consuming and large blocks of data must be transmitted to the operators for each identified object. Accordingly, if the CAC routine is overly sensitive, the vehicle will make numerous racetrack turns and collect optical data on virtually every object on the bottom. If either the CAD or CAC threshold is too coarse, mines will be missed and the search level will suffer. Because every minehunting environment is different, it is anticipated that no single sensitivity setting will be near optimum for the general case. Human identification will be required, at least for the first few generations of minehunting UUVs, to provide the confirmation feedback necessary to adjust CAD/CAC sensitivity.

c. The Feedback Process. When the operators recover individual UUVs, they would immediately retrieve the optical MILC data for viewing. Likewise, when optical snippets are transmitted to the operators by fixed recharging nodes, the first order of business should be to view the snippets and judge which contacts are mines. Assuming optical conditions are sufficient to provide positive identification of each minelike contact, the operators would enter the codes for each identified object (cylindrical mine, Rockan, 55 gallon drum, etc.) into the display system, which will relayed that information back to the CAC routines to calibrate them in the local environment. A standardized set of criteria for CAC and mine attributes will facilitate the use of minehunting information among system types. If mine attributes are scored, as opposed to generating total scores for MILCs, the mission level hunting system can adjust more readily based on the types of mines and nonmines being found in the operation. Neural networking and other learning techniques lend themselves well to the feedback process.

d. Data Fusion. Current minehunting is conducted under "oring" assumptions. I.e., if System A or System B or System C classifies an object as minelike, the object is treated as a potential mine regardless of what the other sensors report. Because the ability to detect and classify objects usually exceeds the resources to identify and neutralize them, future search operations will attempt to apply data fusion techniques (typically "anding," "averaging," "averaging of attributes," "two out of three," etc.) to provide better discrimination during the search phase of the operation. See the Cooperative Organic Mine Defense (COMID) Warfighter Payoff Analysis report for a discussion of data fusion for MILC discrimination and simulation results. [5] With better discrimination between mines and nonmines in the acoustic search process, utilization of time-consuming identification and limited neutralization inventories can be improved. Some data fusion techniques can be applied at the vehicle level to improve CAC. [6] Potentially, data fusion can be applied at the node level to minimize the number of optical pictures that require transmission and to provide feedback to the CAD/CAC process autonomously. However, the first few generations of systems will likely require human intervention and inter-system fusion techniques will most likely be applied at the MCM Commander's level. For data fusion to be effective, it will be necessary to know what the same mine types and nonmine types look like to the different sensors employed in the same environment and in roughly the same time frame. (The Cooperative Organic Mine Defense (COMID) program, which is researching data fusion techniques, refers to these comparative data sets as "coherent" data sets.) The implication is that some overlapping of search and identification data will be needed in the early stages of an operation to adjust the algorithm thresholds, find the optimum fusion techniques, and adjust the search plan accordingly.

e. Future Identification. Computer Aided (or Automated) Identification (CAI) does not exist, and it is unlikely that operators will accept CAI until CAD and CAC have proven their effectiveness. However, it is important to note that the close proximity of the UUV to the object provides opportunities that are not available with longer-range sensor systems. The close proximity provides an opportunity to view the object with new sensing methods, such as detection of RF frequencies emanating from the object. The close proximity enables the object to be seen in three dimensions (acoustically, optically, and perhaps with other sensors) for comparison to preprogrammed templates of potential threat mines. Multi-aspect and multi-altitude sensing can also contribute to the image. The racetrack pattern can be modified to slow the UUV down over the object in order to collect more data for the image. Techniques like ping-to-ping and sensor-to-sensor correlation can be applied. If bottom maps of the area exist, old data can be subtracted from the new images to highlight changes. Operators will want to view the images themselves before unleashing autonomous explosive charges for neutralization, but CAI may be employed to alert the operators to contacts of very high interest early in the search process.

f. Future Neutralization. Mine neutralization is difficult to apply with manned or remotely controlled systems and becomes extremely difficult with autonomous systems within the constraints that the operators are likely to set. Consider the desired characteristics of UUV neutralization systems: unmanned; cheap; reliable; insensitive; easily stored, transported, and handled; applicable to a range of operations; effective against a variety of mine types; able to confirm that neutralization has or has not been achieved; effective in different environments, including the burial environment; and capable of delayed detonation or undetectable neutralization to preserve the clandestine requirement of certain operations. Most of these desired characteristics could be enhanced by information-based technologies. For example, cheapness, reliability, effectiveness against a variety of mine types, effectiveness in different environments, and ability to confirm neutralization are all highly dependent on processing. The operators will

accept some imperfections with most of the characteristics, but they are likely to insist on a reliable ability to confirm neutralization status before accepting any UUV neutralization system. Accordingly, the confirmation function should be considered a minimum requirement and perhaps the hardest requirement for any UUV neutralization concept to satisfy.

6. Route Survey and Bottom Mapping. Route survey and bottom mapping are widely recognized uses of information-based technology to improve minehunting performance. An effective route survey system has three main components:

1. A good sensor for detecting and classifying mine sized objects
2. Precise and accurate navigation
3. Automated route survey data management

Route survey was applied at the individual minelike contact level during the 1980s, but the data was of questionable value because the system was incomplete. The sensor (AN/SQQ-14) was adequate, but reliable navigation and data management functions were missing. Classic route survey attempts to correlate new contact positions with an existing database of contacts to detect changes. The main aim is to provide data that could speed up a minehunting operation by confirming that certain contacts were previously on the seabed and therefore do not require time-consuming prosecution. Recent efforts have been devoted to mapping the entire bottom and not just to compiling MILC positions. For example, in exercises FOAL EAGLE 99 and RIMPAC EAST 00 minelike contacts were confirmed from data provided by previous exercises. The key difference between these and earlier attempts was that the data was in the form of acoustic bottom maps and not just MILC positions. These are some of the advantages of imaging the whole bottom:

- If the bottom is searched with a side-scan or ahead-looking sonar and recorded on electronic media, it can provide a relatively complete ground truth for subsequent operations, including exercises and detection/classification of false contacts in those exercises. Ground truth has been missing in the Navy's ability to calculate false alarm probabilities and to assess how well its sonars have performed. Without the ground truth, it is possible to calculate false contact rate or false alarm density, but not the false alarm probability, which is an input parameters for minehunting models to calculate time required. Also, Non-Mine Bottom Object (NOMBO) density (of the pre-classified variety), another input to planning calculations, cannot be assessed without ground truth.

- Once the proper algorithms are developed, side scan traces can be automatically merged (fused) to provide improved maps. The process will require continual re-confirmation of registration and relocation of the same minelike contacts. Anything that does not match up as expected will constitute a change. This is different from the registration of minelike contacts on paper, where registration and relocation of MILCs is based on the positions of the MILCs themselves. When MILC positions alone are being used for registration and a MILC position is a little off, it is not clear why:

  - Wrong contact?
  - Contact has migrated?
  - Navigation/localization is off?
  - Sensor is off?
  - New Contact - old contact has disappeared

The bottom mapping information around the contacts provides confidence that object registrations are correct and helps explain what is occurring: contact migration, systematic navigation error, range and bearing problems, different contact entirely, etc.

- Systems that rely on operator interpretation of sensor data will always provide sparse and disparate maps of the bottom. No two operators use exactly the same set of criteria to classify objects as minelike. CAD/CAC and bottom mapping routines have the potential to provide much more consistent results.

- The recurring use of bottom maps will confirm the accuracy and precision of MILC positions as measured and calculated by the sensor systems. I.e., if the same object is measured in the same position when two passes are made from opposite directions with the same sensor, those measurements provide a measure of confirmation that the algorithms used to calculate the position are working correctly. If the same position is calculated when the object is located with two different sensors, it helps confirm that both sets of algorithms are working properly. If the two positions (for a known same object) do not match up well with a bottom map, the surrounding bottom features help explain the nature of the error so corrections can be made. If the two positions do not match up with a paper plot of only MILC positions, there could be many reasons why and little insight is gained.

- More than one OPNAV sponsor is interested in bottom mapping. Early coordination of efforts can benefit the Navy at large.

- The operational benefit of route survey (battlespace preparation of the bottom) lies primarily in the speed of minehunting. Historically, MCM planners have used as planning inputs an hour to prosecute every mine and half an hour to prosecute every misclassified nonmine. But there is more to consider. These planning values assume that the time to prosecute (i.e., to identify and neutralize if necessary) is constant, regardless of how many objects require prosecution. In reality, the Navy's ability to detect and classify objects has exceeded its ability to prosecute objects called minelike. For example, an MCM EOD team has a practical limit on how many dives it can make in a day, based on water depth, temperature, and other factors. [7] In exercises, the Navy seldom prosecutes more than about 30 percent of the reported MILCs. If all MILCs are equally likely to be mines, the operation can expect to clear no more than 30 percent of the mines. The best chance of accelerating the minehunting clearance process would be to inject a discrimination factor among the MILCs and to prosecute the most minelike of the MILCs first. Data fusion techniques can help do this. [5]

7. Planning and Tactical Decision Aids. Conventional MCM operations are planned with average values of minehunting performance parameters to calculate the track separation that corresponds to the desired search or clearance level. Once initiated, the plan is executed as planned. For UUVs, some sophisticated maneuvering and autonomous planning will be needed. Some examples of future decision aids are discussed below.

a. Adjusting Search Technique. The search plan is seldom changed significantly, mainly because there is little feedback that would justify the change. (It is noted that detection and classification probabilities cannot be reliably calculated. The values in the NWPs are based on empirical data. Sonar calculations do not provide the same results - the calculated values always being optimistic compared to field data. [5, Appendix G]) Environmentals collected by UUVs might improve estimates of performance by optimizing the UUV body depth and altitude, tilt angles, and detailed tactics that do not apply to more conventional hunting systems. To keep from interfering with the search process, it would be best to collect the needed environmental data

through the sensor, whenever possible. Among the environmental parameters that the COMID project identified as candidates for through-the-sensor collection are:

- Sound Velocity Provide (SVP)
- Reverberation (mainly bottom, but also surface and volume)
- Bathymetry

An example of through-the-sensor data that could enhance performance would be the mean sound speed measured near the bottom where the UUV is working. When the UUV makes its racetrack pattern to identify a MILC, it can calculate mean sound speed from the comparison of the contact's position as observed from the search track and from directly above it and can use this new value to adjust the positions of future detections. As this process is repeated, the measured sound speeds can be combined to provide the best overall result.

b. Pattern Recognition. Mines are often laid in patterns. If line-likeness and other clues are used to highlight the objects that appear to conform to standard minelaying practices, these and other discriminants can be used to alert operators to objects that are more likely to be mines. UUVs having identification capability can confirm or refute the mine pattern hypothesis.

c. Dynamic Planning for Avoidance. MILC information provided by UUVs can be used in the future to enable ships to traverse potentially mined areas by avoiding all minelike contacts found there. For areas with sparse NOMBO fields, this could be easily accomplished by turning away from all objects in the ship's path. For dense NOMBO fields, there may be no path through the area completely clear of mines. A worse case might be an apparent path that the ship takes to avoid known contacts only to detect new contacts in the way. In this case, the ship may be led into an untenable situation where both advance and turning around are blocked by MILCs. There are dynamic programming routines that can calculate optimal paths to the destination. These routines might be modified to optimize UUV search to enhance the probability of the ship's success when the ship is known to use dynamic planning for avoidance.

d. Search Maneuvers. Because of currents and varying distances of MILCs from the search track, a UUV would make an approximate racetrack pattern to go over an object, but the actual pattern might be closer to a Williamson turn or a circle. When a MILC identification is missed on the first fly-by, the resulting pattern to identify it might wind up looking more like a cloverleaf. Also because of optical conditions, the altitude for identification might not be the same as that for search, so altitude changes may be part of the maneuvering strategy. Detected obstructions in the area might make some maneuvers unsafe for the vehicle. For these reasons, a robust control algorithm is needed to steer all maneuvers safely and effectively. Such routines have been developed for UUV operations in rough bottom topography.

e. Reacquisition Maneuvers. Small UUVs will have relatively small detection widths and ranges. Expendable neutralization UUVs will likely have even smaller detection widths and ranges because the vehicle's systems are intended for a single use. If there is information about the mine's position, other bottom features in its vicinity, and localization markers near the mine, dynamic planning can be used to point the transducers to the optimum location for reacquisition and neutralization.

8. Autonomous Controller. A Navy ship has a navigator who tracks the ship's positions and directs her through safe waters to her intended destination. A ship has an Officer of the Deck (OOD) who guides the ship and is responsible for keeping her clear of traffic and other local dangers. A ship has a Tactical Action Officer (TAO) who controls the weapons systems. Higher-

level mission decisions and other issues of ship safety are directed by the Captain and executed by his Executive Officer (XO). Similar functions must reside within a small UUV, which will be tasked to follow a search plan, but must make autonomous decisions for its own safety and to execute the plan in a difficult environment. An autonomous controller should contain the higher level rules for when to do each of the above functions. Among the responsibilities of the Autonomous Controller would be:

- Implementing rules for guidance and control
- Detection of dangerous situations and execution of corrective action
- Controlling the precedence for the following functions:
  - Navigation and diversion from planned routes
  - Maneuvering for identification
  - Marking contacts
  - Replanning based on sensor data
  - Reporting identification snippets and other information
  - Returning to host or fixed node for charging and/or reporting
  - Initiating emergency procedures (and which procedures)
- Receiving and implementing tasking instructions

9. Conclusion and Recommendation. The amount of processing currently employed by minehunting systems is nominal compared to what could be done. On the assumption that processing capability will become more and more affordable, it is recommended that emphasis be placed on information-based technologies that could enhance UUV performance without significantly affecting the vehicle's size and endurance.

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FUTURE MINE COUNTERMEASURES STUDY

COST AND AFFORDABILITY APPENDIX

William M. Kroshl

Katherine A. Sullivan

24 January 2001

Joint Warfare Analysis Department

Johns Hopkins Applied Physics Laboratory

Laurel, Maryland 20723

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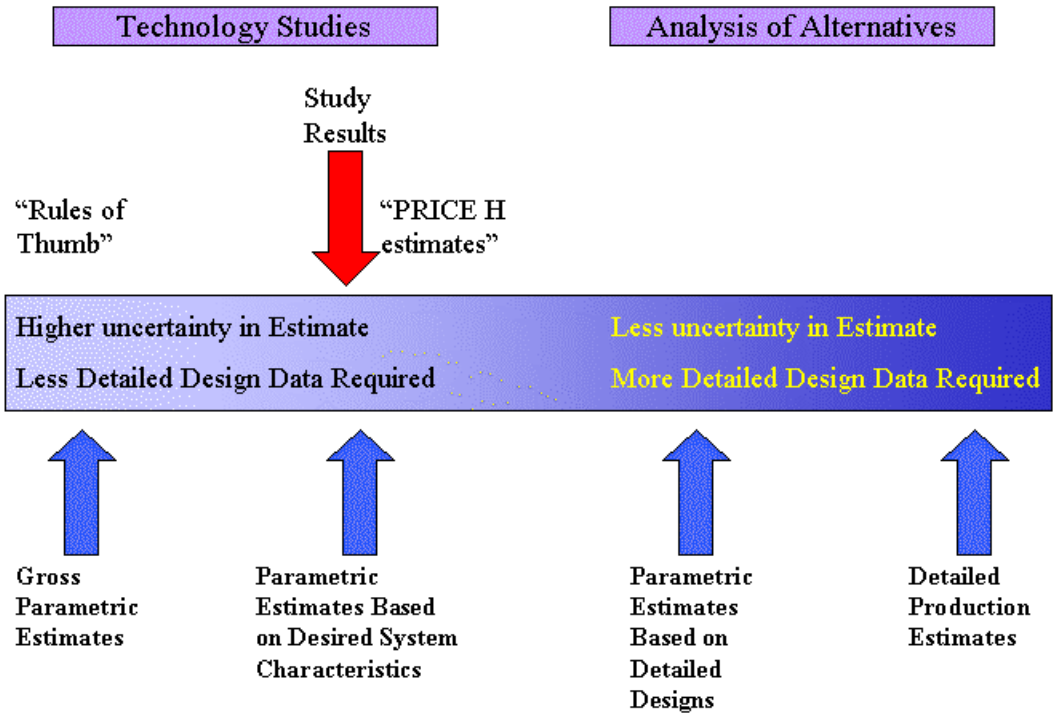
- Cost Estimating “Rules of Thumb”

Overview

The goal of the affordability and cost estimating effort in this study was to compare the costs of various "systems of systems" engaged in completing the MCM mission in several distinct tactical scenarios. Cost and performance estimates were combined to identify configurations that showed the greatest promise. These scenarios were sufficiently developed to allow the generation of meaningful MOE's relating to mine detection and clearance. Depth, bottom type, clutter density, and other such parameters were specified within the scenario. These scenarios were not placed within a larger operational or strategic framework. There was no information available to allow the examination of trade offs in resource allocation between MCM missions and other missions, or between several different sequential MCM missions.

There is a continuum of cost estimating and affordability analysis ranging from very conceptual studies to detailed engineering estimates in bids and proposals. The current study is a very conceptual study with some limited engineering data available, as illustrated below:



All systems were conceptual, based upon engineering judgments of the appropriate levels of technology and performance for systems fully operational in

2015. We did not assume any technology leaps or other breakthroughs in science and technology. We used nominal values for labor, material and design costs. We did not assume any specific efforts at low cost manufacturing or low cost design.

We developed a conceptual Work Breakdown Structure (WBS) for the UUV's and developed costs for a variety of components: Ahead Looking Sonar's (ALS), UUV Bodies, Navigation Systems, and so forth. Costs for these components were estimated from a variety of sources, including commercial prices, engineering estimates, and parametric models using PRICE H software. Our estimates for production and R&D costs for all UUV's are included in the study.

We recognize that a complete study would have included many other items such as storage and shipping containers, recharging racks, software development, and launch/recovery gear. These costs are not included in the study. We chose to focus on the costs of the UUV itself and not on the ancillary equipment needed for full system operation. Had this been an Analysis of Alternatives then we would have needed to include these items (and many others) to ensure an honest comparison between the systems. However, our focus was on the UUV technology itself. We saw little value added for ancillary system estimates for systems in such an early conceptual stage. These estimates are best left to a future study that is more narrowly focused on system comparisons.

Some of the systems required non organic support from other platforms or systems. For example, the Type III (small UUV only) systems required some host platform to deliver them to position. Candidate platforms included Maritime Patrol Aircraft (P3), heavy bombers (B52), and surface ships. These platforms are neither dedicated MCM/UUV platforms nor would they be specifically procured for the MCM mission. For existing systems the procurement cost is a "sunk cost": already expended. Adding a fraction of this expense is meaningless when considering alternative new procurements. The real cost of using existing systems to support the MCM UUV mission is the time taken away from those support system's other, primary missions such as ASW, maritime surveillance, or strike. These "opportunity costs" should properly be measured in hours expended in support of the secondary (MCM) mission.

We mentioned these opportunity costs by listing the outside support needed for certain systems (some of the Type I systems, and for delivery on certain Type III systems). Without a fully developed operational level scenario to examine the impact of diverting these assets from their primary mission the further development of these costs contributed nothing to the understanding of the systems.

The production costs are divided into two distinct classes: expendable and nonexpendable. This division became important when comparing Type III systems with Type I and II systems. Our CONOPS did not include recovering

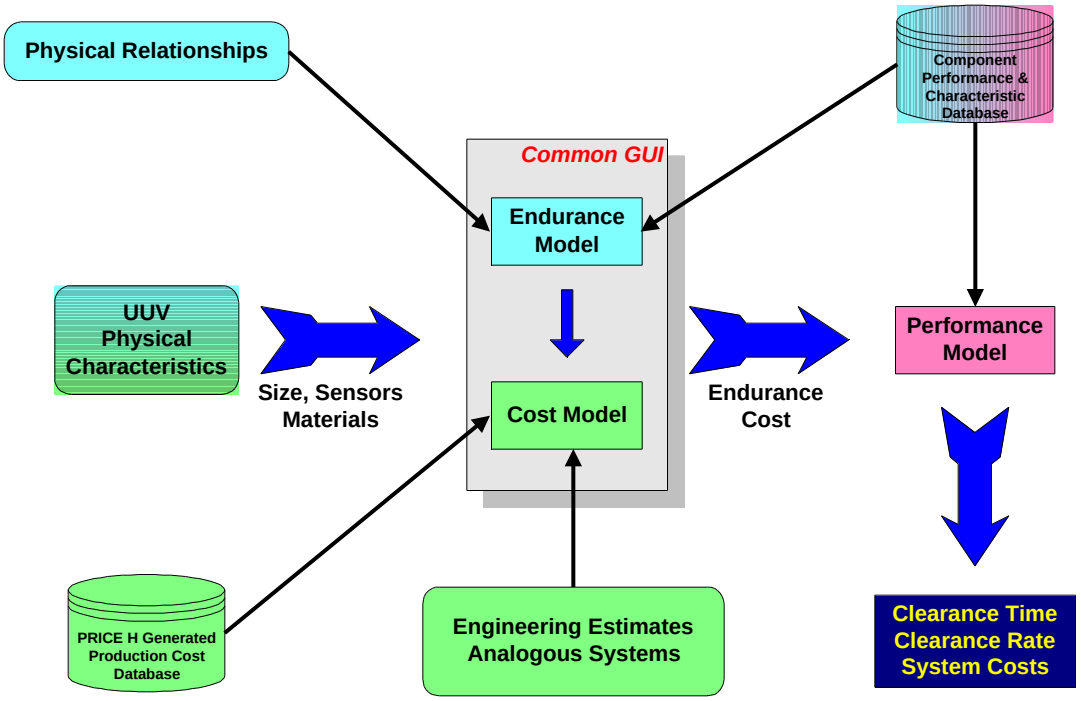
Type I systems. They were equipped with primary batteries for maximum endurance. Neither the UUV nor the battery was recovered. The entire production cost was expended upon one mission.

Some of the Type I and II systems were recoverable. Some of these systems had primary batteries (which were removed after use, discarded and fresh battery packs inserted) and others had secondary batteries that were recharged. Some CONOPS had a second set of rechargeable batteries included with each system. The UUV was recovered, a recharged battery pack installed, and the exhausted battery pack recharged while the UUV was put back in the water to continue its mission.

In order to adequately assess and compare these costs, it is necessary to take a lifecycle approach. Such an approach requires additional parameters and decisions such as system life expectancy, anticipated usage rates (missions per year), and a refurbishment/rework policy. An analysis of this type would allow the difference between single use “disposable” and multi use “reusable” systems to be evaluated. This sort of detailed life cycle planning would be part of a detailed AOA. However, this operational and strategic framework was not available for this study. Rather than make unsupported assumptions in these matters, we chose to report the expendable and reusable component production costs separately, but not to develop the comparison further.

Model Architecture:

The relationship between the various models used in this study are illustrated in this diagram:



Three core models are used in the study: The Endurance Model, the Cost Model, and the Performance Model. The Endurance and Cost models have a common GUI based on Microsoft Excel. The performance model consists of MATLAB code run on a PC. Data analysis of the MATLAB results is done using Excel or other standard data analysis tools. A brief outline of each element in the model architecture follows:

Physical Relationships:

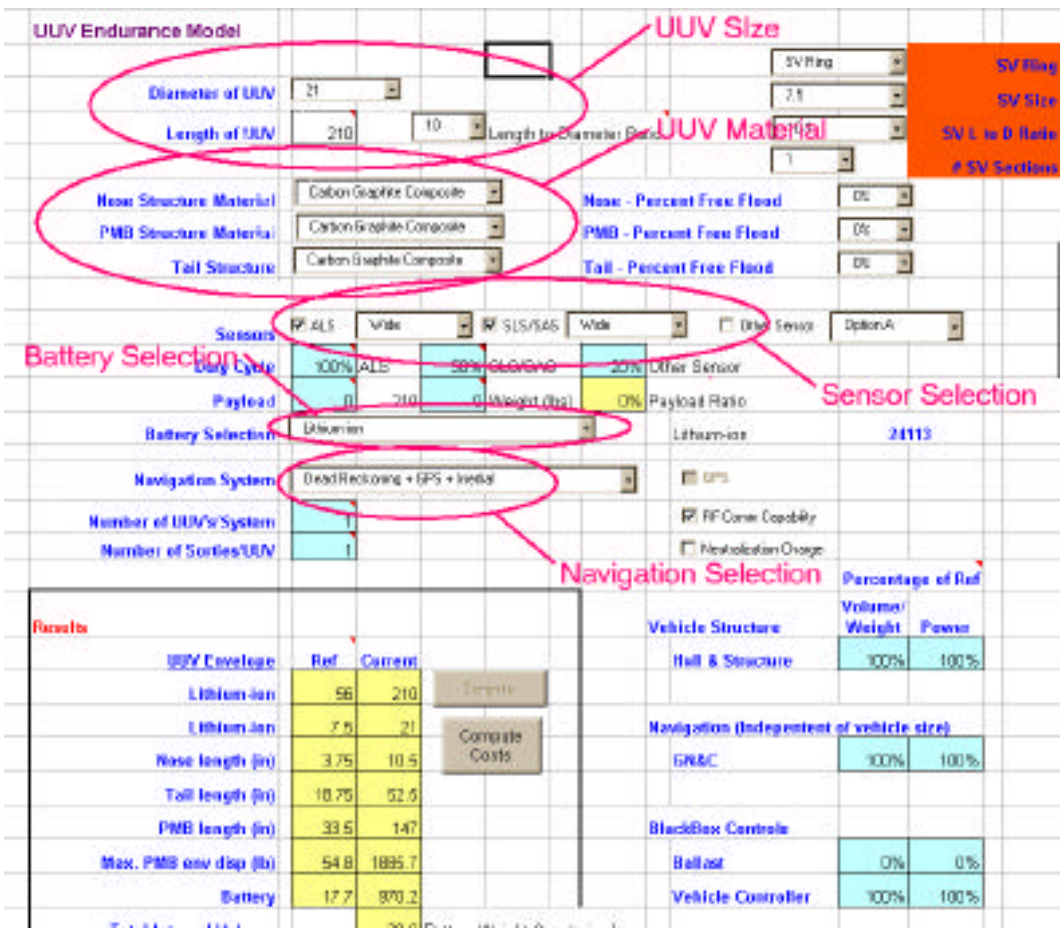
This refers to physics based performance and relationships. Examples of this would include the determination of the weight of UUV (obtained by combining the UUV size with the assumption of neutral buoyancy and the nominal density of water) and power requirements (nonlinear power and speed relationships)

UUV Physical Characteristics:

In order to make this a usable model we limited certain parameters of the UUV to discrete values. Possible diameters are 4.875 inches (Sonobuoy), 7.5 inches (REMUS), 12.75 inches (Light Weight Torpedo), 21 inches (Heavy Torpedo), 36 and 54 inches (based on SDV). We used either an 8:1 or 10:1 length to diameter ratio for all vehicles except the 4.875 inch. We used a 15:1 length to diameter ratio for the 4.875 inch vehicle. We found that length necessary to provide the minimum volume and weight allowance for a battery large enough to provide useful endurance. Other characteristics were the hull material (composite or aluminum), sensor selections (ALS or SAS), payload (markers, other UUV's, or explosive charges) and navigation system options.

Common GUI:

The Cost and Endurances models have a common GUI for entering the physical characteristics of the UUV under consideration. Using the GUI the user specified the design of the UUV by selecting among standard sizes and options that had been selected for the study. Following is a partial screenshot of the GUI:



Databases:

There are two major databases used by models. The cost model uses the cost database and the endurance model uses the performance database. The performance database contains physical characteristics (weight, volume, electrical power requirements, etc), which are used as inputs into the physical relationships that determine UUV properties such as battery capacity and endurance.

The cost database has two major groups. These groups are differentiated by the basis of estimate. One group (batteries and navigation systems, for example) is based upon engineering and subject matter experts' judgments. The other group is based on the PRICE H estimates.

Regardless of the basis of estimate, the cost database contains an estimate for unit production costs and, for many components, R&D costs as well. These estimates are key inputs into the cost model.

Cost Model:

The cost model is a combination of Visual Basic (VB) modules and pages in the Excel workbook. It takes the data defining the UUV (size, diameter, material, and so forth) from the GUI and, using the database, calculates the UUV cost and returns the data to the user via the GUI.

Endurance Model:

The endurance model is a combination of Visual Basic (VB) modules and pages in the Excel workbook. The model is discussed in detail in another appendix. Briefly, the model assumes neutral buoyancy and uses the design mass and volume of the components to determine the volume and mass of the UUV (less the battery). The remaining weight and volume (consistent with neutral buoyancy) are then assigned to the battery. Battery size, power density, and energy requirements then drive the equations in the endurance model, which calculates the endurance at several different speeds.

Performance Model:

This model is not integral to the other models. It consists of MATLAB code running on a PC. A more complete discussion of the performance model is contained in another appendix. It combines the endurance results from the

combined cost/endurance model with the sonar performance parameters contained in the component database as inputs to the MATLAB model.

PRICE H Models

Introduction

The Parametric Review of Information for Costing and Evaluation Hardware Model (PRICE H) is designed to derive cost estimates of mechanical and electrical hardware. It is a commercial software package that uses a system of equations and a database to estimate the cost of development and production of hardware. PRICE H was chosen primarily for its track record with previously estimated vehicles such as LMRS.

The database is composed of information from all types of mechanical and electrical assemblies from previously produced components. This database allows PRICE H to coordinate the complexity and cost of the item to be estimated with a similar item already in the database.

Typically, PRICE H is used to estimate the costs of components from detailed engineering specifics. In the case of the MCM Study, the PRICE H software was utilized to estimate the cost of future technologies.

Models

Instead of creating a model for each possible combination of components in an UUV, models were created of the components such that a user of the Endurance Cost Model could “produce” a unique UUV and find out the cost of such vehicle.

To create the models, the UUV was broken down into the components necessary to produce a vehicle. A PRICE H cost model would then be created for each component at a specific weight and volume. The weight and volume corresponds to the weight and volume of a specific diameter and length combination of UUV. Cost models were created for the following diameter and length combinations:

- 4.875” diameter and 8:1 length ratio,
- 4.875” diameter and 10:1 length ratio,
- 4.875” diameter and 15:1 length ratio,
- 7.5” diameter and 8:1 length ratio,
- 7.5” diameter and 10:1 length ratio,
- 12.75” diameter and 8:1 length ratio,
- 12.75” diameter and 10:1 length ratio,
- 21” diameter and 8:1 length ratio,
- 21” diameter and 10:1 length ratio,
- 54” diameter and 8:1 length ratio, and

- 54” diameter and 10:1 length ratio.

Every component cost model created relates to one of these diameter/length combinations. In terms of components, the following cost models were designed.

- Nose,
- Body,
- Hull,
- ALS Wide,
- ALS Narrow,
- SAS Wide,
- SAS Narrow,
- Propeller/Fins,
- Shafting,
- Servo Motor, and
- Propeller Motor.

In addition to those cost models, simple cost models were also developed for those items that were considered purchased items and not produced by the main manufacturer. These items included:

- Battery,
- Computer, and
- Guidance and Control.

Assumptions

For each of the component models, there were assumptions that were required in order to create the model. Several assumptions were general to any UUV. There were other assumptions that were specific to the type of component cost model being developed. This section will state explicitly any assumptions made and their reasoning in the creation of the PRICE H cost models.

General Assumptions

There were a number of assumptions required from PRICE H that transcended the type and size of the UUV. These assumptions are used in every component model and full UUV model created. The following is a list of these assumptions.

- Platform Complexity for all models was 1.60, which corresponds to Military Unmanned Submersible Vehicles

The platform value was determined upon the PRICE H Platform Value Table and instructions from PRICE H representatives. According to the table and the

representatives reporting on research conducted at PRICE Systems, the 1.60 platform value is the best platform value for unmanned submersible vehicles.

- Development of First Prototype date was January 2002

The date for the development of the First Prototype was determined by backtracking from the 2015 operational date. It was assumed that it would take about 8 years to finalize the design and technology for each component for production.

- Production of First Unit was January 2010

The date for the Production of the First Unit was chosen as January 2010 since it seems reasonable to allow for 5 years of production for the units necessary for deployment in 2015. This is consistent with production runs for other systems.

- Production of Last Unit was January 2015

Since the date of deployment was the year 2015, it was determined to have the last unit finish production in January 2015.

- Integration of Structure considered Normal & Routine (0.50)

When the component cost models are combined to create a complete UUV cost model, Integration of the structure is necessary. The assumption here was there was no information that the integration of the structures would deviate from a Routine interface. Therefore, the Integration of Structure factor was left at Normal & Routine Interface.

- Integration of Electronics considered Normal & Routine (0.50)

As with the Integration of Structure, the Integration of Electronics is a necessary factor when combining the component cost models together. Again, there was no additional information to lead to an interface other than Routine. Hence, the Integration of Electronics factor was also left at the Normal & Routine Interface.

- Engineering Complexity considered Normal (1.00)

The last general assumption was the Engineering Complexity. Since there was no information that concluded the complexity would be more or less than Normal, the factor was left at the PRICE H default of Normal.

In addition to the above assumptions, there were also assumptions on production and prototype development. These assumptions were relative to the diameter of the UUV in the model. The following list states the production unit level or prototype development level with regards to the diameter of the UUV.

- 1000 units produced for UUV's 7" and smaller in diameter,
- 100 units produced for UUV's 12" in diameter,
- 20 units produced for UUV's 21" and larger in diameter,
- 10 Prototypes developed for UUV's 12" and smaller in diameter, and
- 2 Prototypes developed for UUV's 21" and larger in diameter.

The number of units to be produced was varied based on diameter size since the number of UUV's needed for a scenario depended on the diameter of the UUV. The number of prototypes was at 10% of the number of units produced or at 2 whichever was greater.

The last general assumption made in the PRICE H models was to leave any input at the PRICE H default if no other information was available. Examples of these inputs are Labor Cost per Hour, Material Costs, Labor Hours per Month, Overhead, and Escalation Factors. Due to the nature of the study, there was no information regarding potential manufacturers. Hence, any input relating to specific manufacturers, like Labor Cost per Hour, was left at the PRICE H default.

Hull Assumptions

When the component models for the hull of a UUV were created, several assumptions were required by PRICE H in order to generate the estimates. The hull design called for differences in the free-flood capability with relation to the nose, body, or tail. To accurately represent this design element in PRICE H, three separate component models were created for the nose, body, and tail sections at each UUV diameter/length combination.

There were also two materials in consideration for UUV design: Graphite Composite and Aluminum. To capture the material options in PRICE H, two cost component models were created for each nose, body, and tail section for each UUV diameter/length combination. This corresponds to 6 cost component models to represent the entire hull for 1 UUV diameter/length combination.

For each material type, there were some assumptions made for PRICE H. To determine the Structural Complexity (MCPLXS) of a Graphite composite component, the model used the Conceptual Generator provided by PRICE H to calculate the MCPLXS. The Conceptual Generator requires 5 inputs in order to complete the calculation. They are as follows:

- Construction Type,
- Function,
- Weight Range
- Material

- Platform (complexity surrogate)

It was assumed that the Construction Type for each UUV would be Machined. It was also assumed that the Function would be Machined Parts for Support or Containment. Additionally, the Weight Range was selected based on where the Total Weight of the specific hull section for each UUV fell in the ranges provided by PRICE H. The input for Material was Composites since the hull was to be Graphite Composite. The last input required was the Platform value, which, from the General Assumptions, was 1.60.

When the component models for Aluminum hulls were designed, the MCPLS was assumed to be Cast Aluminum, at the 1.60 Platform value, from the MCPLXS Table Values provided by PRICE H. This corresponds to a MCPLXS value of 5.670.

ALS and SAS Assumptions

The design of the cost component models for the ALS and the SAS were assumed to only include the array transducers and mechanical structure. This assumption requires that the electronic component of the ALS and SAS be modeled in the Computer Component. Hence, the cost component model for the ALS and SAS only contained structural/mechanical elements from PRICE H. The weights and volumes for all variants of the SAS and ALS were taken from the Study Workbook.

In order to complete the component model for each ALS and SAS, the structural complexity or MCPLXS, needed to be considered. PRICE H has a MCPLXS table section called Ship Structures that includes an Acoustic Systems complexity value. This MCPLXS value or 6.390 for the 1.60 Platform was assumed to represent both the ALS and SAS arrays.

There were 2 cost component models created for each UUV diameter considered for each the ALS and SAS arrays. One cost component model represented the weight and volume for the ALS or SAS wide array and the other cost component represented the weight and volume for the ALS or SAS narrow array. This method allowed for the creation of 4 cost component models per UUV diameter to represent the ALS Wide, ALS Narrow, SAS Wide, and SAS Narrow arrays.

Propeller, Shafting, and Motor Assumptions

For the components of Shafting, Propellers/Fins, and the requisite motors (Servo and Propeller), several assumptions were made. Each component model considered each Structural/Mechanical elements since there were no electronics involved.

The first assumption relates to the Shafting and the Propellers/Fins. For these two components, the Structural Complexity was taken from the Ship Structures section under the MCPLXS table. Here, the element called Shafting & Propellers was used with a MCPLXS value of 3.36 for the Platform of 1.60.

The second assumption made related to the type of motor used for each the Servo and Propeller motors. It was assumed that each was an Electric Motor and that category in the MCPLXS Table was used generating a MCPLXS value of 5.10.

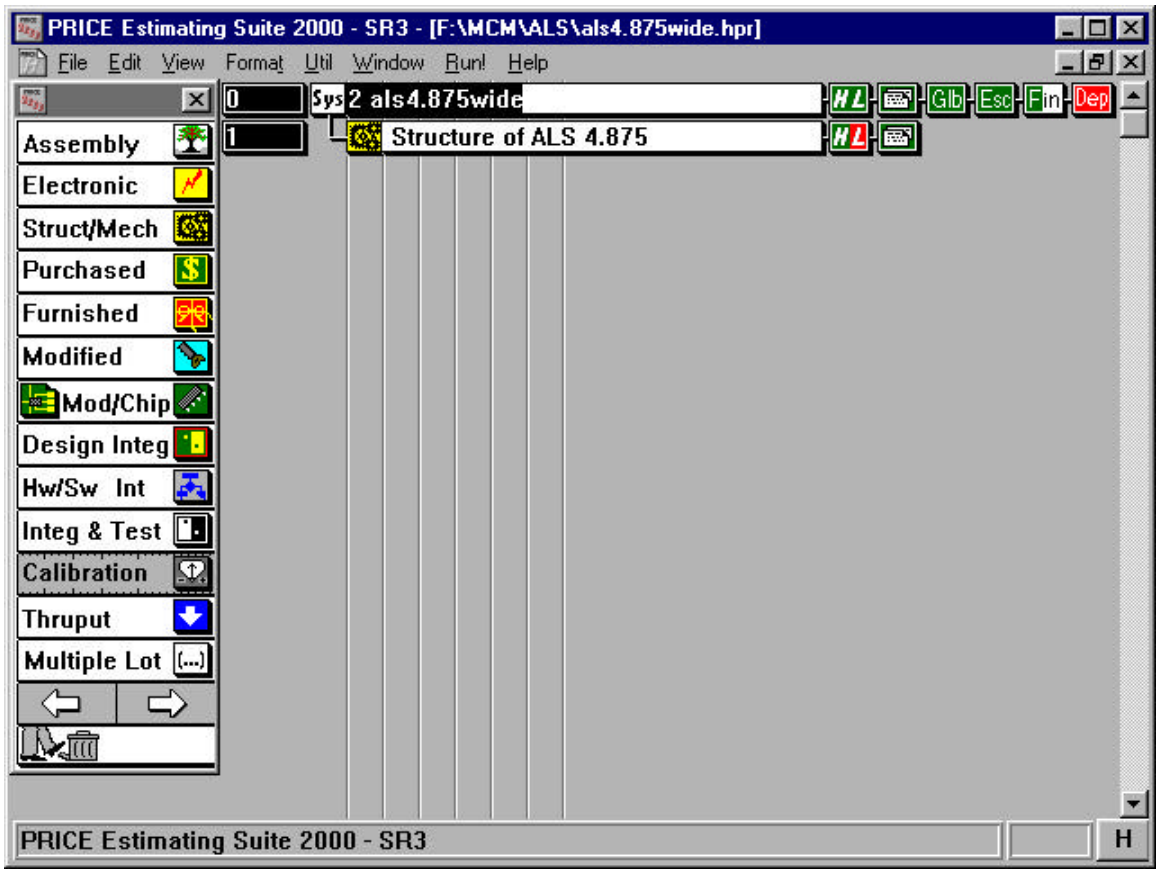
Additionally, in order to validate the Servo Motor and Propeller Motor component models, the Mechanical Reliability factor needed to be determined. Here, PRICE H provides a table to select a value from depending on the RPM of the motor. Information was obtained from SSD that stated the motors would not exceed 1000 RPM. Hence, the PRICE H factor chosen was for Rotary Movement of less than 1000 RPM. This translated into a Mechanical Reliability factor of 1.00 for both the Servo and Propeller motors.

Computer, Guidance & Control, and Battery Assumptions

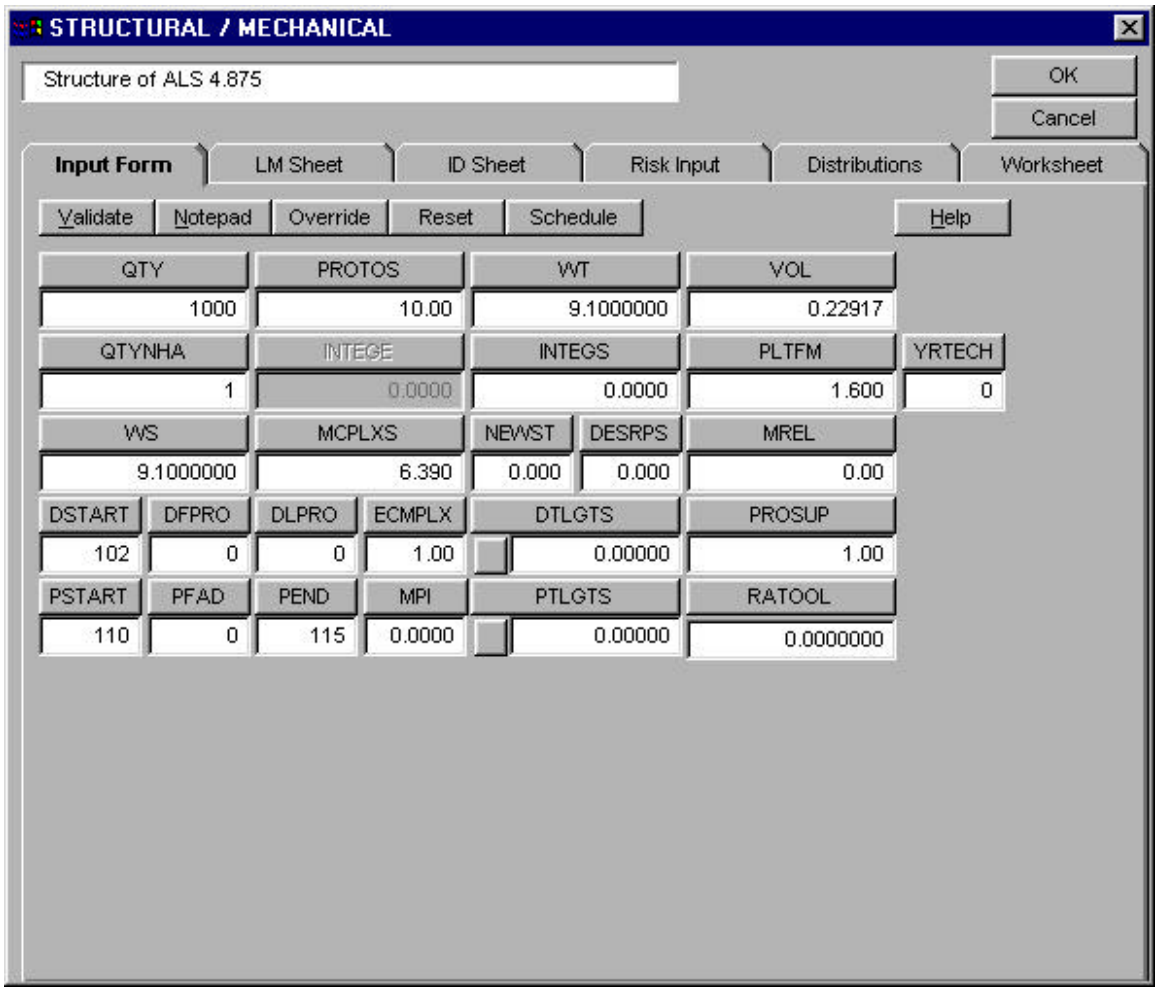
For the Computer, Guidance & Control, and the Battery components of each UUV, it was assumed that these components would be purchased as off-the-shelve items. The PRICE H model accurately represents this through the element Purchased. To properly validate this element, three assumptions were required. The first assumption was that the Year of Technology was set to the year Production Begins – 2010. The second assumption was that the Cost Basis year was also to be the year Production Begins – 2010. The last assumption was the cost was Fixed. Each of these components and assumptions were utilized in any Full UUV model developed.

Model Development

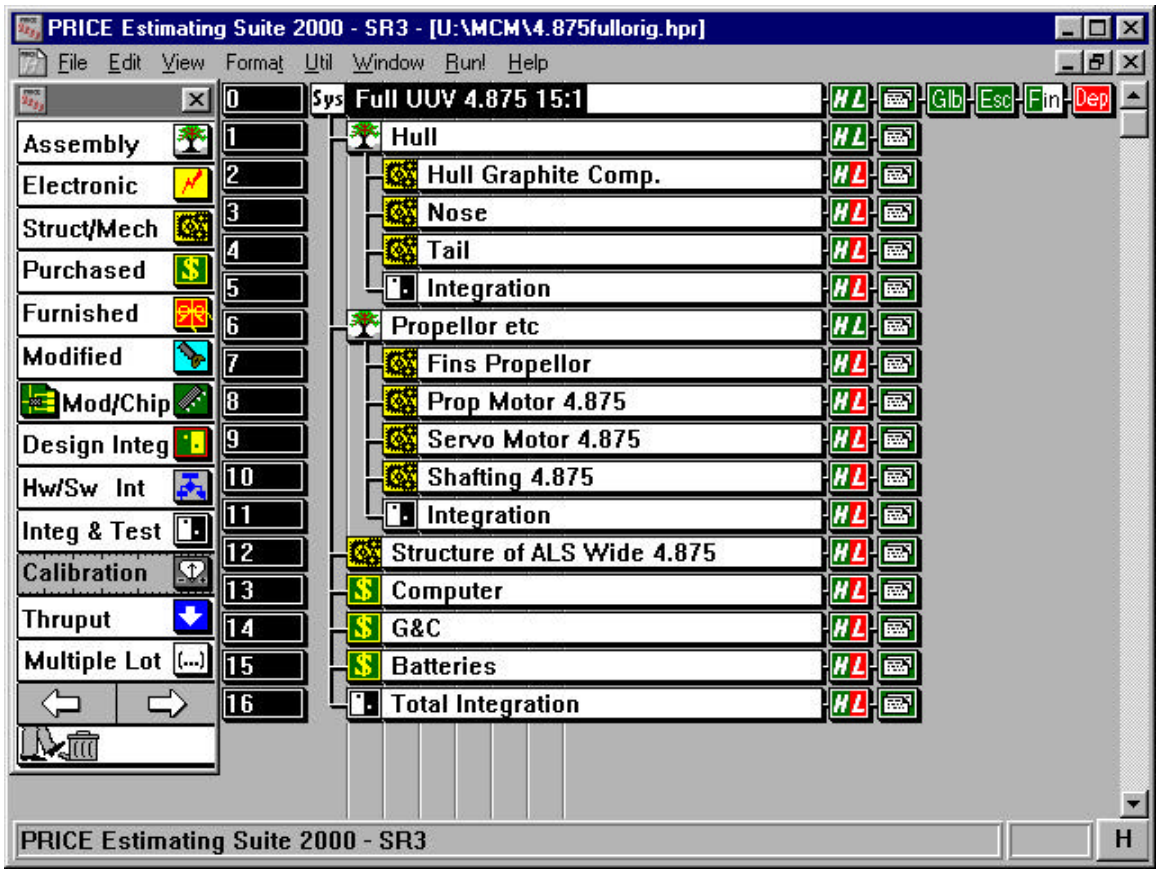
When each of the components' inputs was finalized, they were entered into the models designed for that particular component. This enabled the capability to combine different components to create unique UUVs. Below is a screen capture of the PRICE H software for a component.



Each component has a similar associated model. The next screen capture shows what the typical Structural/Mechanical input screen looks like for each model. When a different element is used, such as the Electronic Element, there are some changes in the types of inputs available to the use to complete that element.



In addition to the component models, a few models of complete UUVs were assembled in PRICE H. This was primarily to investigate the integration costs inherent with the production of a UUV and secondarily to view how the complete UUV cost structure appears. The screen capture below shows what the complete assembly of a 4.875” UUV looks like in PRICE H.



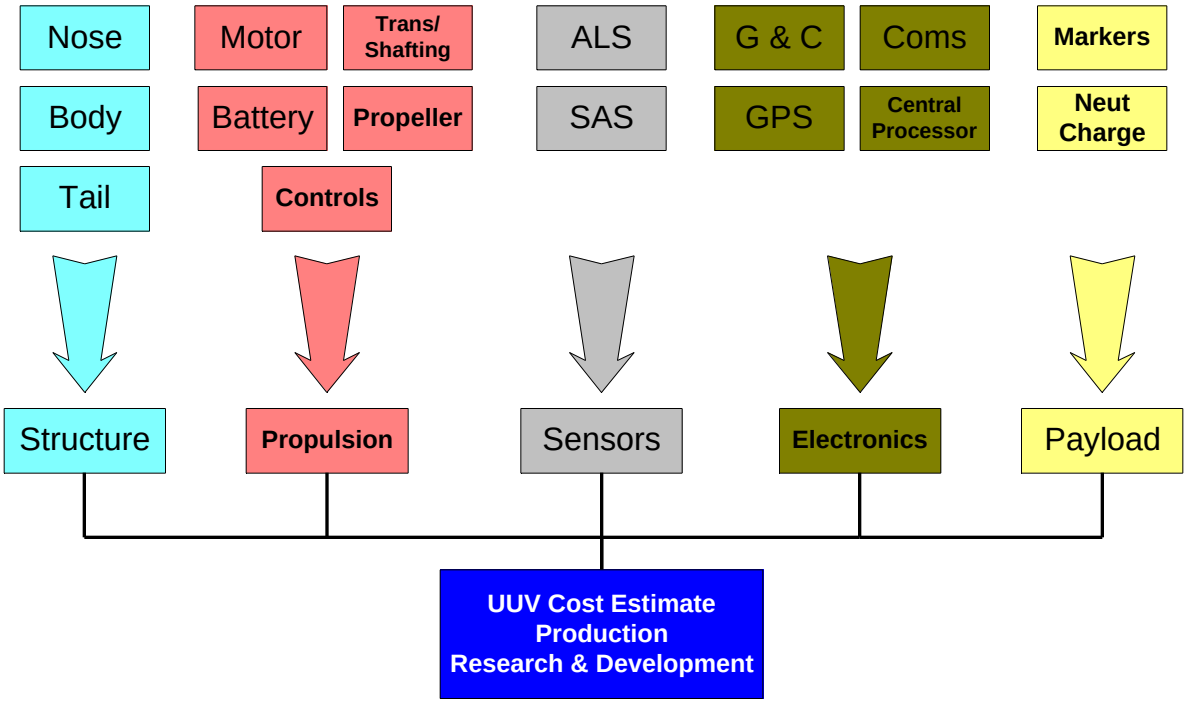
As one can see, there are Integration elements incorporated into the PRICE H model. These elements allow for PRICE H to estimate the amount of time and the cost for integrating and testing components with each other. In this model, as in all other complete UUV models, the individual components are placed in Assemblies that represent similar components. For example, the Nose, Body, and Tail components are all placed in an Assembly called Hull. This assembly process is necessary since in production similar components will be assembled together before that assembly is merged with other components or assemblies.

The other assembly in the complete UUV models is the Propeller etc. Assembly. This one includes the Servo and Propeller motors, Fins and Propeller, and Shafting.

Since all of the other components did not logically fit with the remaining components, they were all left outside assemblies and assumed integrated into a UUV separately. In addition, one last Integration element is added to the model at the end to capture the overall integration and testing done when combining all of the assemblies and separate components together.

Cost estimation details

In order to develop cost estimates quickly for a large number of different UUV's we took a modular approach. We developed a functionally based Work Breakdown Structure (WBS) which accommodated the all the potential UUV's under consideration. This structure is graphically depicted as illustrated below:



This graphic shows the five broad groups (Structure, Propulsion, Sensors, Electronics, and payload) within the WBS. These are not a complete WBS for a functional UUV, but they represent the best balance between the level of detail available at a conceptual level and the time available to develop those estimates balanced with the desire for accuracy.

Structural Element Estimates (other than batteries):

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
11211	PRICE H	**$69,655**	**$174,095**	Nose	54	all	Aluminum
11311	PRICE H	**$29,445**	**$78,394**	Nose	36	all	Aluminum
11411	PRICE H	**$8,472**	**$27,775**	Nose	21	all	Aluminum
11511	PRICE H	**$1,308**	**$27,140**	Nose	12.75	all	Aluminum
11611	PRICE H	**$200**	**$6,756**	Nose	7.5	all	Aluminum

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
11711	PRICE H	$101	$3,451	Nose	4.875	all	Aluminum
11212	PRICE H	$54,260	$131,422	Nose	54	all	Graphite Composite
11312	PRICE H	$23,774	$61,078	Nose	36	all	Graphite Composite
11412	PRICE H	$7,125	$22,538	Nose	21	all	Graphite Composite
11512	PRICE H	$1,130	$23,074	Nose	12.75	all	Graphite Composite
11612	PRICE H	$217	$7,200	Nose	7.5	all	Graphite Composite
11712	PRICE H	$110	$3,660	Nose	4.875	all	Graphite Composite
12221	PRICE H	$620,109	$1,684,416	Body	54	8x	Aluminum
12321	PRICE H	$304,809	$780,510	Body	36	8x	Aluminum
12421	PRICE H	$94,913	$286,210	Body	21	8x	Aluminum
12521	PRICE H	$14,108	$282,760	Body	12.75	8x	Aluminum
12621	PRICE H	$2,483	$84,953	Body	7.5	8x	Aluminum
12721	PRICE H	$1,247	$41,728	Body	4.875	8x	Aluminum
12222	PRICE H	$373,451	$975,048	Body	54	8x	Graphite Composite
12322	PRICE H	$190,912	$474,254	Body	36	8x	Graphite Composite
12422	PRICE H	$58,349	$172,308	Body	21	8x	Graphite Composite
12522	PRICE H	$8,703	$170,093	Body	12.75	8x	Graphite Composite
12622	PRICE H	$1,572	$52,586	Body	7.5	8x	Graphite Composite
12722	PRICE H	$771	$25,523	Body	4.875	8x	Graphite Composite
12231	PRICE H	$805,468	$2,214,406	Body	54	10x	Aluminum
12331	PRICE H	$399,829	$1,025,572	Body	36	10x	Aluminum
12431	PRICE H	$124,522	$375,840	Body	21	10x	Aluminum
12531	PRICE H	$19,518	$372,465	Body	12.75	10x	Aluminum
12631	PRICE H	$3,239	$111,903	Body	7.5	10x	Aluminum
12731	PRICE H	$1,632	$54,907	Body	4.875	10x	Aluminum
12232	PRICE H	$485,258	$1,284,096	Body	54	10x	Graphite Composite
12332	PRICE H	$236,493	$591,679	Body	36	10x	Graphite Composite
12432	PRICE H	$77,293	$226,840	Body	21	10x	Graphite Composite
12532	PRICE H	$11,783	$224,527	Body	12.75	10x	Graphite Composite
12632	PRICE H	$1,980	$66,861	Body	7.5	10x	Graphite Composite
12732	PRICE H	$1,023	$33,798	Body	4.875	10x	Graphite Composite
12741	PRICE H	$2,494	$85,370	Body	4.875	15x	Aluminum
12742	PRICE H	$1,577	$52,789	Body	4.875	15x	Graphite Composite
13211	PRICE H	$211,601	$544,964	Tail	54	all	Aluminum
13311	PRICE H	$94,802	$243,900	Tail	36	all	Aluminum
13411	PRICE H	$27,140	$85,368	Tail	21	all	Aluminum
13511	PRICE H	$4,152	$83,592	Tail	12.75	all	Aluminum
13611	PRICE H	$602	$20,237	Tail	7.5	all	Aluminum
13711	PRICE H	$301	$10,143	Tail	4.875	all	Aluminum
13212	PRICE H	$185,141	$464,248	Tail	54	all	Graphite Composite
13312	PRICE H	$85,644	$213,568	Tail	36	all	Graphite Composite
13412	PRICE H	$25,554	$77,653	Tail	21	all	Graphite Composite
13512	PRICE H	$3,829	$75,972	Tail	12.75	all	Graphite Composite
13612	PRICE H	$710	$23,507	Tail	7.5	all	Graphite Composite
13712	PRICE H	$341	$11,327	Tail	4.875	all	Graphite Composite

Notes on Structural Element Estimates:

All of the estimates were generated using PRICE H. The difference in body lengths was taken up wholly in the "body" component. We considered that any structural bracing or internal auxiliary structure was taken up in the hull structure. At our standard assumption of 1% of the UUV weight allocated to aux structure we considered that quantity to be of negligible cost.

Structural Element Estimates (Batteries)

ID Number	Basis of Estimate	Price per pound	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
24111	SME	$2	$0	Battery	all	all	Lead Acid
24112	SME	$33	$0	Battery	all	all	Li/thionyl chloride (Pri)
24113	SME	$33	$0	Battery	all	all	Lithium-ion
24114	SME	$33	$0	Battery	all	all	Lithium-polymer
24115	SME	$10	$0	Battery	all	all	Nickel-cadmium
24116	SME	$12	$0	Battery	all	all	Nickel-metal hydride
24117	SME	$33	$0	Battery	all	all	Silver Oxide (Pri)
24118	SME	$33	$0	Battery	all	all	Silver Zinc
24119	SME	$17	$0	Battery	all	all	Zinc/Air (Pri)

Notes on Battery Element Estimates:

These estimates are a "per pound" estimator for a UUV sized battery. They are based on Subject Matter Expert (SME) opinions taking likely commercial advances in the 2015 timeframe into account.

Propulsion Element Estimates

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
21210	PRICE H	**$114,769**	**$298,868**	Motor	54	all	NA
21310	PRICE H	**$51,314**	**$135,137**	Motor	36	all	NA
21410	PRICE H	**$14,760**	**$47,253**	Motor	21	all	NA
21510	PRICE H	**$3,231**	**$65,622**	Motor	12.75	all	NA
21610	PRICE H	**$661**	**$22,831**	Motor	7.5	all	NA
21710	PRICE H	**$279**	**$9,752**	Motor	4.875	all	NA
22210	PRICE H	**$3,658**	**$12,348**	Transmission & Shafting	54	all	NA
22310	PRICE H	**$1,825**	**$6,486**	Transmission & Shafting	36	all	NA

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
22410	PRICE H	**$604**	**$2,795**	Transmission & Shafting	21	all	NA
22510	PRICE H	**$149**	**$3,594**	Transmission & Shafting	12.75	all	NA
22610	PRICE H	**$35**	**$1,490**	Transmission & Shafting	7.5	all	NA
22710	PRICE H	**$12**	**$738**	Transmission & Shafting	4.875	all	NA
23210	PRICE H	**$5,899**	**$19,378**	Propeller	54	all	NA
23310	PRICE H	**$2,940**	**$10,125**	Propeller	36	all	NA
23410	PRICE H	**$976**	**$4,331**	Propeller	21	all	NA
23510	PRICE H	**$243**	**$5,729**	Propeller	12.75	all	NA
23610	PRICE H	**$56**	**$2,363**	Propeller	7.5	all	NA
23710	PRICE H	**$27**	**$1,166**	Propeller	4.875	all	NA
25210	PRICE H	**$62,104**	**$162,636**	Control System	54	all	NA
25310	PRICE H	**$27,782**	**$73,668**	Control System	36	all	NA
25410	PRICE H	**$7,975**	**$25,826**	Control System	21	all	NA
25510	PRICE H	**$1,744**	**$35,448**	Control System	12.75	all	NA
25610	PRICE H	**$355**	**$12,346**	Control System	7.5	all	NA
25710	PRICE H	**$150**	**$5,279**	Control System	4.875	all	NA

Propulsion Element Estimate notes:

All estimates came from PRICE H. The “control system” element refers to an actuator system for control surfaces.

Sensor Element Estimates

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
31210	PRICE H	**$83,355**	**$196,122**	ALS Wide	54	all	NA
31310	PRICE H	**$51,456**	**$118,551**	ALS Wide	36	all	NA
31410	PRICE H	**$25,640**	**$71,410**	ALS Wide	21	all	NA
31510	PRICE H	**$10,741**	**$211,574**	ALS Wide	12.75	all	NA
31610	PRICE H	**$4,768**	**$165,459**	ALS Wide	7.5	all	NA
31710	PRICE H	**$4,211**	**$145,556**	ALS Wide	4.875	all	NA
32210	PRICE H	**$333,906**	**$805,425**	ALS Narrow	54	all	NA
32310	PRICE H	**$214,218**	**$529,640**	ALS Narrow	36	all	NA
32410	PRICE H	**$92,055**	**$269,603**	ALS Narrow	21	all	NA
32510	PRICE H	**$32,288**	**$670,271**	ALS Narrow	12.75	all	NA
32610	PRICE H	**$9,040**	**$319,902**	ALS Narrow	7.5	all	NA
32710	PRICE H	**$7,744**	**$272,876**	ALS Narrow	4.875	all	NA
33210	PRICE H	**$137,555**	**$326,391**	SAS Wide	54	all	NA
33310	PRICE H	**$69,025**	**$157,806**	SAS Wide	36	all	NA
33410	PRICE H	**$24,905**	**$68,679**	SAS Wide	21	all	NA
33510	PRICE H	**$7,659**	**$147,913**	SAS Wide	12.75	all	NA

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
33610	PRICE H	**$2,289**	**$77,432**	SAS Wide	7.5	all	NA
33710	PRICE H	**$1,664**	**$55,661**	SAS Wide	4.875	all	NA
34210	PRICE H	**$241,846**	**$594,922**	SAS Narrow	54	all	NA
34310	PRICE H	**$119,680**	**$281,672**	SAS Narrow	36	all	NA
34410	PRICE H	**$41,836**	**$115,852**	SAS Narrow	21	all	NA
34510	PRICE H	**$10,437**	**$204,920**	SAS Narrow	12.75	all	NA
34610	PRICE H	**$3,597**	**$123,548**	SAS Narrow	7.5	all	NA
34710	PRICE H	**$2,587**	**$87,938**	SAS Narrow	4.875	all	NA

Sensor Element Estimate Notes:

All estimates were generated from PRICE H. The weight and volume of the sensors was from the study workbook.

Electronics Element Estimates

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
41111	SME	**$250**	**$0**	Guidance & Control	all	all	NA
41112	SME	**$2,500**	**$0**	Guidance & Control	all	all	NA
41113	SME	**$12,000**	**$0**	Guidance & Control	all	all	NA
42110	SME	**$500**	**$0**	RF Comms	all	all	NA
43110	SME	**$4,000**	**$0**	Central Processing	all	all	NA

Electronics Element Estimates notes:

The guidance and control estimates were for three different levels of accuracy. The lowest level was a simple dead reckoning system based on compass and propeller turn counts. The second system augmented the first system with a differential GPS system and attitude sensor system. The most accurate (and most expensive) system added an inertial navigation system to the intermediate system.

RF Comms included a small line of sight transceiver and antenna. The Central Processing element was considered to house all the computing and data storage for the UUV. We considered that a “high end” laptop would have the computational capability to meet the data processing and data storage needs of the UUV for the duration of the mission. After correcting for the cost of a display (clearly not needed in this application) we estimated this cost at $4000.

Payload Element Estimates

ID Number	Basis of Estimate	Unit Price	Unit R&D	Component	Diameter in Inches	Length to Dia Ratio	Material
51110	SME	**$10**	**$0**	Markers	all	all	NA
52110	SME	**$2,000**	**$0**	Neutralization Charge	all	all	NA

Payload Element Estimate notes:

The markers were a small “D Cell” sized sonar transducer and power supply which would be dropped by one UUV to assist a second UUV in locating and identifying a particular location. Some of CONOPS had one UUV searching and dropping markers near mines. Other UUV’s would then use the combination of GPS coordinates and the markers to locate a mine and target it for destruction. The Neutralization charge was an allowance for a simple explosive charge with detonation controlled by the UUV computer.

Sensitivity Analysis

Given that the PRICE H cost models provide only a point estimate based on user inputs, sensitivity analysis on user inputs is necessary. This analysis provides additional information to the user on the sensitivity of the cost estimate to changes in different factors.

The PRICE H cost estimation model has a few factors that are weighted more important than other factors. These factors are Weight/Volume, Structural Complexity, Electronics Complexity, and Platform Value. Given the nature of the component models, there was no value added to changing the Structural and Electronic Complexities. The types of materials and electronics, at this time, were not changeable. Hence, the complexities based on these materials and electronics would not change. The only inputs that had possible variation were the Weight/Volume of components and the Platform Value. Sensitivity analysis was performed on both of these inputs.

To perform the sensitivity analysis, it was determined to perform the analysis on completed UUV models rather than the individual component models. Considering that not all of the components would be used in the study, it was more efficient to choose the UUV models that were most likely to be used. This would also allow for any differences in Integration costs to appear as well as the differences in the component costs and total UUV costs. The analysis was performed on 15:1 ratio of the 4.875”, the 10:1 ratio of the 12”, and the 10:1 ratio 21” UUV models. All of the models had hulls constructed from Graphite Composite.

Weight/Volume

PRICE H software depends highly on the weight and volume of each element in the model. For the UUV models, there was a high probability of error with the estimation of the weight and volume of each component. The only solid information in the calculation of the weight and volume of a component was the diameter of the vehicle. Equations using diameter/length ratios and densities were used to estimate the weight and volume of each component. Generally speaking, the weight was calculated and the volume was derived from the weight and density of the component.

For the sensitivity analysis, it was determined to vary the weight of each component in a few selected UUV’s. The analysis varied the weight of a component by increasing and decreasing the weight by 10%. Since the volume was derived from the weight, the density of each component was calculated and the new volume was derived from maintaining the old density with the new

weight. This allowed the model to simulate what would happen to the cost if the components in an UUV were 10% smaller or 10% larger than expected.

In the essence of time, only the extreme cases of each UUV selected were analyzed. Hence, only the two scenarios where all components had an increase of 10% of weight and where all components had a decrease of 10% in weight were analyzed for each UUV. This allowed for an extreme range in costs based on a 10% change in weight.

The following tables exhibit the results from the sensitivity analysis on weight. Each table represents a UUV of which analysis was completed. In each table, one will find the Original Research and Development Costs followed by the 10% Increase and 10% Decrease Research and Development Costs. After those costs, one will find the Original Production Costs also followed by the relevant 10% increase and 10% decrease costs. Additionally, each table displays the percentage difference that the 10% increase or decrease made with respect to the original costs.

The first table is shown for the 4.875" UUV with a length to diameter ratio of 15:1. In general, it is shown that a 10% increase in the weight of each component will increase the cost of the UUV by a little more than 8%. A decrease in cost by about 8% can be seen in the case where the weight is uniformly decreased by 10%.

4.875" 15:1 Ratio UUV		
Cost Type	**Cost in Dollars ($)**	**Percentage Difference**
Original R&D Cost	$230,266.31	
Weight +10% R&D Cost	$249,260.43	8.25% increase in cost
Weight -10% R&D Cost	$210,951.18	-8.39% decrease in cost
Original Production Cost	$39,743,979.28	
Weight +10% Prod. Cost	$42,950,684.69	8.07% increase in cost
Weight -10% Prod. Cost	$36,478,028.32	-8.22% decrease in cost

The next table shown is for the 12.75" UUV with a length to diameter ratio of 10:1. Here, it is shown that an increase of 10% in weight uniformly over all components will cause an increase in cost by around 8%. Similar to the 4.875" UUV, the decrease in weight by 10% will cause the cost to decrease by around 8%.

12.75" 10:1 Ratio UUV		
Cost Type	**Cost in Dollars ($)**	**Percentage Difference**
Original R&D Cost	$793,452.62	

Weight+10% R&D Cost	$858,520.10	8.20% increase in cost
Weight-10% R&D Cost	$727,255.00	-8.34% decrease in cost
Original Production Cost	$4,020,464.24	
Weight+10% Prod. Cost	$4,337,898.75	7.90% increase in cost
Weight-10% Prod. Cost	$3,696,678.35	-8.05% decrease in cost

The last table shown is for the 21" UUV with a 10:1 ratio of length to diameter. In this case, the increase in weight by 10% has caused around an 8% increase in cost. With a decrease of 10% in weight, one sees that the cost will decrease by closer to 8.2%.

21" 10:1 Ratio UUV		
Cost Type	**Cost in Dollars ($)**	**Percentage Difference**
Original R&D Cost	$547,325.32	
Weight+10% R&D Cost	$591,481.77	8.07% increase in cost
Weight-10% R&D Cost	$502,350.71	-8.22% decrease in cost
Original Production Cost	$3,696,675.06	
Weight+10% Prod. Cost	$3,996,511.36	8.11% increase in cost
Weight-10% Prod. Cost	$3,391,579.04	-8.25% decrease in cost

Platform Value

As with the Weight sensitivity analysis, the Platform Value sensitivity analysis was performed on only those selected UUV's. In this analysis, the new Platform Values were based on the PRICE H Platform Value Table. The table shows three values for military ships and submersibles: 1.20, 1.60, and 1.80. PRICE H corresponds their Structural Complexity (MCPLXS) and Electronic Complexity (MCPLXE) values to their Platform Value Table. In order to pick a platform value not in the table, one would need to manually extrapolate the MCPLXS and MCPLXE values for each component. To eliminate any added error to the models, the platform values to be tested were 1.20 and 1.80. These values were already in the PRICE H tables and had corresponding MCPLXS and MCPLXE values.

The sensitivity analyses on the Platform Values were also tested at the extreme cases. These two cases were 1) all of the components in a model were at the increased value of 1.80 and 2) all of the components in a model were at the decreased value of 1.20.

The first case shown is the 4.875" UUV with a Platform Value of 1.20. The reduction in the platform value resulted in a decrease in both R&D and

Productions costs by 37.25%. Since all other factors remained the same, the decrease in costs can be attributed only to the reduction in the platform value and resulting effect from the PRICE H equations.

4.875” 15:1 Ratio UUV	Platform = 1.20		
Component	MCPLXS	R&D Cost	Prod. Cost
Body	5.391	$33,873.98	$5,980,929.22
Nose	5.391	$2,493.17	$435,771.05
Tail	5.391	$7,517.68	$1,328,936.98
Prop. Motor	4.650	$6,399.49	$1,149,316.41
Servo Motor	4.650	$3,816.97	$627,172.86
Fins/etc.	3.060	$662.17	$87,277.31
ALS	5.830	$88,786.13	$15,275,460.32
Shafting	3.060	$413.44	$52,741.07
Totals		$144,497.03	$24,937,605.22
Percentage Difference		**-37.25%**	**-37.25%**

The next case examined was the 4.875” UUV with a Platform Value of 1.80. When the platform value was increased, it resulted in an increase of costs in both the R&D and Production areas. However, in this case, the R&D costs had a smaller increase of 44.56% than the Production costs of 48.25%. This difference is attributed how the platform value increase affected the MCPLXS and PRICE H equations.

4.875” 15:1 Ratio UUV	Platform = 1.80		
Component	MCPLXS	R&D Cost	Prod. Cost
Body	6.138	$63,351.45	$11,117,222.78
Nose	6.138	$4,294.97	$788,883.81
Tail	6.138	$13,420.74	$2,461,101.76
Prop. Motor	5.300	$11,333.87	$1,998,054.26
Servo Motor	5.300	$6,094.83	$1,068,250.31
Fins/etc.	3.660	$1,403.04	$202,556.92
ALS	6.950	$232,103.60	$41,163,533.16
Shafting	3.660	$870.26	$122,475.92
Totals		$332,872.76	$58,922,078.92
Percentage Difference		**44.56%**	**48.25%**

The third case that was examined was the 12.75” UUV with the 1.20 Platform Value. Here, it is shown that there was a difference in the decrease in costs for the R&D costs than for the Production costs. The difference between the 37.53% decrease for R&D costs and the 38.89% decrease for Production costs are attributed to the relation of the Platform value to the MCPLXS and the PRICE H equations.

12.75” 10:1 Ratio UUV	Platform = 1.20		

Component	MCPLXS	R&D Cost	Prod. Cost
Body	5.353	$139,999.74	$693,832.84
Nose	5.391	$15,081.13	$74,676.29
Tail	5.353	$48,506.57	$239,877.28
Prop. Motor	4.650	$44,034.54	$208,689.37
Servo Motor	4.650	$24,266.00	$114,147.20
Fins/etc.	3.060	$3,409.94	$13,939.46
SAS	5.830	$90,102.55	$456,319.42
ALS	5.830	$128,130.56	$646,984.43
Shafting	3.060	$2,109.23	$8,442.28
Totals		$495,640.26	$2,456,908.57
Percentage Difference		**-37.53%**	**-38.89%**

The fourth case that was analyzed was the 12.75” UUV with the 1.80 Platform Value. In this case, as with the 4.875” UUV with the 1.80 Platform Value shown above, there was a difference in the increase in costs for R&D and Production. Here, the increases were 38.71% to 40.99% respectfully.

12.75” 10:1 Ratio UUV	Platform = 1.80		
Component	MCPLXS	R&D Cost	Prod. Cost
Body	6.095	$272,598.27	$1,382,240.86
Nose	6.138	$27,499.36	$144,580.62
Tail	6.095	$91,414.17	$476,901.31
Prop. Motor	5.300	$77,854.10	$390,464.69
Servo Motor	5.300	$41,787.89	$209,817.24
Fins/etc.	3.660	$7,400.17	$32,531.41
SAS	6.950	$236,134.76	$1,248,680.73
ALS	6.950	$341,361.12	$1,763,372.96
Shafting	3.660	$4,551.91	$19,730.21
Totals		$1,100,601.75	$5,668,320.03
Percentage Difference		**38.71%**	**40.99%**

The next to last UUV examined was the 21” with a Platform Value of 1.20. Here, the decrease in cost was not uniform across the R&D and Production costs. There was a smaller decrease for the R&D costs at 36.89% than the Production costs at 44.38%.

21” 10:1 Ratio UUV	Platform = 1.20		
Component	MCPLXS	R&D Cost	Prod. Cost
Body	5.351	$140,808.09	$822,099.82
Nose	5.353	$14,869.58	$80,009.34
Tail	5.353	$49,569.21	$277,673.85
Prop. Motor	4.650	$31,925.43	$182,754.79
Servo Motor	4.650	$17,938.14	$100,435.8
Fins/etc.	3.060	$2,779.37	$11,459.17

SAS	5.830	$41,977.52	$283,243.45
ALS	5.830	$43,801.11	$291,511.95
Shafting	3.060	$1,772.65	$6,974.3
Totals		$345,441.1	$2,056,162.47
Percentage Difference		**-36.89%**	**-44.38%**

The last UUV examined was the 21" with a Platform Value of 1.80. Here, as with all of the UUVs at the 1.80 platform, the costs for R&D increased less than those for Production with the increases being 31.23% and 40.19% respectfully. This is probably caused by the combination of different calculated MCPLXS and the internal PRICE H equations relating to the new platform value.

21" 10:1 Ratio UUV	Platform = 1.80		
Component	MCPLXS	R&D Cost	Prod. Cost
Body	6.092	$276,351.91	$1,999,217.00
Nose	6.095	$26,866.12	$184,013.57
Tail	6.095	$93,712.55	$666,298.00
Prop. Motor	5.300	$55,677.03	$364,873.21
Servo Motor	5.300	$30,198.64	$196,191.12
Fins/etc.	3.660	$5,565.65	$27,302.05
SAS	6.950	$111,059.49	$851,768.20
ALS	6.950	$115,286.18	$875,953.46
Shafting	3.660	$3,514.00	$16,672.41
Totals		$718,231.57	$5,182,289.02
Percentage Difference		**31.23%**	**40.19%**

In summary, each of the UUVs chosen for sensitivity analysis on the Platform Value had large increases or decreases in their costs when the Platform Value was increased or decreased. Below is a table that lists the percentage change of each UUV relative to original cost.

Production	**4.875"**	**12.75"**	**21"**
10% Weight Increase	8.1%	7.9%	8.1%
10% Weight Decrease	-8.2%	-8.1%	-8.3%
Platform Complexity Increase	48.3%	41.0%	40.2%
Platform Complexity Decrease	-37.3%	-38.9%	-44.4%

R&D	**4.875"**	**12.75"**	**21"**
10% Weight Increase	8.3%	8.2%	8.1%
10% Weight Decrease	-8.4%	-8.3%	-8.2%
Platform Complexity Increase	44.6%	38.7%	31.2%
Platform Complexity Decrease	-37.3%	-37.5%	-36.9%

REMUS Model Validation

With the construction of the REMUS UUV prior to this study by the Woods Hole Institute, it was necessary to create a PRICE H model to estimate the cost of the REMUS for comparison against the publish unit cost by Woods Hole. The REMUS PRICE H model was developed using the same component breakdown structure as for the other models.

REMUS is a 7.5" diameter UUV that is "designed for coastal monitoring and multiple vehicle survey operations." (source: http://adcp.whoi.edu/REMUS/index.html). It has the ability to extend its length with the addition of a module in the body and the capability of carrying several types of sonar. The battery used in REMUS can be either a lead-acid or lithium-ion battery.

The cost model was composed of the normal UUV components as seen in the other models. Due to the fact that the REMUS documentation did not give specifics on several details, the Endurance Model was also used to provide those details. This was done by inputting the general parameters for the REMUS and calculating the details needed.

The following system was assembled to produce a REMUS-Like Vehicle in the PRICE H software.

- Body – Aluminum Nose, Tail, and 8:1 ratio body,
- Fins,
- Propulsion Motor,
- Shafting,
- Servo Motor,
- ALS – Wide,
- Guidance and Control,
- Lithium Ion Battery, and
- Computer.

The system used all of the assumptions of the other UUV's modeled in PRICE H including the dates of R&D and production. The exception was in the GN&C where the dead reckoning system was used given the information found in the original Endurance spreadsheet. It is possible to choose any type of GN&C for the REMUS-Like vehicle however; there was not a plethora of information on this area to make any other choices.

For the system, the 8:1 ratio body was chosen since that is the length used in the original Endurance spreadsheet and also exhibited as the main option on the Woods Hole website. Additionally, the sensor was chosen as ALS wide since

that particular one matched the FLS sensor specifications used in the original Endurance spreadsheet.

The following are the costs obtained from PRICE H using 5 production items and 1 prototype.

Cost Type	Cost in Dollars ($)
Total Development Costs	$61, 788.82
Total Production Costs	$317,003.54
Overall Total Cost	$378,792.36

Per unit, this costs a REMUS-Like UUV at:

Cost Type	Cost in Dollars ($)
Total Development Costs	$12,357.76
Total Production Costs	$63,400.71
Overall Total Cost	$75,758.47

According to the above information, the Development cost of a REMUS-like vehicle with 5 produced and 1 prototype will cost $61,788.82. The individual UUV cost there is $12,357.76. Depending on if the Development cost is to be carried into the sale cost of the UUV, the cost per UUV is either $63k or $75k. These costs are based at the 2010 timeframe, when construction is estimated to begin for the UUVs. Additionally, the PRICE H defaults for items such as the cost of labor hours were used since the information necessary to change those assumptions were not available.

There are a few areas where questions have developed when trying to duplicate the REMUS vehicle costs. Here are some of the areas in question.

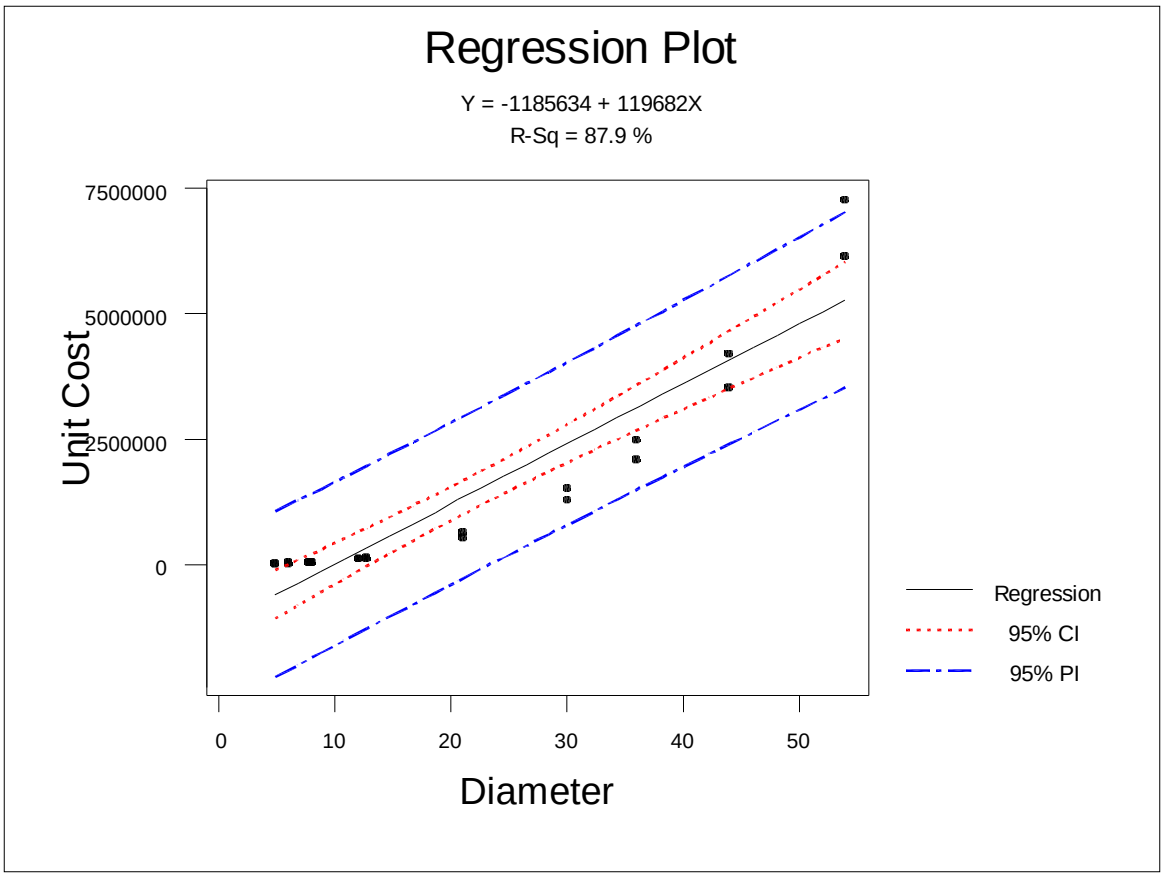
- How many REMUS vehicles were produced?
- How many prototypes of REMUS were constructed?
- How was the R&D cost considered in the final cost of REMUS?
- Was the cost paid for upfront?
- Was R&D rolled into each REMUS?
- What year was used for costing?

These issues greatly affect the applicability of the model to a REMUS like vehicle. The information told to the cost team was that a production REMUS would cost in the vicinity of $70k. With that in mind, the cost estimate from PRICE H for a REMUS-Like Vehicle is similar.

Cost Rules of Thumb:

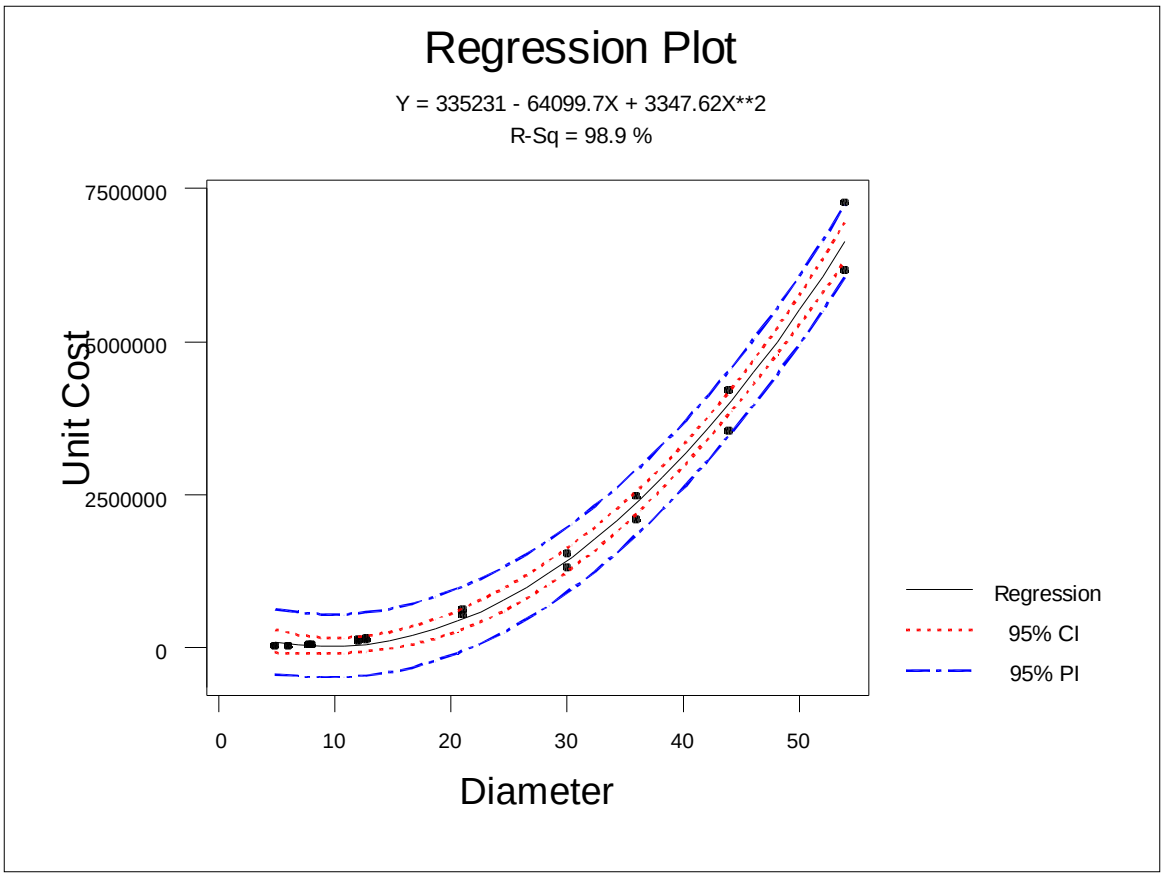
Early in the study we needed a tool to make rough order of magnitude comparisons between various systems. In order to meet this need we made some very rough cost estimates of nominal UUV's at several key values (diameter/length combinations) and then performed a regression analysis.

We first tried a linear regression as summarized in the following graph:



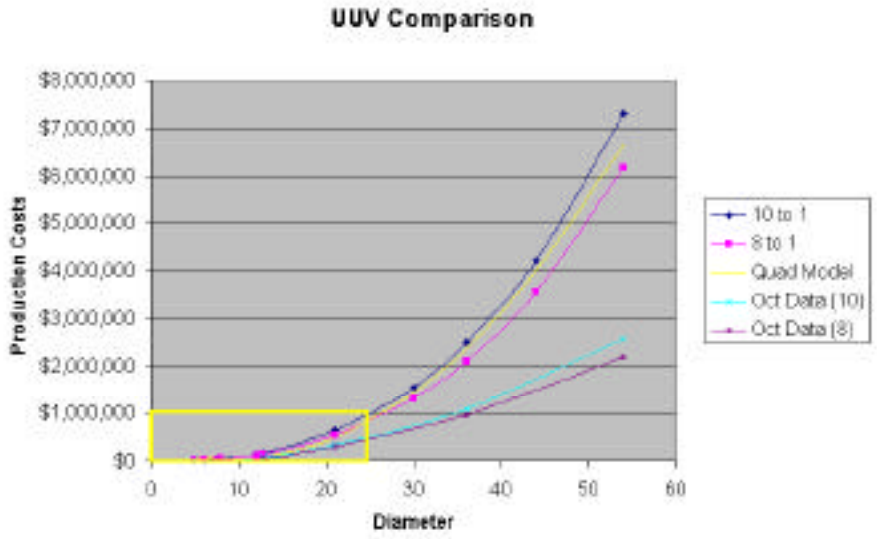
This equation had a low R squared value. By inspecting the graph above we can see that the predictive value at any given point of this model is low.

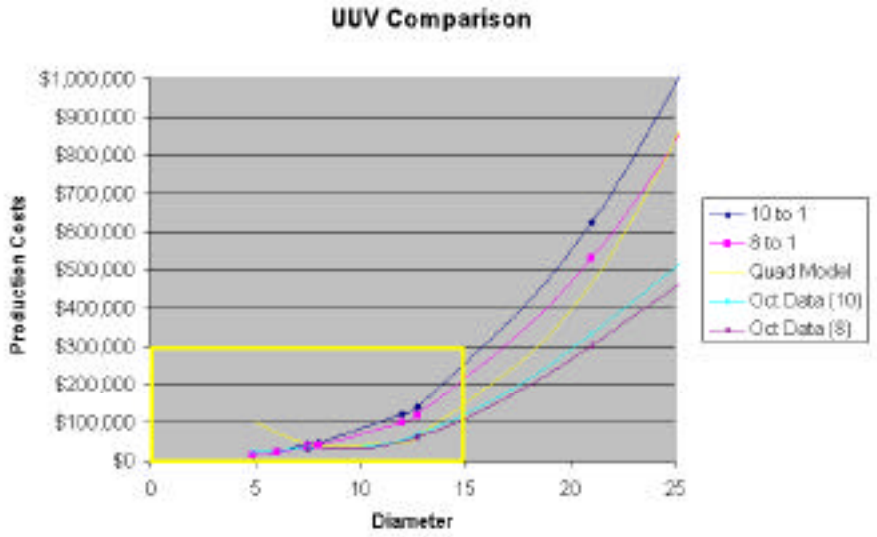
The following graph shows the results of a quadratic regression:

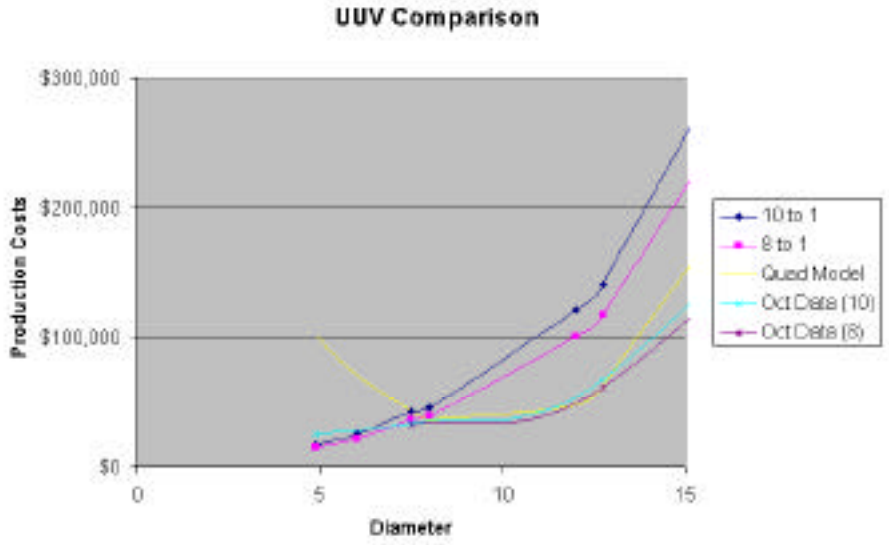


This equation has a reasonable R squared value. By inspection it follows the general form of the data. This is expected because the basis for the estimates was weight and volume, both of which have a quadratic relationship to diameter under the constant density assumption we used. While it was possible to show modest improvement in goodness of fit with a higher order polynomial regression, there was no physical basis for any higher order relationship. We chose the quadratic unit cost estimation equation as the best “rule of thumb” estimator for UUV cost based solely on diameter. This tool was used for some preliminary analysis in the early stages of the study.

After we developed the full cost estimating tool we completed a brief validation study for the “rules of thumb”, comparing them to the final results. The results are shown in the following three graphs (the yellow highlighted area shows the area of the next graph in the sequence):







The model tended to overestimate the costs of the small (4.875 inch) UUV's and underestimate the costs of the larger UUV's. This tool was useful in the early stages of the study as a "scooping tool" but was not used as we proceeded further due to the availability of a more accurate model.

For further information on the models described or the cost estimation and affordability analysis of this study contact:

William M. Kroshl
William.Kroshl@jhuapl.edu

240-228-4870
240-228-5910 (fax)

Katherine A. Sullivan
Katherine.Sullivan@jhuapl.edu

240-228-4834
240-228-5910 (fax)

Johns Hopkins University
Applied Physics Laboratory
Joint Warfare Analysis Department
11100 Johns Hopkins Road
Laurel, Maryland
20723-6099

Sonar Performance Assessment Process:

Target Detection and Close-Tethered Target Discrimination

A sonar performance prediction program, like Mineray 3, provides the basis for evaluation of acoustic sensors used for detection, discrimination, and classification (see definitions below). As shown in Figure 1, Mineray 3 is used for prediction of active high frequency sonar performance in a multi-path acoustic environment. Mineray 3 implements an eigenray based propagation model and evaluates the sonar equation in computation of signal and noise components. An overview of Mineray 3 can be viewed at http://www.arlut.utexas.edu/~asdwww/xmineray/.

The primary inputs to Mineray 3 are sonar parameters and environmental characteristics. The ocean environment is characterized primarily in terms of the sound velocity profile, bottom type, and sea state. The Mineray 3 environmental acoustic submodels implemented are the OAML approved HF-EVA models (alternatively, the acoustic submodels in the OAML approved MCM model, CASTAR, may be applied). Multi-path acoustic propagation is implemented with an eigen-ray propagation model.

The fundamental acoustic performance measurements used to characterize detection and discrimination sonar performance are signal-to-noise ratio (SNR) and reverberation-to-noise ratio (RNR). The performance assessment process is shown in Figure 2. The SNR is computed directly my Mineray 3. The RNR is computed from the Mineray 3 noise computations as the ratio of the direct path reverberation component to the total noise contribution from all other components. Sonar detection performance (for all target types) is directly related to SNR. Close-tethered (CT) target discrimination (see definitions below) performance is related to both SNR and RNR.

Detection and discrimination signal processing provides a certain amount of processing gain, which in effect, increases the SNR and RNR. The Mineray 3 outputs should be adjusted

for processing gain terms. The initial processing gain term is associated with coherent processing (replica correlation or matched filter processing). This term is automatically applied to SNR in Mineray 3. The other processing gain terms are associated with detection and discrimination processing (a.k.a. Computer Aided Detection or CAD). These terms are multi-ping processing gain (associated with multi-ping integration due to CAD) and multi-aspect angle processing gain (associated with integration through target fluctuations over a range of aspect angles).

The multi-ping processing gain is 5 log (N) for N pings (looks); this gain term is applied to both SNR and RNR. N represents the number of pings that a target is observed within the sonar field of view. Multi-ping gain is not expected to increase without bound with increasing number of pings. Therefore, the multi-ping gain is limited to a maximum of 8 dB (N=40). The number of pings is computed based on the platform velocity, ping rate, and sonar field of view. The number of pings and multi-ping gain versus lateral range (across-track) is plotted in Figure 3A for a typical forward-looking sonar configuration (speed=7 Knots, range scale=1000 Yards, horizontal sector=150 degrees, vertical beamwidth=10 degrees). At the center of the sector (near zero lateral range), the number of pings is limited primarily by the vertical beamwidth. With increasing lateral range, the number of pings increases until the horizontal sector angle limits are reached. As lateral range increases beyond this point, the number of pings decreases to zero until the horizontal sector edge is reached at the maximum range scale. The number of pings and multi-ping gain versus lateral range (across-track) is plotted in Figure 3B for a typical volume search sonar configuration (speed=7 Knots, range scale=1000 Yards, horizontal beamwidth=8.25 degrees, vertical beamwidth=150 degrees). The number of pings increases approximately linearly with increasing range.

The second processing gain adjustment term is associated with the target aspect angle observed over multiple pings; this gain term is applied only to SNR and only for bottom targets (volume or close-tethered targets aren't expected to have significant aspect angle fluctuations within the sonar field of view). Figures 3A and 3B also contain a plot of the aspect angle versus lateral range for typical forward-looking and volume search sonars, respectively. The

aspect angle of Figures 3A and 3B is used along with the plot in Figure 3C to determine the multi-aspect gain to be applied versus lateral range.

After the application of the processing gains, the adjusted SNR and RNR values are converted into a probability of detection (PD) and probability of classification (PC) with the Swirling-1 receiver operating characteristic (ROC) curve shown in Figure 3D. The Swirling-1 ROC represents detection performance with slowly varying ping-to-ping signal fluctuations (the probability of false alarm has been fixed at 1e-5 in this example) in stationary Rayleigh distributed background noise.

The final output is the PD, PC, and PD-PC product (PDPC) versus lateral range. These probability functions are equivalent to the P(y) curves (in NWP-27-1-1 terminology) for detection and discrimination. From these P(y) curves, the characteristic search width, A, and characteristic search probability, B, can be derived (see PEO-MIW Note 3370 for the method of computation). For bottom target and close-tethered target detection/discrimination, it is recommended that the PDPC versus lateral range curve be used in determining the A and B values. For volume target detection/discrimination (for targets clearly localized within the water column away from the surface/bottom), the PD versus lateral range curve should be used in determining the A and B values.

Definitions:

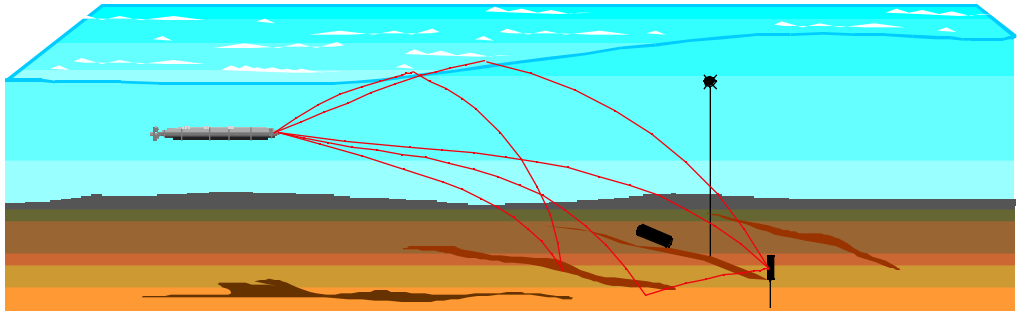
1. Detection is the process of determining that an object is present.

2. Classification is the process of determining if the detected object is a mine-like object (MLO) or non-MLO.

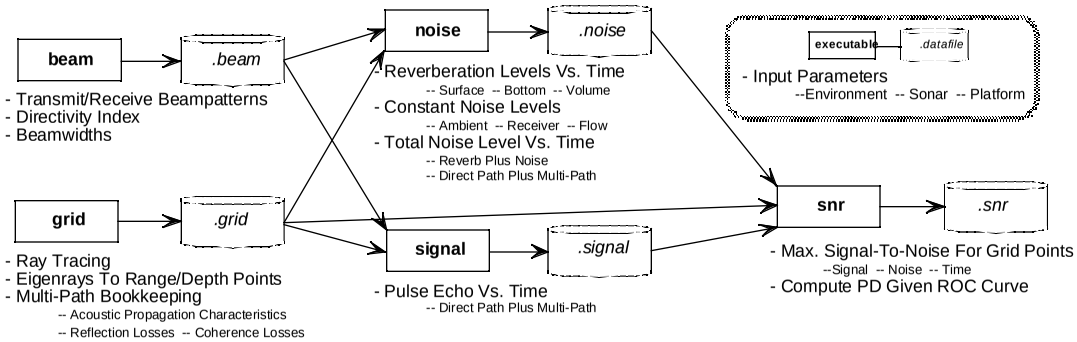
3. Discrimination is preliminary classification using a high resolution, wide-sector, search sonar. Discrimination is the process of determining that a detected object is non-mine-like so that it can be excluded from further, higher fidelity classification processing (i.e. imaging). MLOs are discriminated by evaluation of their high range resolution echo returns over multiple pings (looks) and aspect angles (look

angles). An objects mine-like characteristics are evaluated in terms of spatial extent (range and bearing), ping-to-ping location stability (stationarity), vertical location with respect to the ocean bottom (a.k.a height above bottom or HAB), echo signal-to-background noise level (S/B a.k.a SNR), and echo to background statistical context. Close-tethered target discrimination (a.k.a. Long Range Classification, or LRC in AN/SQQ-32 terminology) is the process of determining that an object is positioned in the water column above (below) the ocean seafloor (surface). This requires detection and localization (in range, bearing, and elevation angle) of the object as well as the seafloor (surface) at the object location. Adequate SNR and RNR are needed to support close-tethered target discrimination.

Mineray 3 Sonar Performance Prediction Model



MINERAY 3 Computer Model



INPUTS

- Environmental Parameters
- Sonar Parameters
- Platform Parameters

COMPUTATIONS

- Range-Independent Multi-Path Eigenray Propagation Model
- Empirically Based Acoustic Submodels
  - Statistical Mean Reverberation/Noise And Target
  - Incoherent Multi-Path Processes
- Sonar Equation Based Performance Measures

PRODUCTS

- Ray Path Characteristics
- Range-Depth & Time Dependent Acoustic Contour Le
  - Signal • Noise • Reverberation • SNR

APPLICATIONS

- Sea Test Performance Evaluations
  - AN/SQQ-14,30,32 • DARPA UUV • AN/BQS-15/EC-17
- Sonar Performance Comparison Studies
  - AN/SQQ-32 COEA • LMRS COEA
  - AN/BSY-1 HFU COEA • LMS V4 Sensor Trade Study
- Training
  - AN/SQQ-32
- Tactical Decision Aids
  - MEDAL (CASTAR)

Figure 1
ATL.RSB
FMCM-99-1
March 1999

Performance Assessment Process For Detection & Discrimination Sonar

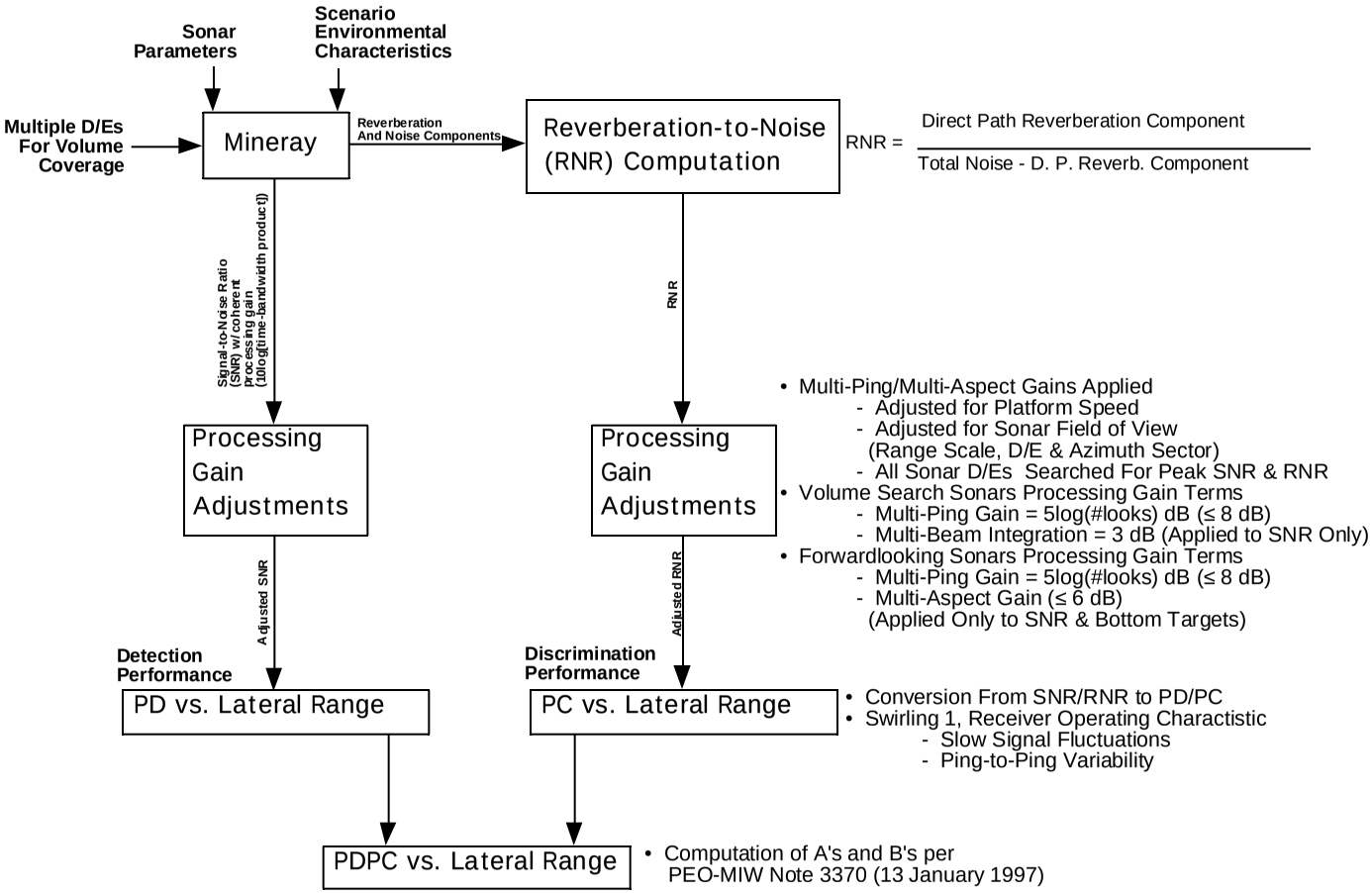
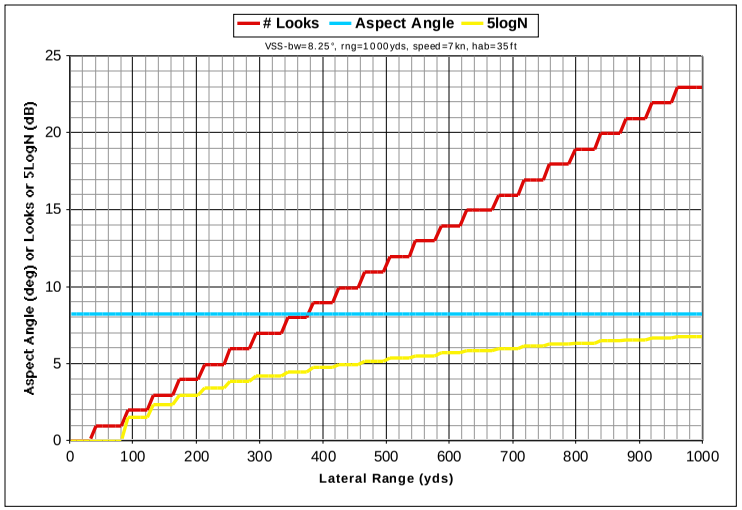
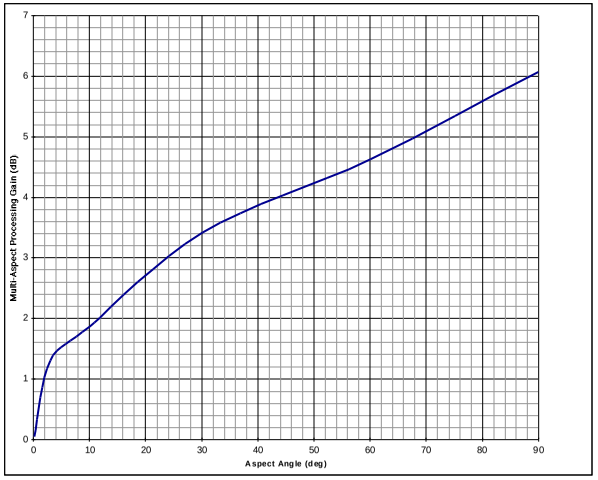


Figure 2
ATL.RSB
FMCM-99-2
March 1999

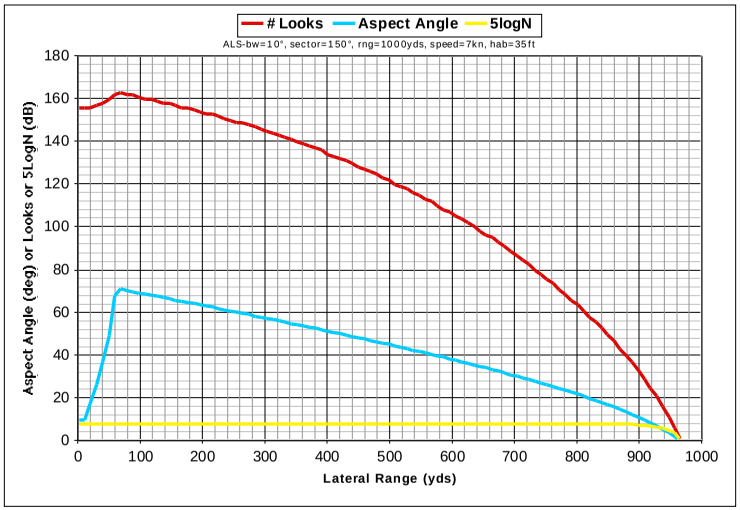
Performance Assessment Process
Processing Gain Adjustment And ROC Curve



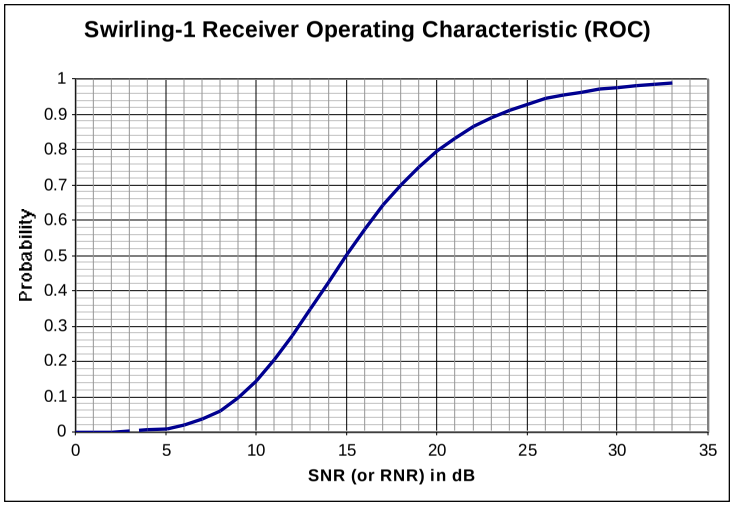
B: Volume Search Sonar, Multi-Ping Gain And Aspect Angle Vs. Lateral Range



C: Multi-Aspect Gain Versus Aspect Angle



A: Forwardlooking Sonar, Multi-Ping Gain And Aspect Angle Vs. Lateral Range



D: ROC Curve For Conversion From SNR/RNR to PD/PC

Figure 3
ATL.RSB
FMCM-99-3
March 1999

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

OVERVIEW

- Goal: To investigate the required number of small vehicles (bird-dogs) that should be carried by the large search vehicle (LV) in the “bird-dog” concept

- Calculate individual SV travel times to contact and back to LV

- Estimate the number of SV requirements
  - given vehicles speeds, contact call density, and LV search swath

- SV required expected endurance estimates

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

INDIVIDUAL BIRD-DOG SV TRAVEL TIMES

- **Basic Assumptions**
  - **LV searches area with large swath sensor**
  - **LV detects and discriminates contacts**
  - **SV is deployed when contact is broadside to LV**
  - **one SV deployed per contact**
  - **launch, recovery, and contact investigations times handled separately**
  - **LV and SV velocities**
  - **each SV path requires a simple G&C scheme**

- **SV path options (fig 1)**
  - **out-going path is direct to contact**
  - **return path options**
    1) **optimal path: straight line return path**
    2) **“dog-chase-hare” path: SV always heads toward LV**
    3) **Manhatten path: SV returns to point-of-launch then follows LV (near worst case)**

FUTURE MCM STUDY

BIRD-DOG TRAVEL PATH OPTIONS

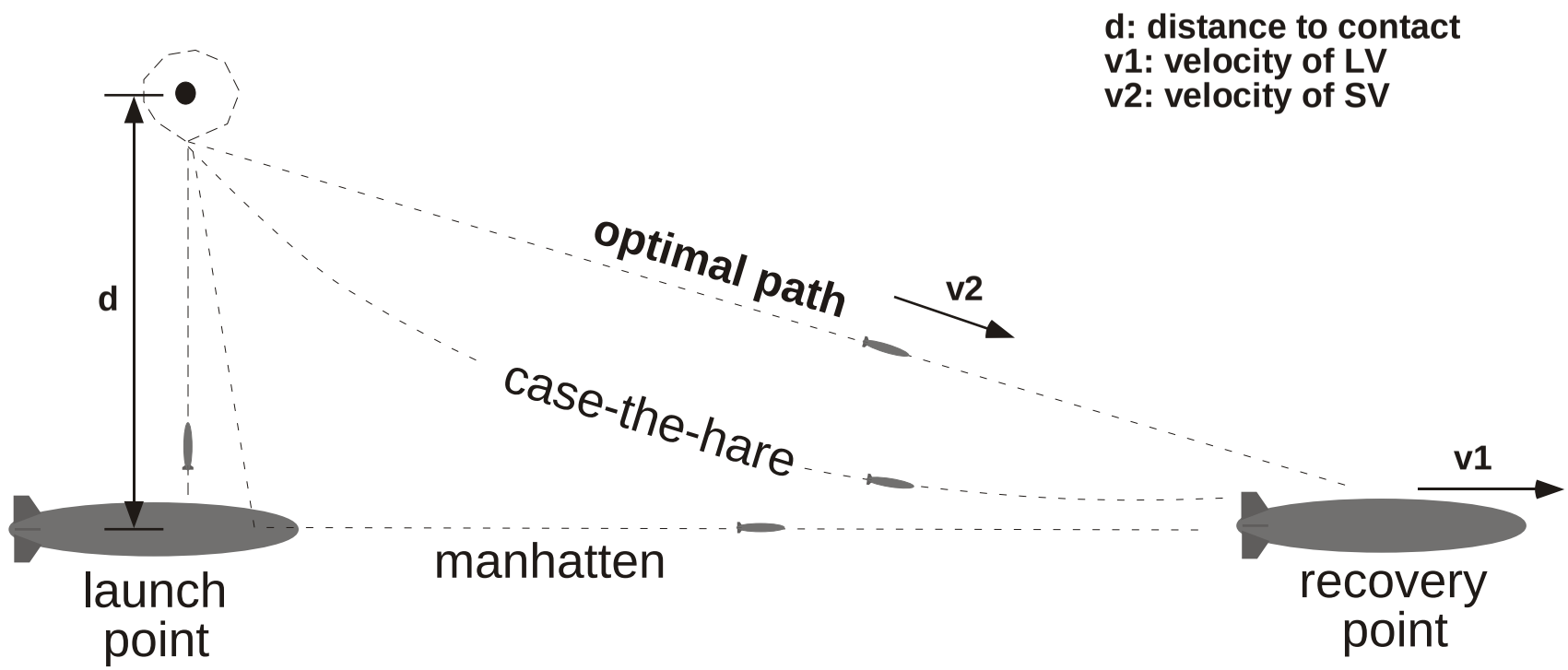


Figure 1: SV 3 Optional Path Geometries

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

TRAVEL TIMES

- **Optimal Case**

  - governing equation for return time (T_r)

$$\left(v_2 T_r\right)^2 = d^2 + \left(\frac{v_1}{v_2} d + v_1 T_r\right)^2$$

  - solved for the return time

$$T_r = -d \frac{v_1^2 + v_2^2}{v_2\left(v_1^2 - v_2^2\right)}$$

$$v_2 = \alpha \ v_1 \qquad T_d = \frac{d}{v_2} \qquad T_r = \frac{T_d(\alpha^2 + 1)}{\alpha^2 - 1}$$

  -total travel time

$$T_{tot} = \frac{2\alpha^2}{(\alpha^2 + 1)} T_2 \qquad T_{tot} = \frac{2 d \alpha}{v_1(\alpha^2 - 1)}$$

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

- **Dog-Chase"Path[1]**

return path

$$\frac{d^{\alpha}\ x^{1-\alpha}}{2\ (\alpha-1)}+\frac{x^{\alpha+1}}{2\ d^{\alpha}\ (\alpha+1)}+\frac{d\ \alpha}{1-\alpha^{2}}$$

path length

$$\frac{d}{1-\alpha^{2}}$$

- **Manhatten Path**

$$T_{tot}=\frac{2d}{v_2-v_1}$$

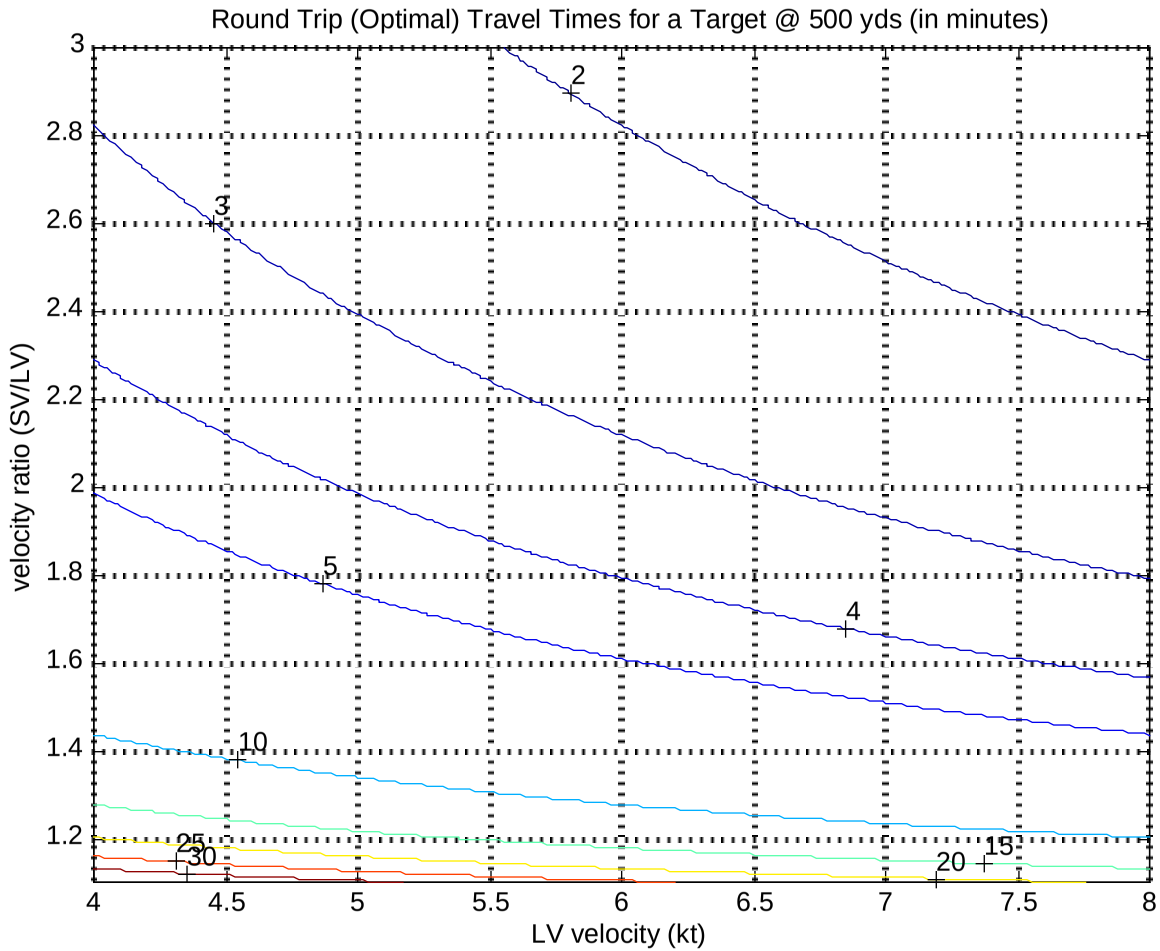
or

$$T_{tot}=\frac{2d}{v_1(\alpha-1)}$$

[1] "Recreations in Mathematics", H. E. Licks, D.Van Nostrand Company, Inc, New York 1917, pp 102

FUTURE MCM STUDY

BIRD-DOG OPTIMAL PATH TRAVEL TIMES

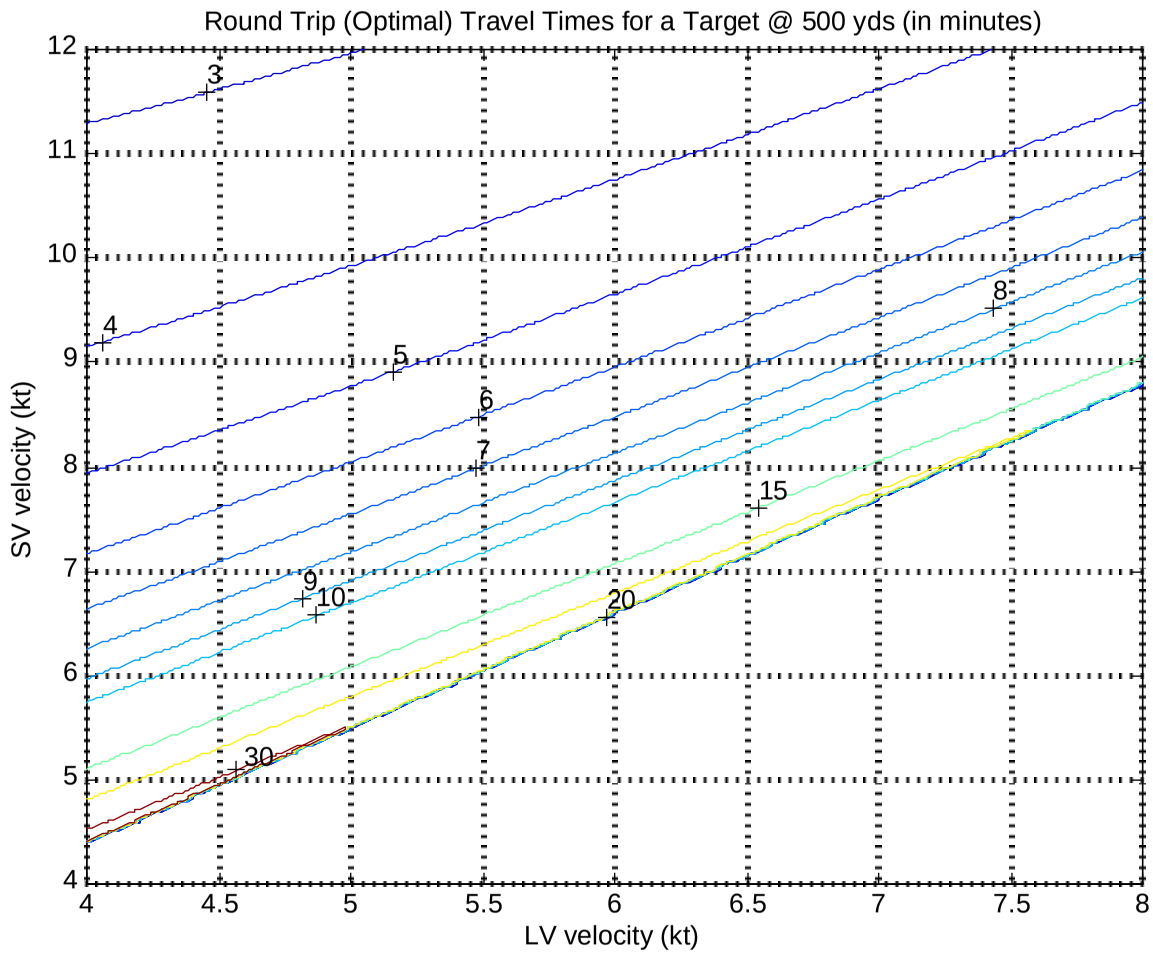


time in minutes

Figure 2: Optimal Path Travel Times, re: alpha

FUTURE MCM STUDY

BIRD-DOG OPTIMAL PATH TRAVEL TIMES

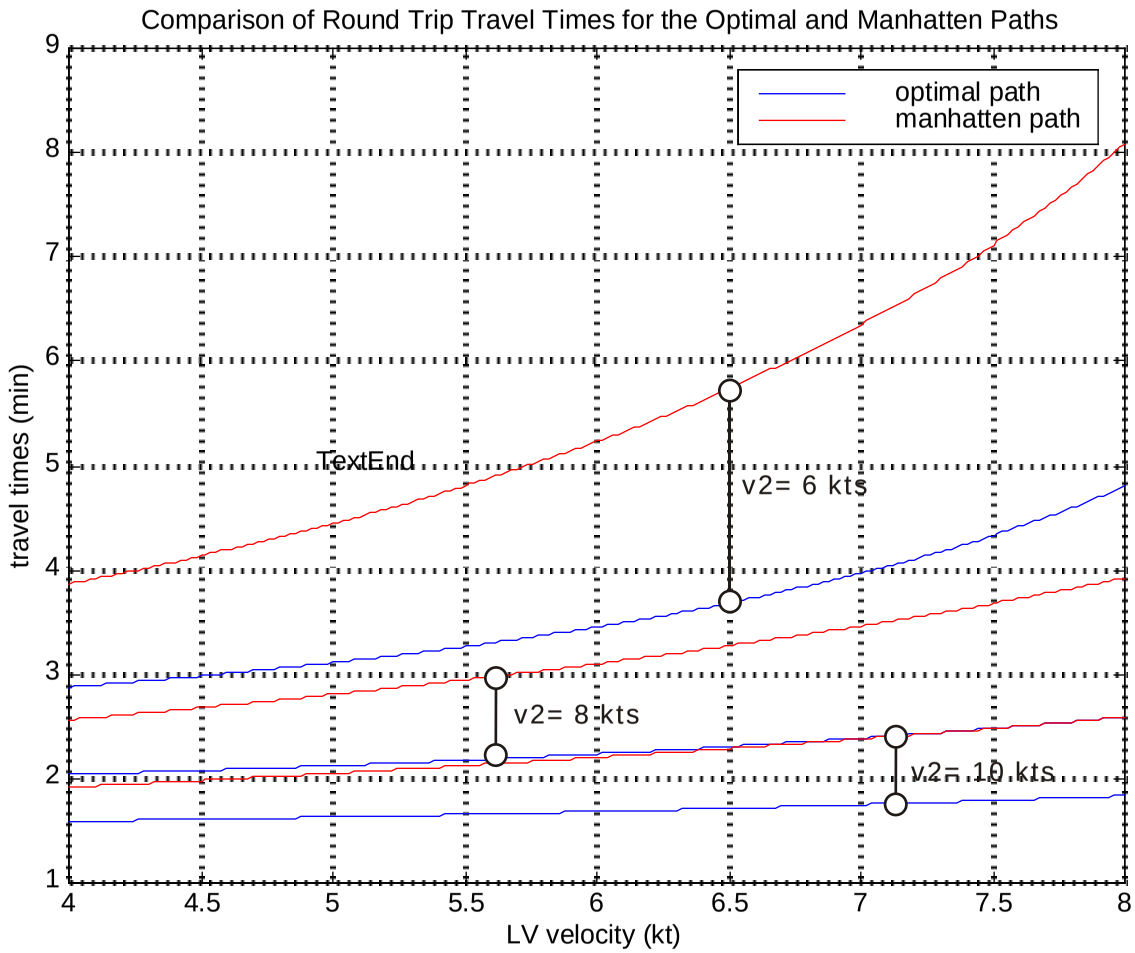


time in minutes

Figure 3: Optimal Path Travel Times, re: v1 & v2

FUTURE MCM STUDY

BIRD-DOG PATH TRAVEL TIME COMPARISON



time in minutes

Figure 4: Path Travel Times Comparisons, Optimal vs. Manhatten

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

BIRD-DOG VEHICLE DEPLOYMENT REQUIREMENTS

- Goal: determine the number SVs required in a system

- Approach: develop a simple simulator
  - random uniformly distributed false contacts (FCs) along a track
  - adjust FC/nm2 & LV swath width
  - adjust LV & SV velocities
  - use optimal path travel times
  - incorporate launch and recovery (L&R) times

- Parameters
  - FC/nm^2
  - LV swath width
  - LV & SV velocities

- Results
  - PDFs of the number of SVs required at each moment along the track
  - likelihood of exceeding a given number of SVs in a system configuration

FUTURE MCM STUDY

BIRD-DOG DEPLOYMENT SIMULATOR

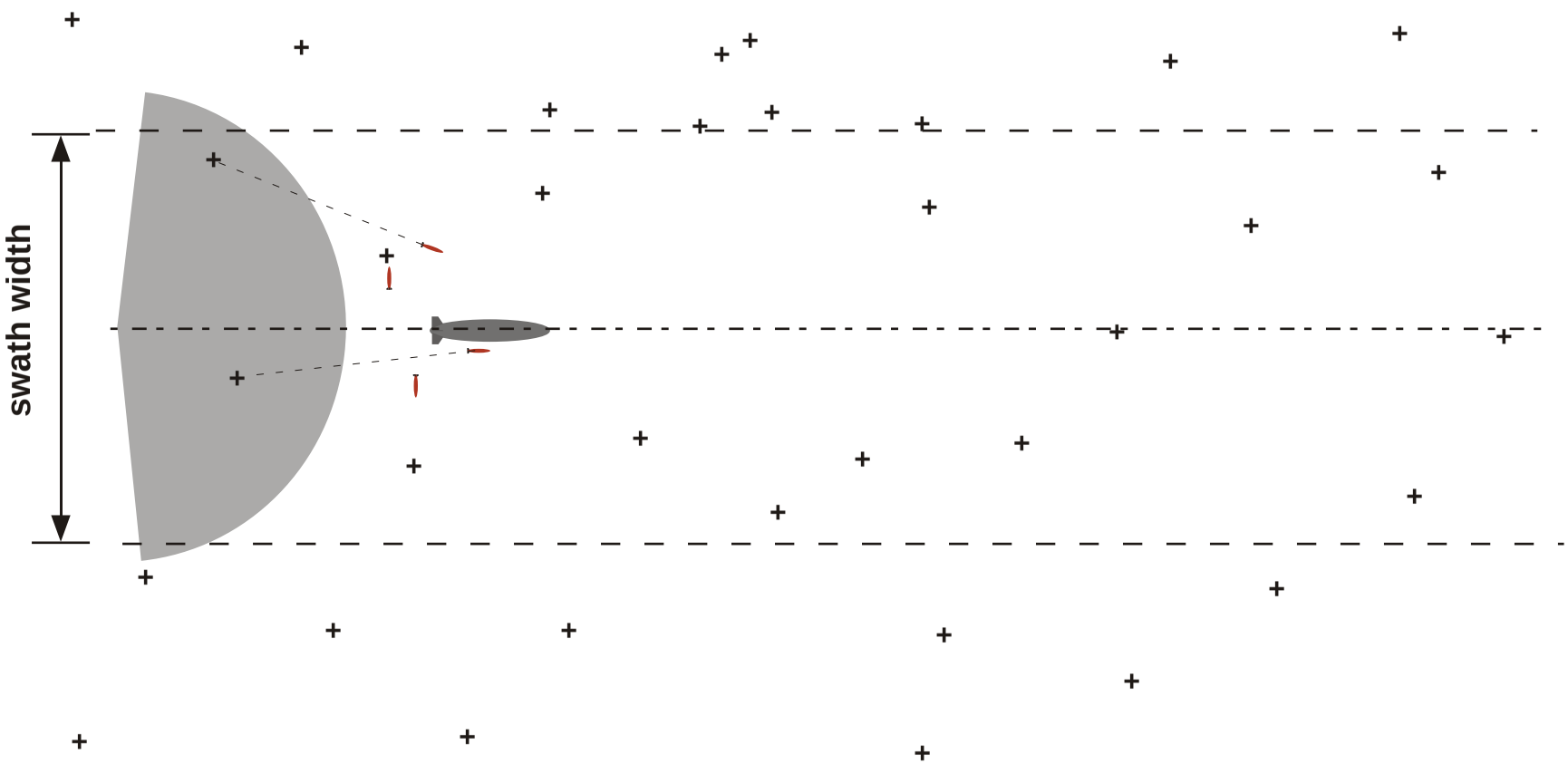


Figure 5: SV 3 Optional Path Geometries

FUTURE MCM STUDY

PDF of NUMBER of BIRD-DOG SVs DEPLOYED

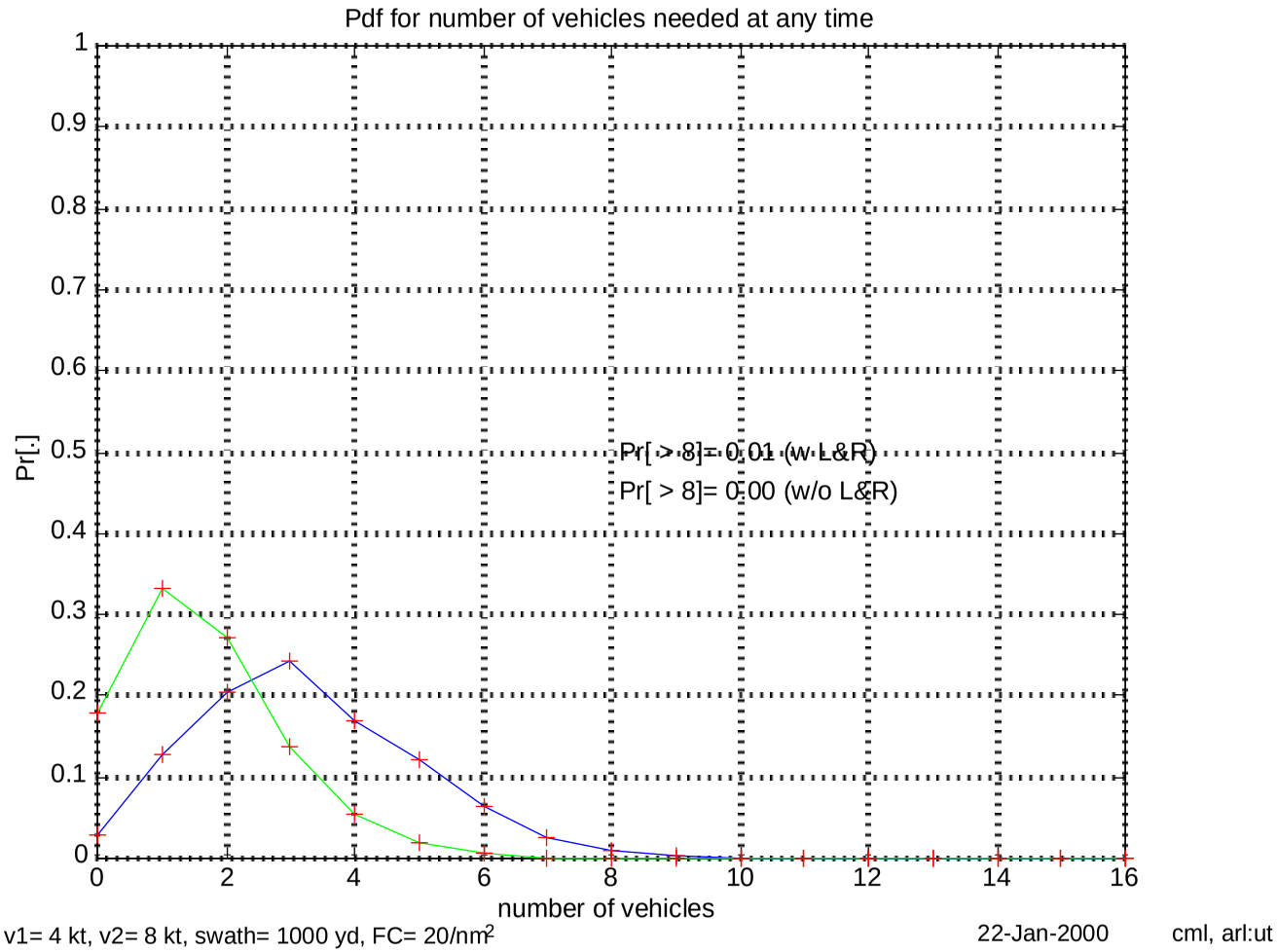


Figure 6: PDF of Number of Bird-dog SV Deployed, alpha= 2

FUTURE MCM STUDY

PDF of NUMBER of BIRD-DOG SVs DEPLOYED

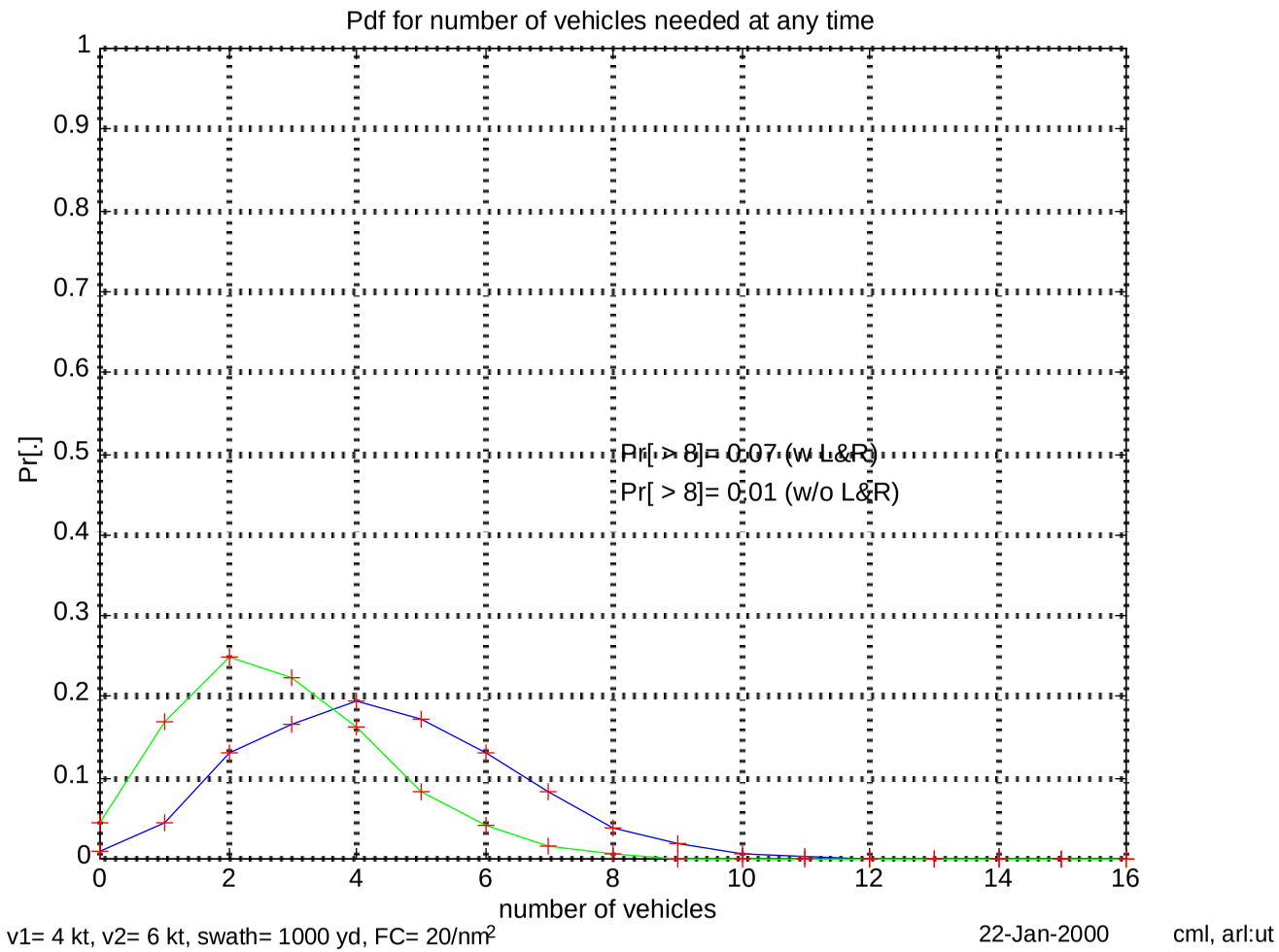


Figure 7: PDF of Number of Bird-dog SV Deployed, alpha= 1.5

FUTURE MCM STUDY

PDF of NUMBER of BIRD-DOG SVs DEPLOYED

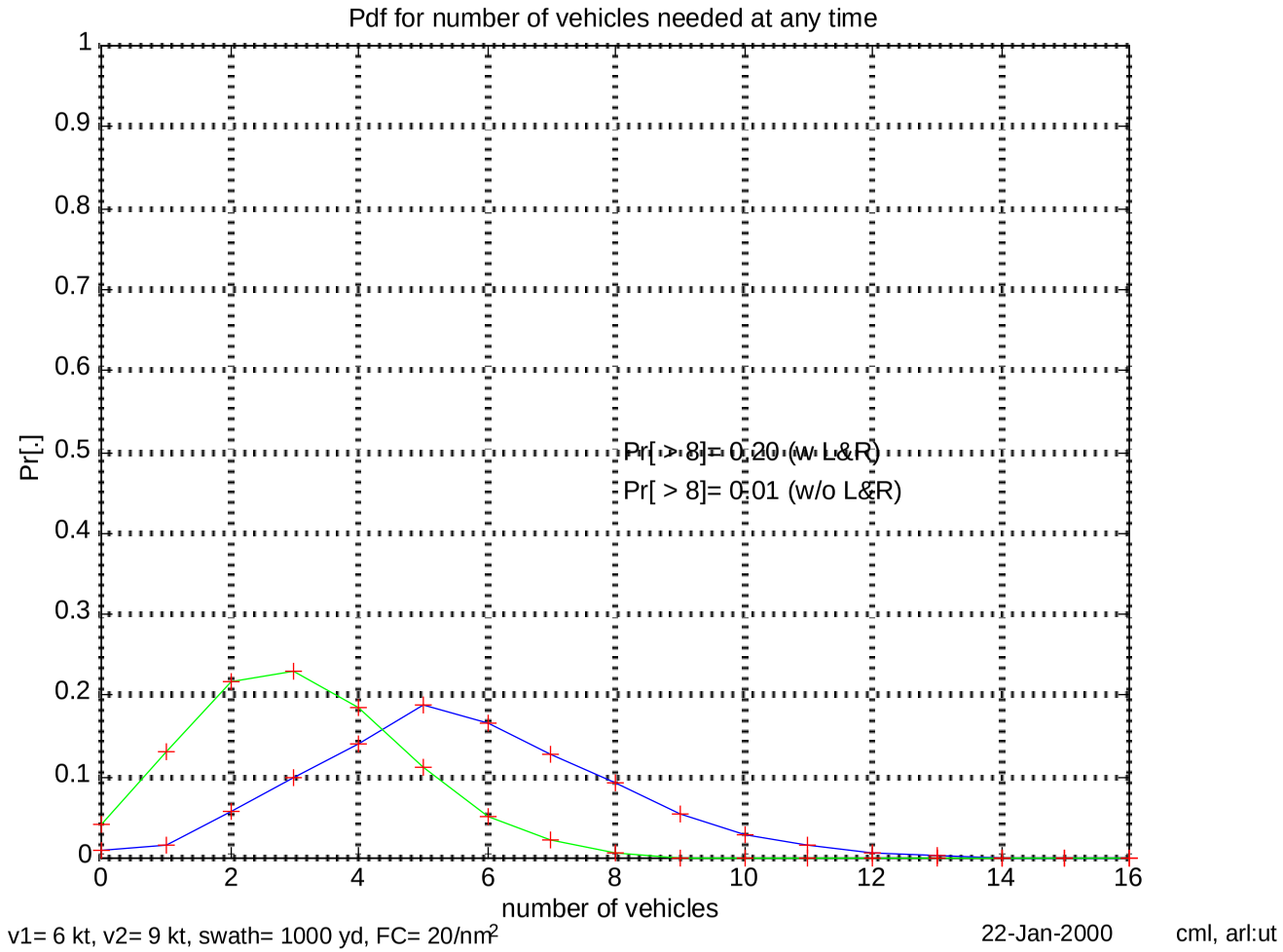


Figure 8 PDF of Number of Bird-dog SV Deployed, alpha= 1.5

FUTURE MCM STUDY

LIKELIHOOD OF TOO MANY SVs NEEDED

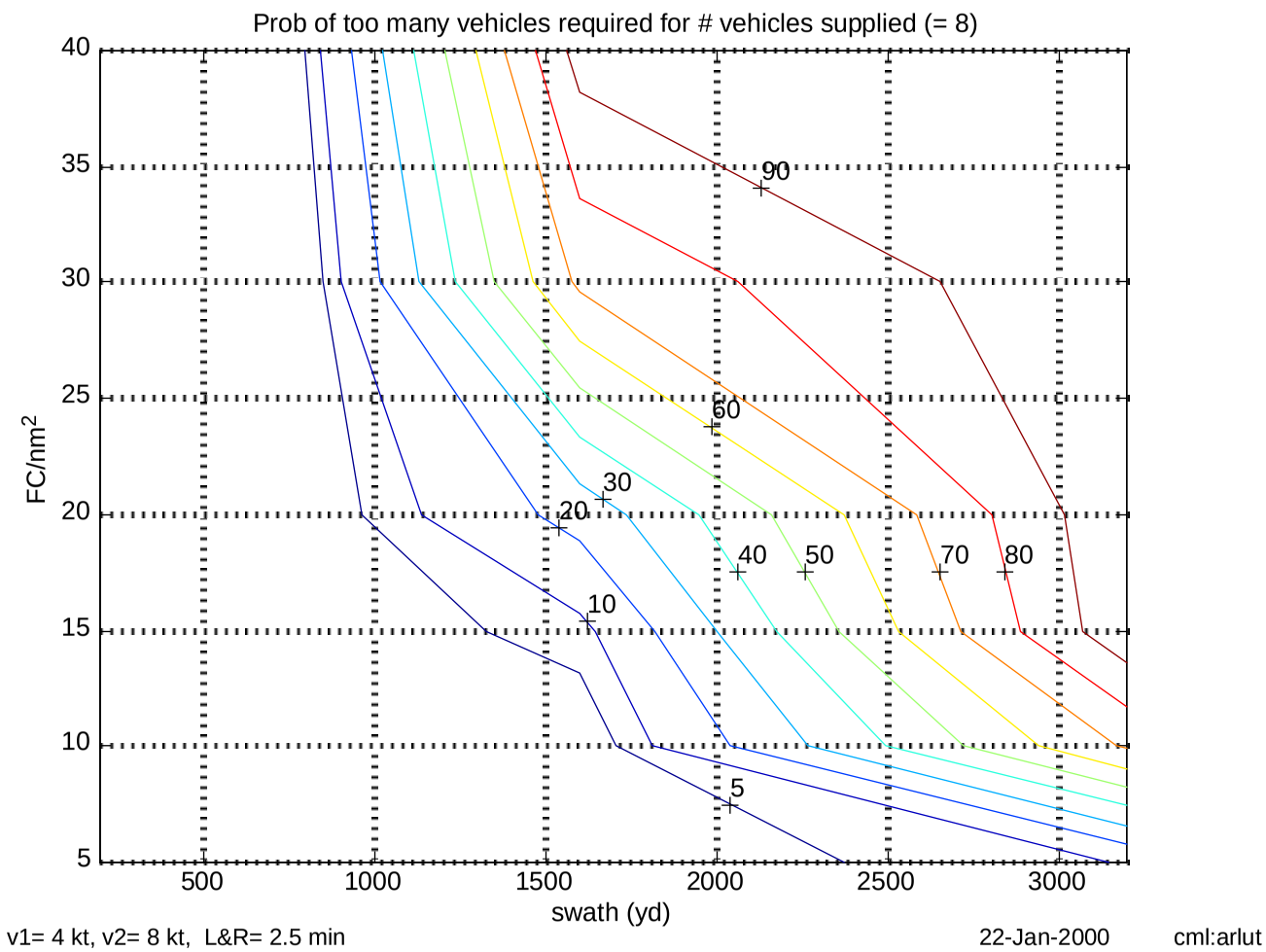


Figure 9: Likelihood of Too Many SVs Needed

FUTURE MCM STUDY

LIKELIHOOD OF TOO MANY SVs NEEDED

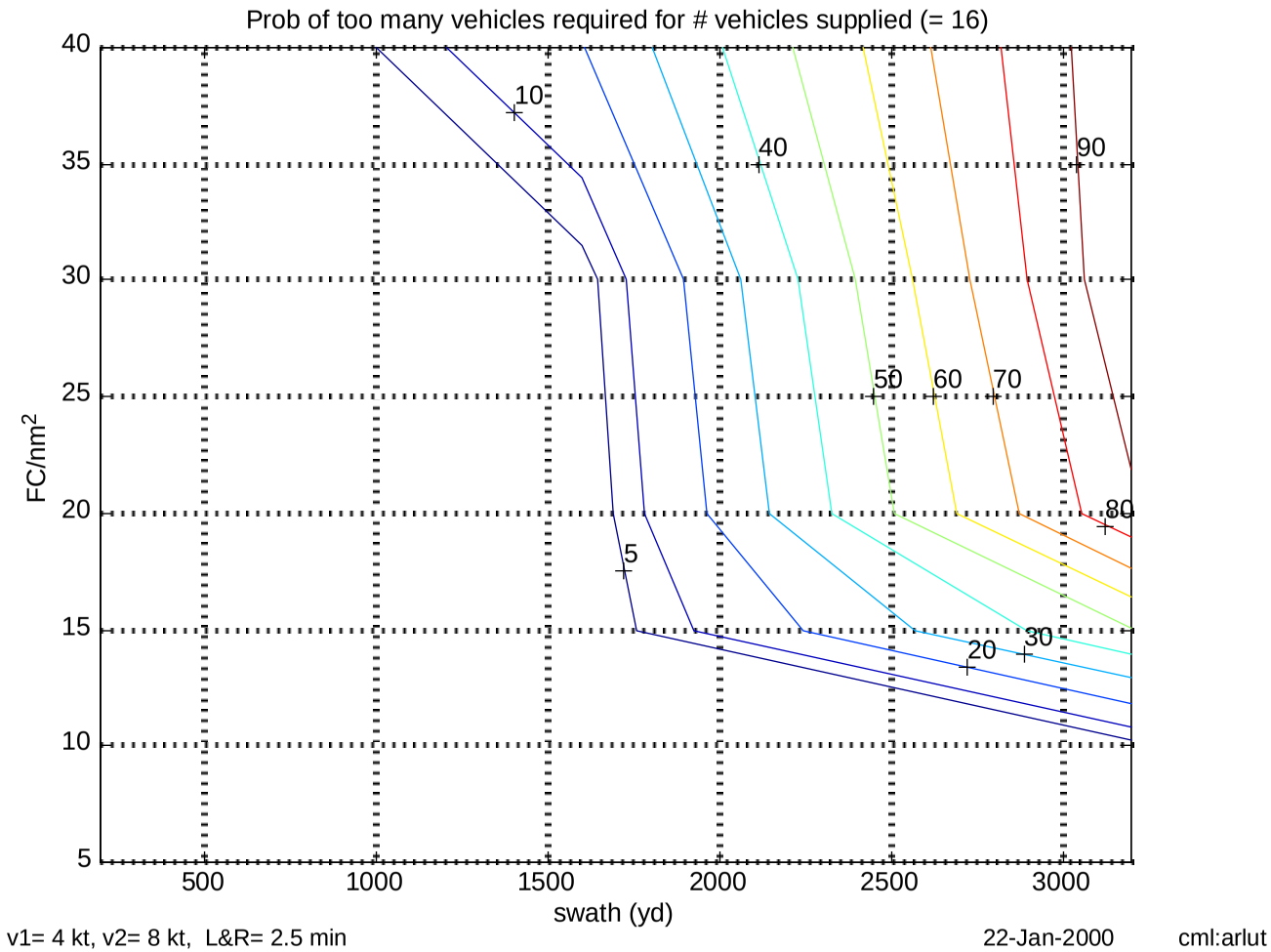


Figure 10: Likelihood of Too Many SVs Needed

FUTURE MCM STUDY

LIKELIHOOD OF TOO MANY SVs NEEDED

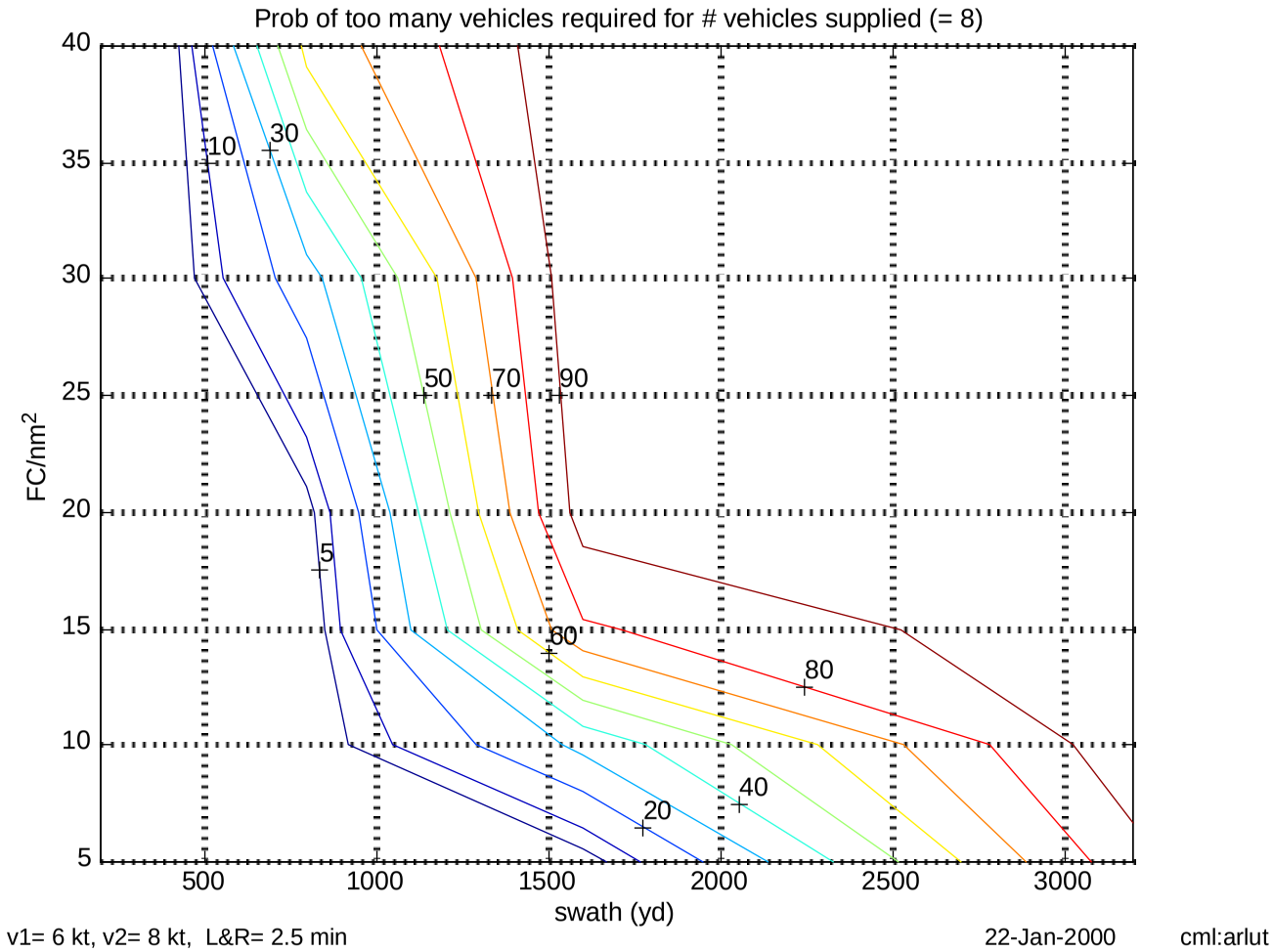


Figure 11: Likelihood of Too Many SVs Needed

FUTURE MCM STUDY

LIKELIHOOD OF TOO MANY SVs NEEDED

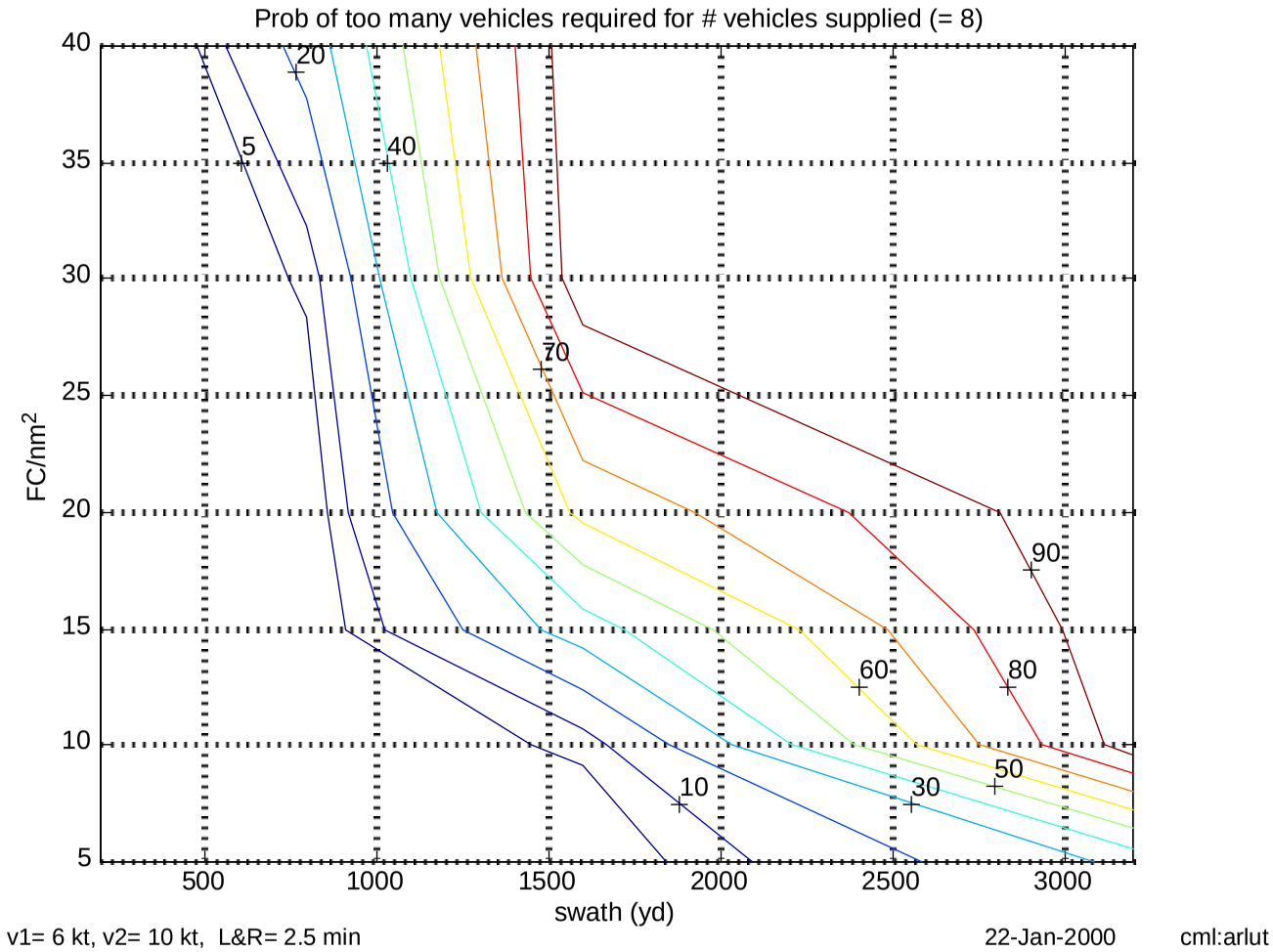


Figure 12: Likelihood of Too Many SVs Needed

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

MITIGATION OPTIONS FOR TOO MANY SVs REQUIRED

- Mitigation techniques which do not change the overall ACR

  - Do nothing and ignore some contacts
  - Minimize L&R times by deploying an SV as soon as it returns if a new MLO contact has been detected
  - Increase SV speed during high contact density times
    - obvious cost of reducing the SV endurance
  - Deploy an SV to investigate two or more contacts
    - encountered in close proximity.
  - Direct SVs after launch

- Mitigation options which will reduce the ACR of the system include

- Slow down the LV
  - reduces the FC encounter rate and the travel times of the SVs
- Reduce the search swath width of LV
  - reduces the FC encounter rate and the travel times of the SVs
  - this also reduces the total area coverage since the LV must run more lanes
- Require the LV the perform a loop maneuver.

FUTURE MCM STUDY

SVs NEEDED TO MEET FC-SWATH NEEDS

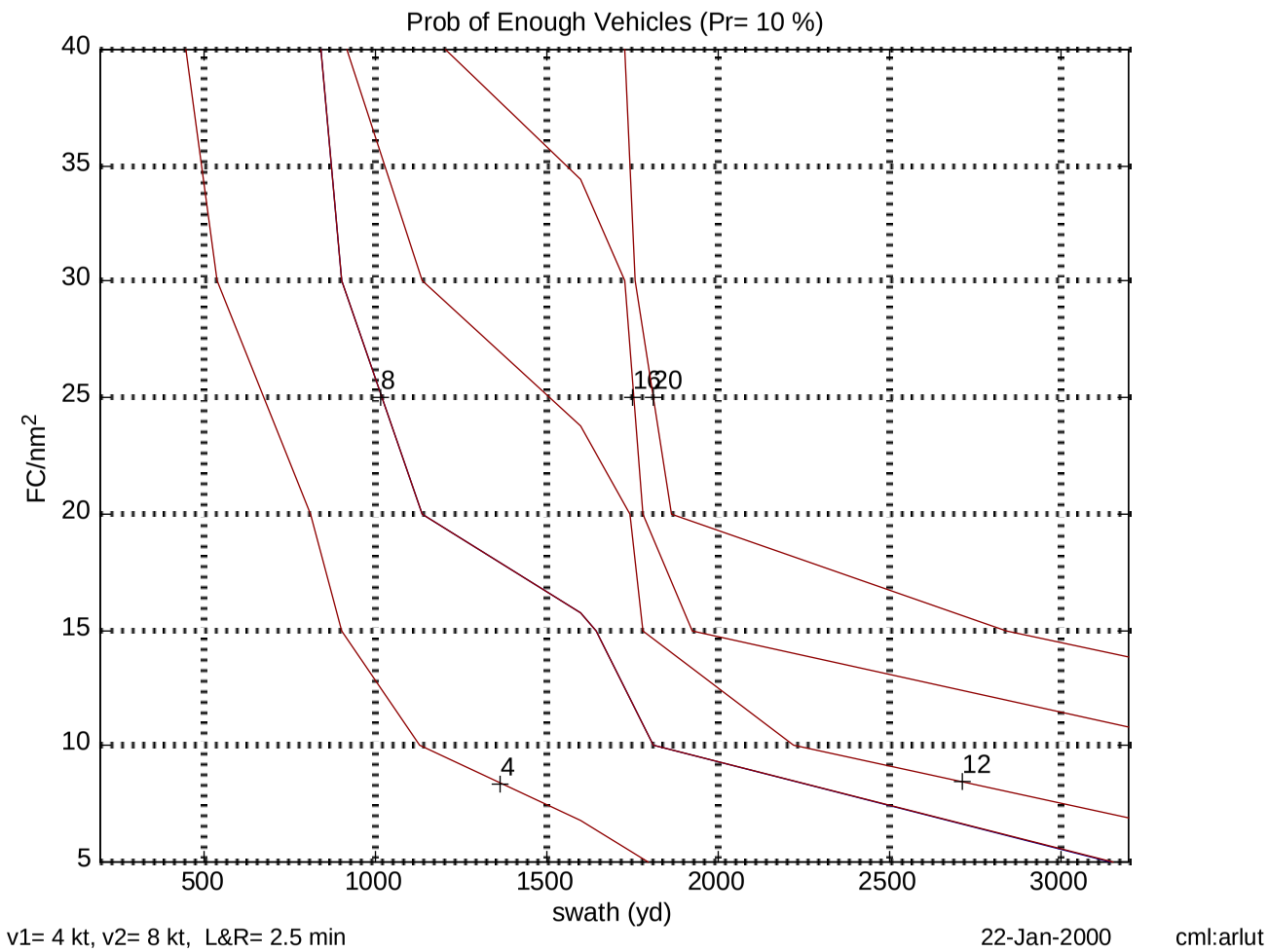


Figure 13: Likelihood of Too Many SVs Needed Low Pr

FUTURE MCM STUDY

SVs NEEDED TO MEET FC-SWATH NEEDS

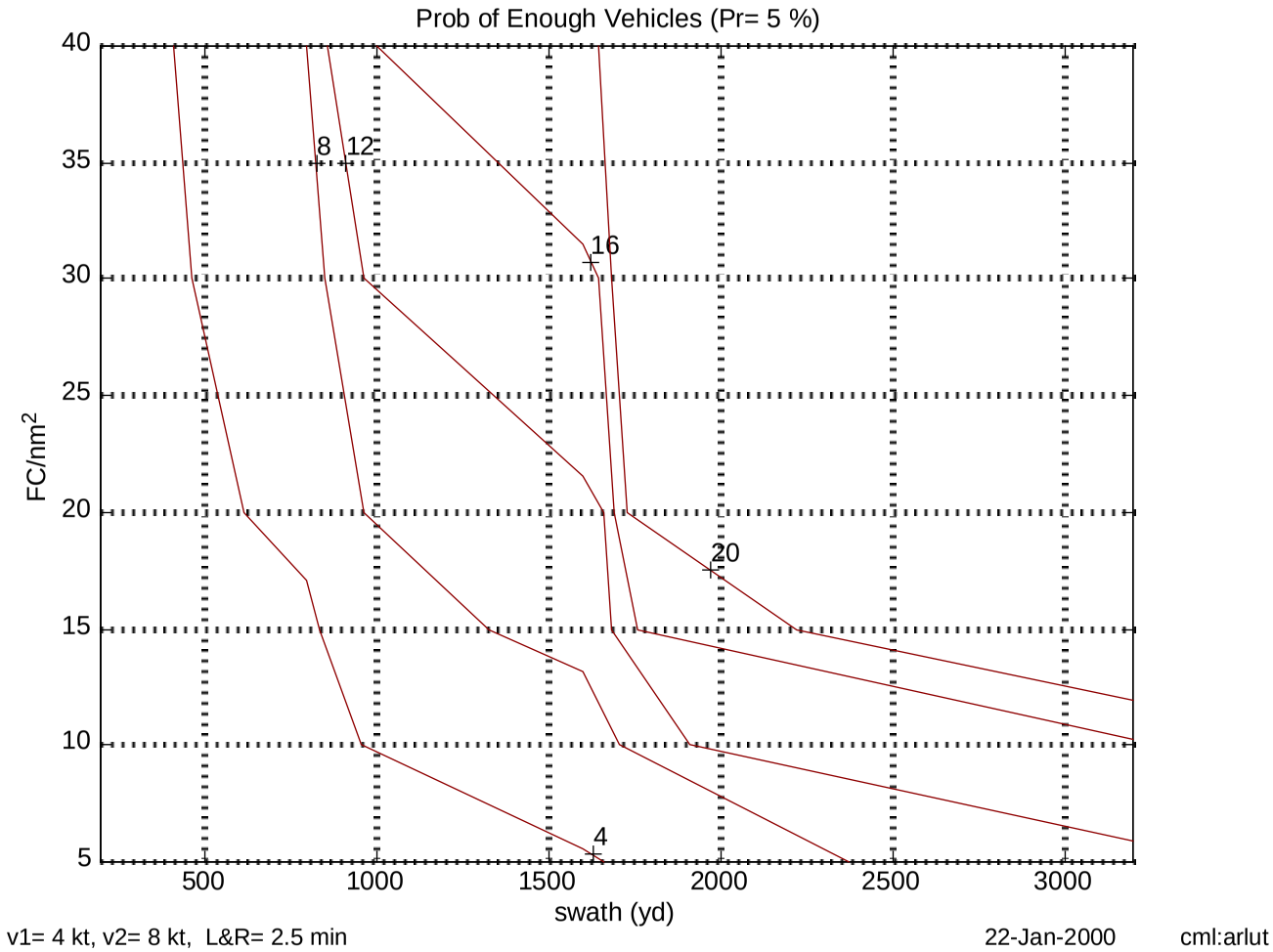


Figure 14: Likelihood of Too Many SVs Needed Low Pr

FUTURE MCM STUDY

SVs NEEDED TO MEET FC-SWATH NEEDS

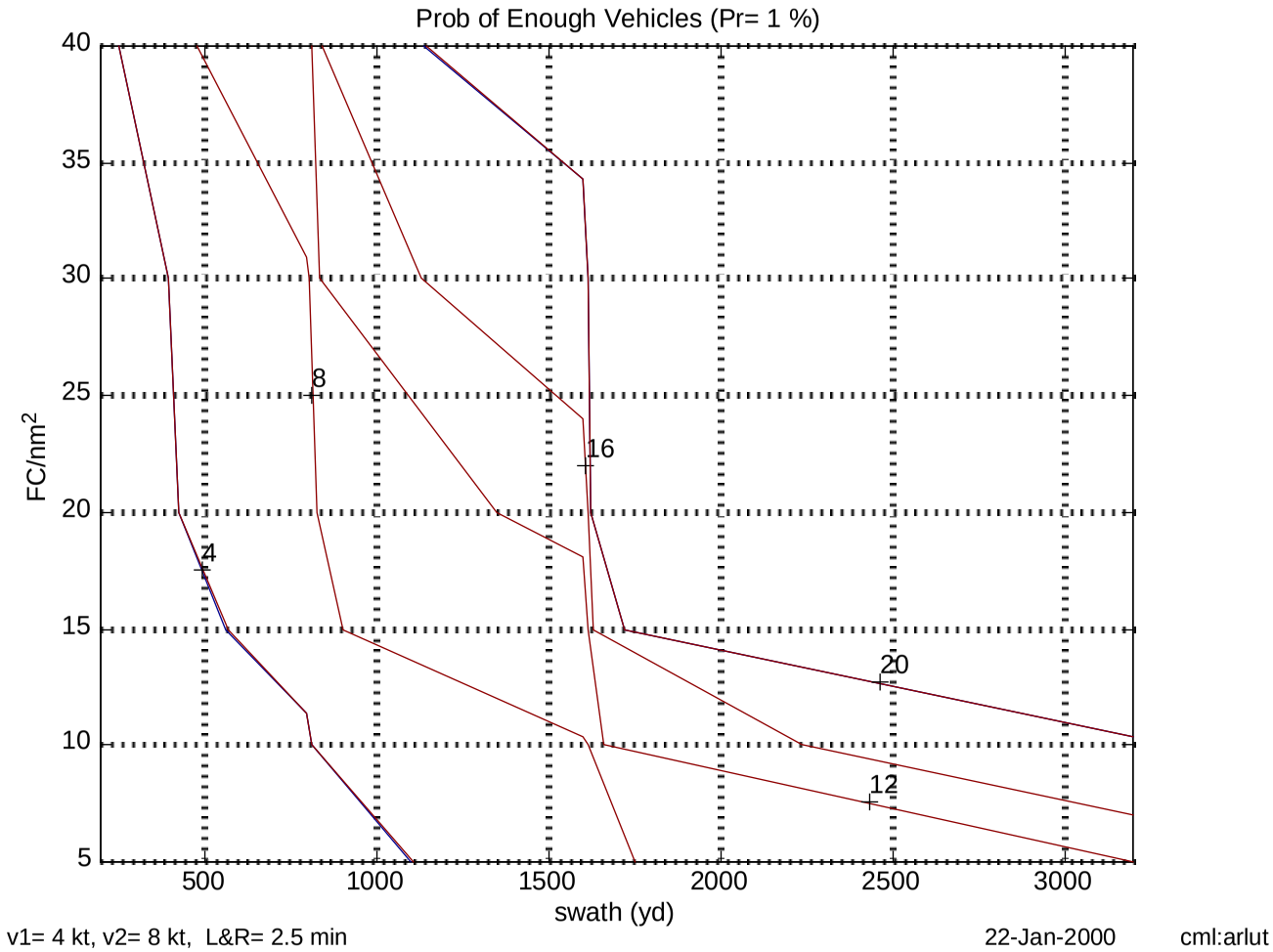


Figure 15: Likelihood of Too Many SVs Needed Low Pr

FUTURE MCM STUDY

SVs NEEDED TO MEET FC-SWATH NEEDS

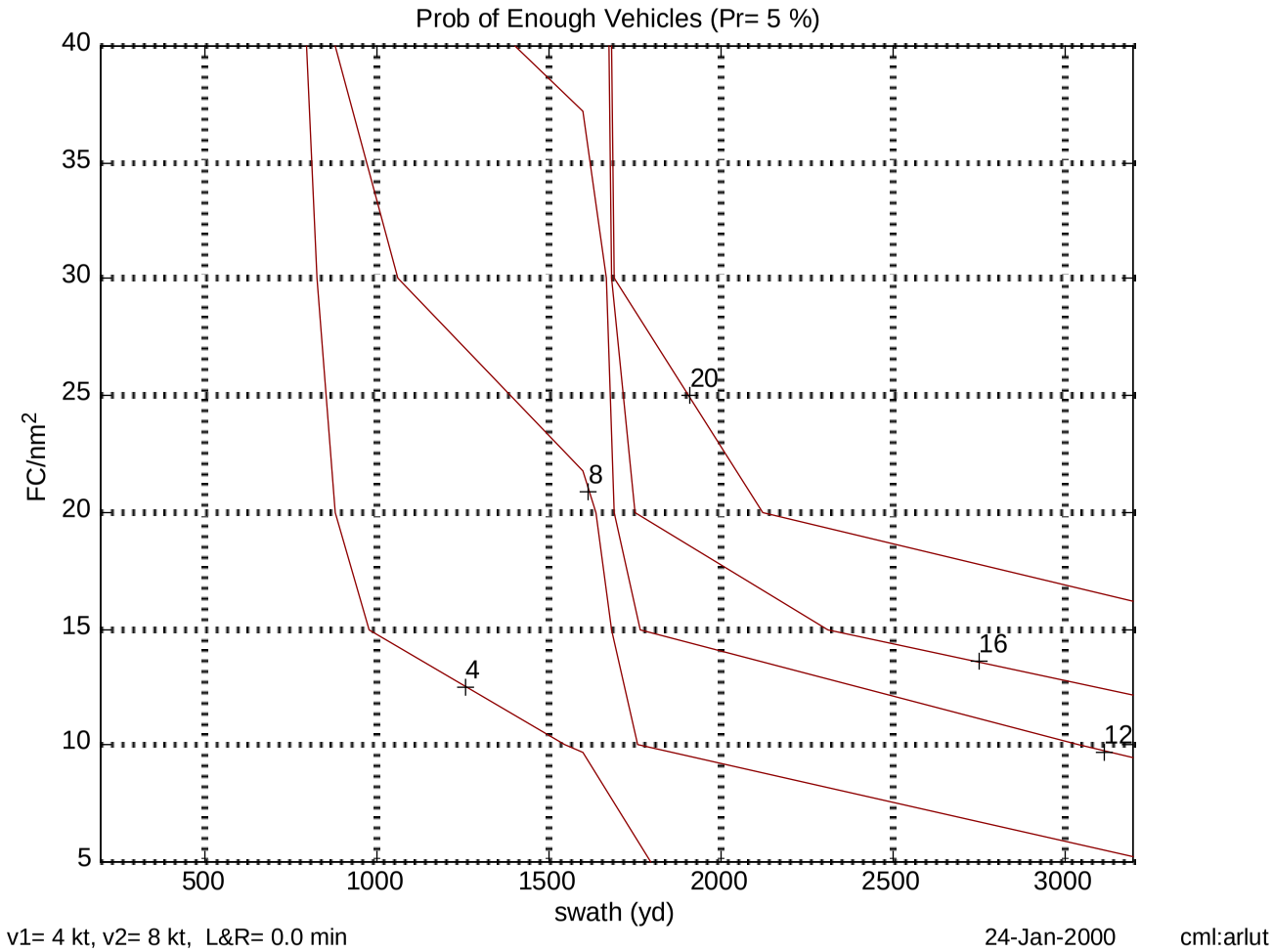


Figure 16b: Likelihood of Too Many SVs Needed Low Pr

FUTURE MCM SYSTEM ALTERNATIVES

BIRD-DOG DEPLOYMENT REQUIREMENTS

CONCLUDING REMARKS

- Observations

  - SV deployment factors
    - increases with FC density
    - increases with swath width
    - increase with LV velocity
    - decreases with SV velocity

- Conclusions
  - search sensor w/ good detection and discrimination sensor is important
  - exceeding # of SVs mitigation scheme are probably necessary
  - moderate number of SVs (8+) have a significant FC/Swath-Width Space coverage

  - FC/Swath-Width Space coverage matches “most” environments (with a good search sensor)

FUTURE MCM STUDY

AVERAGE # SVs

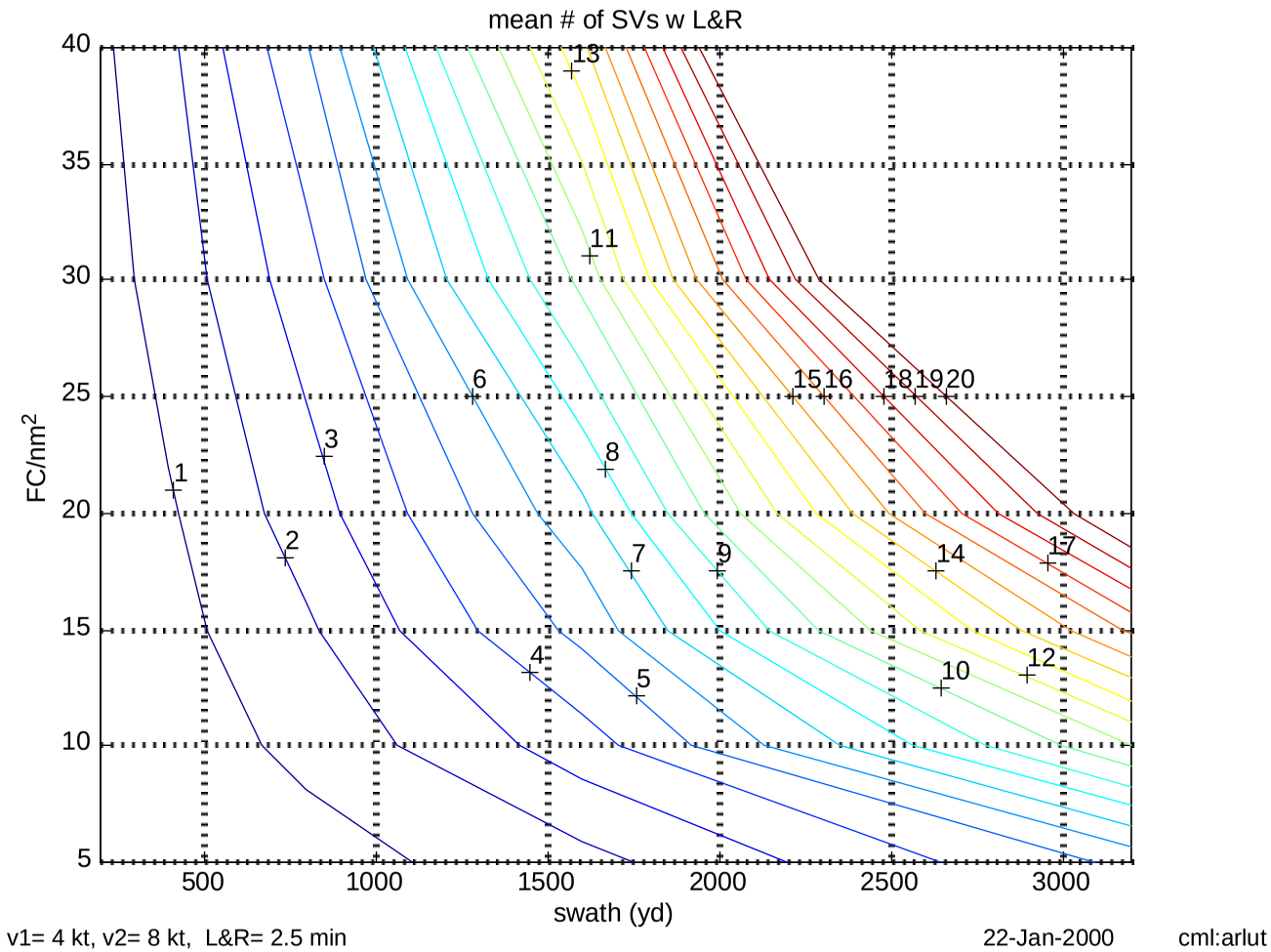


Figure 17: Average number of SVs

FUTURE MCM STUDY

AVERAGE RUN TIME PER SV

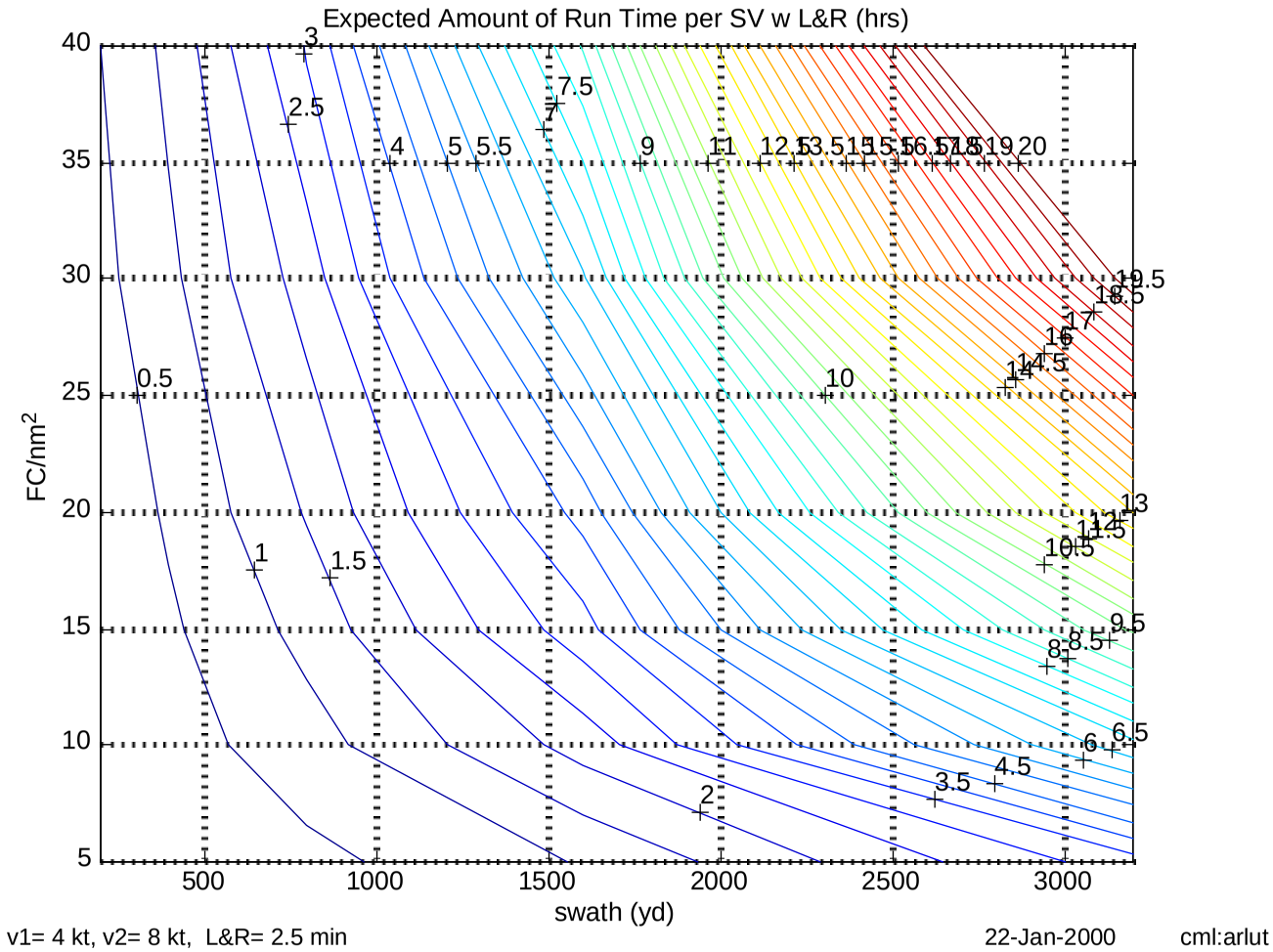


Figure 18: Average number of SVs

Applied Research Laboratories
University of Texas at Austin
Inter-Office Memo

May '00

To: Rick Bailey
From: Charles Loeffler

Subj: Some Statistics on Search and Clearing with Multiple-Vehicles

This memo is a first look at search and clearing an area of objects with a multiple independent vehicles. This is not meant to be a complete system level analysis but rather a study to bound or outline some of the issues. This study was motivated by observing a software vehicle simulator in which multiple vehicles search and destroyed randomly placed objects in a field. In the observations a number of issues arose. These will be enumerated and discussed in the remainder of this memo.

In the first part of this study a set of simplifying are made. These are

• The vehicles are completely independent and have no communications among themselves. Communication systems is a complicating issue in the simulator, system design, and system utilization. This simplified the GNC of the vehicles and requires less intelligent coordination.

• The vehicles are set on parallel overlapping tracks and have perfect navigation. Clearly, the vehicles will not have perfect navigation in a realistic implementation; however, for the purposes of this study, the "prefect nav. Scenario" provides a useful baseline and insights.

• The vehicles have a "cookie cutter" search sector with a probability of one for detection in the sector.

• All detected objects in the search are assumed to be mines and should be prosecuted and destroyed.

• Vehicles travel until they detect an object, then steer to it, and destroy it (and themselves) when they get very close to the object. If a vehicle detects multiple objects, it proceeds to the closest object.

• At the end of a track the vehicles stop.

Some of the questions that will be addressed are;

> Given the assumptions stated above, how many vehicles are required to clear an area to a pre-defined level?
>
> How many vehicles are wasted (i.e. ran down empty lanes)?

Area Model

The area is a rectangular area with uniformly distributed objects. The number of objects is defined probabilistically in terms of object density (Objects/nm^2). The pdf of the number of the objects in an area or sub-area (like a vehicle track) is based on a binomial distribution that converges to a Gaussian. To determine the pdf, an area is subdivided in many small areas. The small areas are selected to be so small that it is very unlikely that they small contain more than one object. The probability, p, that a small area has an object is the object density times the area. For example, if the object density is D, the area of the large area of interest is A, and the large area is divided into M smaller areas, then the probability that each small area has an object is

$$p = D\frac{A}{M}$$

and the probability that there are m objects in the large area is

$$f(m) = p^m (1-p)^{M-m} \frac{M!}{m!(M-m)!}$$

For large M (or very small sub-areas) and Mp small, this distribution converges to the Poisson distribution;

$$f(m) = \frac{AD^m}{m!} e^{-AD}$$

which has a mean and variance of $A \;\; D$.

Also large M (or very small sub-areas) this distribution is nearly Gaussian with mean and variance, $M \;\; p$ or $D \;\; A$;

$$f(m) = \frac{1}{AD\sqrt{2\pi}} e^{-\frac{(m-AD)^2}{2A^2D^2}}$$

Clearly, these distribution are mostly centered around the expected number of objects, AD. The same formulas can be used to determine the distribution in the area for each track by substituting the track area, A' for A and $\frac{A'}{A}M$ for M.

Observations on a Typical Low Density Run

Figure 1show a typical simulation run for an area with low contact density. It can be seen that at low contact densities the likelihood of a vehicle having no contacts in its track is relatively high yet at the same the likelihood of several tracks having multiple targets is also fairly high. This means that numerous vehicles will be "wasted" since there are no objects in their tracks to detect and numerous rows of vehicles will be required to remove all the objects in "high density" tracks. Of course, multiple rows of vehicles compounds the the of vehicles wasted on empty tracks. The probability that a track is empty (i.e. m=0) is

$$e^{-AD}$$

Similarly, the likelihood that the number of objects is less than the number of vehicles assigned to that track is

$$\Pr[\#\,objs < n] = Q(1 + Floor(n), AD)$$

where $Q(\cdot)$is the regularized incomplete gamma function. Figure 4 shows a set of cummlative distributions for increasing expected number of objects, AD, and relative to the expected value. The general shape of the plots is independent of AD, so one can roughly determine the number of vehicles required to reach certain clearence confidence levels. Table 1 summarizes these estimates of the number vehicles required for a given probability of "clearance" for a lane is

Pr[#vehicles > num objects]	# vehicles/expected_#_objs
99 %	2.0
98 %	1.9
90 %	1.4
80 %	1.24
50 %	0.9

Table 1: The number of vehicle required to clear a lane to a specified level of confidence.

If one sets the confidence level for clearance one can determine the expected number of vehicles which remove an object and the expected number of vehicles which are wasted. For high clearance confidence level, 80% to 99%, the expected number vehicles which remove an object is approximately $A\ D$, the expected number of vehicles in the area. For high clearance confidence level, the expected number of wasted vehicles is number for vehicles used (see Table 1) minus the expected loss. For a lower clearance confidence level, the approximation is not as good. For 50% confidence level, the relationship is less straight forward and is shown in Figure 2.

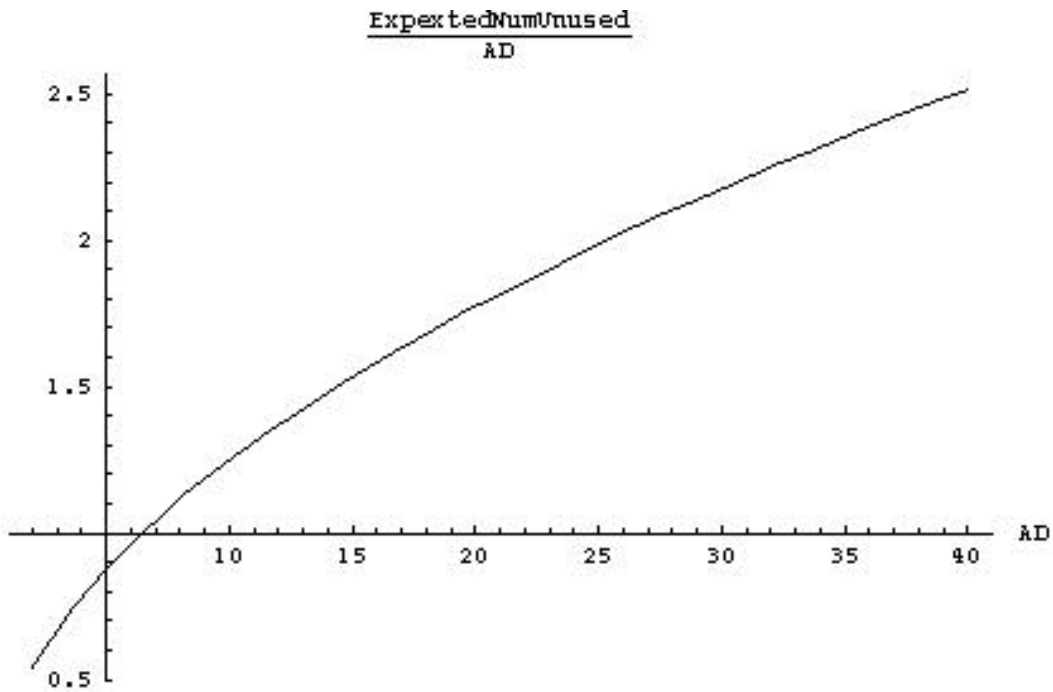


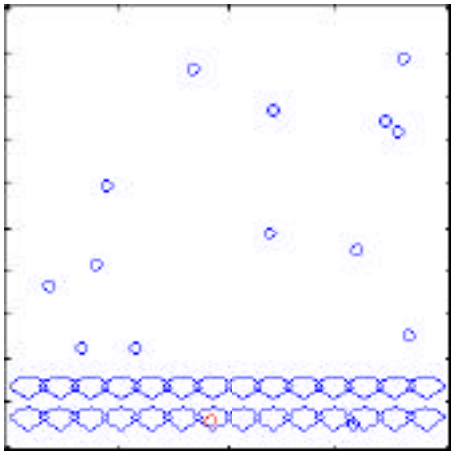
Figure 2: Ratio of the Expected number of unused vehicles to the expected number of objects for low clearance confidence level of 50%.

Conclusion: These evaluations and the simulations show using multiple vehicles along parallel tracks, in which each vehicle's mission is to search and neutralization a mine along it own search (i.e. one vehicle per mine), is a very ineffective approach to the problem. In order to obtain a high probability that each search lane is cleared of mines one must employ many vehicles per lane and many more vehicles than there are mines, which guarantees that there will be numerous vehicles that are wasted.

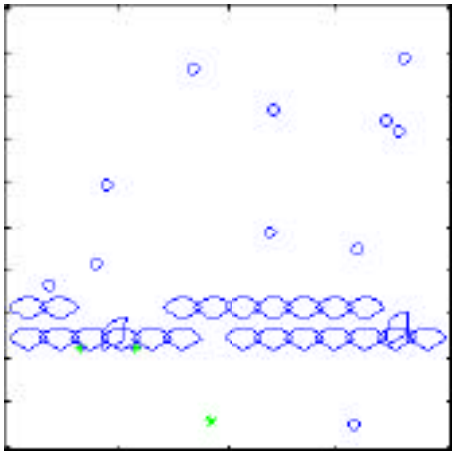
To counteract these trends, one must apply some significantly adaptive and intelligent re-assignment strategies to the vehicles.

FMCM STUDY

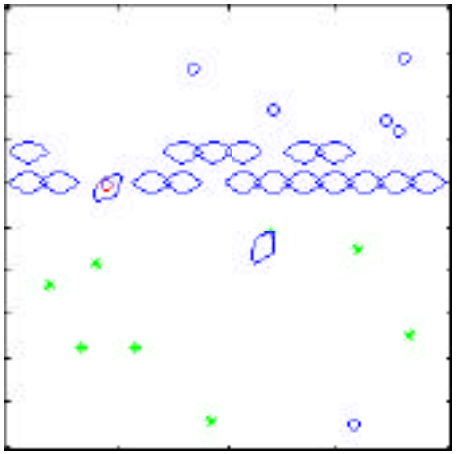
SIMULATION OF “MARCHING” SEARCH-AND-NEUTRALIZE VEHICLES



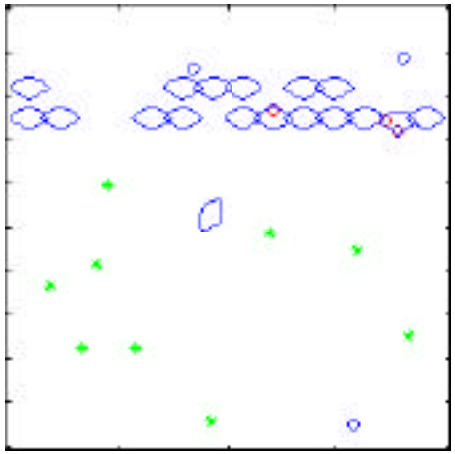
starting position



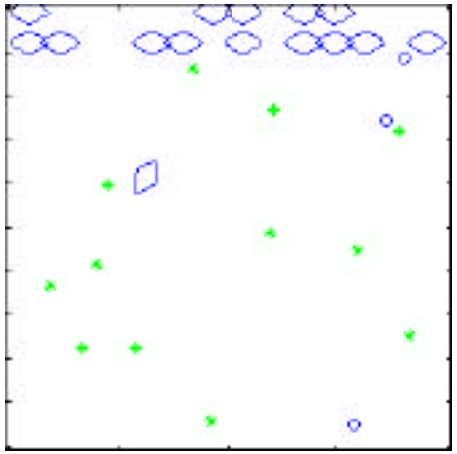
1/4 distance down lanes



second half of lane



3/4 distance down lane



finish lane

- multiple rows of vehicles
- each vehicle searches a parallel lane
- if a vehicle detects a mine it neutralizes it
  - “one vehicle per mine”
- vehicles search their laneindependently of others

- even for low density scenarios multiple rows of vehicles are required for a low Pr[missed mine in lane]
- number of unused vehicles is high
  - ratio of vehicles to mines is high

Figure 1: Example of Multiple Rows of Vehicles Search and Neutralizing a Target Field