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5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 MARITIME DOMAIN PROTECTION (MDP) ARCHITECTURE

One insight gained in the Naval Postgraduate School (NPS) MDP Study was the recognition of the extreme difficulty in designing a system to sufficiently address the MDP problem. Despite keeping the political and legal considerations out of the problem space, there were a myriad of variables resulting from various international participants in a largely unregulated, vulnerable industry that was simultaneously critical to the worldwide economy. The interconnected nature of the commercial shipping industry also held challenges, as any improvement or enforcement that was made across the entire industry would lead to significant shipping costs, especially due to delays. On the other hand, if improvements or enforcement were only made in a few areas by cooperative players, this could lead to either those players disproportionately assuming the cost burden or those areas being avoided altogether by nonconforming shippers.

As a result of the multidiscipline, interrelated nature of the MDP problem, a Systems Engineering approach was critical. There was no other approach that would necessarily focus on the entire problem as an integrated whole, instead of focusing on “stovepipe” or point solutions, although this had historically been the problem-solving method. There could be no lasting solution to the MDP problem, as technology, public attitudes, and threats would continuously change. Although the NPS MDP Study focused on three specific threat scenarios, a continuous reassessment of the threat capabilities and intentions versus industry and infrastructure vulnerabilities would be required to determine the direction of future resource focus.

5.1.1 Weapons of Mass Destruction (WMD) Scenario

The WMD Scenario integrated all five MDP System components (Sensors, Command, Control, Communications, and Intelligence (C3I), Force, Land Inspection, and Sea Inspection) in an attempt to detect a nuclear weapon outside of the Straits of Malacca. A 20-KT, Russian-made, nuclear device was assumed for this scenario.

5.1.1.1 Conclusions

The largest gain in architecture performance in the WMD scenario came with the addition of a Land Inspection System installed in the highest volume ports-of-origin for cargo destined for the Straits. The Land Inspection alternative that was evaluated also relied on industry participation, using qualified "Trusted Agent" shipping companies to help find or deter WMDs from being loaded in their shipping containers. This allowed resources to be focused on nonparticipating shippers, since they should be more likely to transport illegal cargo. Unfortunately, the cost to the shipping industry was significant for this Land Inspection alternative due to the worldwide extent of the industry, and the vast number of containers that were loaded and transported each day. Also, there was a tradeoff that occurred between the number of ports that actively inspected for WMD, thereby reducing the opportunity for WMD shipment, and the high cost to install the Land Inspection System in those ports—in order to install Land Inspection Systems in a meaningful number of ports, significant resources would be required.

Another less costly alternative architecture offered a significant improvement over the "As-Is" architecture, although the improvement was far less than the architecture that included the Land Inspection System. This lower-cost alternative architecture used an improved Sensor system to detect inbound ships at 250 to 300 NM from the area of interest, along with a Sea Inspection System that used a 12-man boarding party to search suspect ships. Due to the incidence of false alarms, this Sea Inspection System was only cost-effective with a C3I System that could accurately correlate positive detections made by the boarding party to determine the cause of the false alarm (i.e., radiation source due to pottery, medical equipment, etc.).

5.1.1.2 Recommendations

In order to achieve the most effective near-term defense against the WMD scenario, investments in sensors should be made that would allow the detection of contacts of interest at much further ranges. This would give Command and Control (C2)/Intelligence Centers more time to process inbound contacts. Additionally, in order to detect WMD prior to an area of interest, a Sea Inspection System using boarding teams with handheld sensors should be established that would be forward-deployable to allow the inspection of cargo

ships while en route. Increasing Intelligence capabilities would also be required in order to offset false alarm detections by the boarding teams.

More effective defense against the WMD scenario could only be accomplished by installing Land Inspection systems in high-volume ports. These systems would take advantage of cargo delay times and close contact with transportation equipment in order to detect illegal cargo. Additionally, establishing a program to certify and randomly test "Trusted Agent" shipping companies would be required to deter the shipment of WMD.

5.1.2 Ship As a Weapon (SAW) Scenario

The SAW scenario integrated three MDP System components (Sensors, C3I, and Force) in an attempt to defeat a ship used as a weapon against the Port of Singapore. The most difficult-to-defeat assumptions were used in this scenario, in which the attack was not initiated until the harbor pilot came aboard the Contact of Interest (COI) at five NM. This limited the scenario by restricting the time available to recognize the attack and mobilize forces. This made the scenario as difficult as possible, but masked some architecture benefits that could be achieved with earlier detection of hostile intent.

5.1.2.1 Conclusions

The "As-Is" Force System that loaded Sea Marshals on high-value COIs at five NM with the harbor pilot was effective, given the specifics of the scenario. Only slight improvements in performance were attained with longer engagement times; however, increasing Sea Marshal training and armament significantly improved close-in performance.

The Rapid Response Force alternative was not effective when COI hostile intent was determined at five NM. There simply was not enough response time to brief and deploy the forces. However, if hostile intent was determined at or before ten NM, the Rapid Response Force was highly effective.

The Temasek Defense Systems Institute (TDSI) transport was effective in defeating the in-close SAW attack; however, the system cost was extremely high, and their materially destructive means of defeating the attack would increase the commercial costs and risk associated with this alternative.

Throughout this scenario, improvements in performance were possible by increasing the amount of time the Blue Forces could counter the attack. The largest increase in response time was achieved by improving the Sensor's capability, out to 250 to 300 NM. Improvements in C3I capabilities resulted in more timely decisions, but the increase in response time was less than that obtained by the Sensor's improvement.

5.1.2.2 Recommendations

Effective near-term defense against the SAW scenario was already in place. The only recommended improvement would be to increase the training and armament of the Sea Marshals. Also, despite their not being effective in the in-close scenario, the Rapid Response Force should be maintained. Procedures to increase the response time by either recognizing hostile intent earlier (possibly loading the Sea Marshals onboard earlier) or by slowing down the COI (barriers or other procedural wickets) should be implemented to increase performance against this type of attack.

More robust defense against the SAW scenario would be possible by installing Sensor systems that could track COIs out to 250 to 300 NM. This would allow the correlation of a specific COI with any suspect information from external intelligence, including the activation of a ship's Automatic Identification System (AIS) "panic button" that could indicate a potential hostile boarding. In any case, the deployment range of the Rapid Response Force should be increased in order to enable a response at longer distances, in order to increase the engagement time to defeat any attack.

5.1.3 Small Boat Attack (SBA) Scenario

Due to the extremely short time available to sense and respond to the SBA, the Force System was the only MDP System component that was effective for an attack in progress. The SBA assumed a suicide speedboat loaded with 1,000 lbs of TNT and a contact fuse.

5.1.3.1 Conclusions

Loading Sea Marshals on high-value COIs transiting an area of interest was a cost-effective solution alternative to counter the SBA scenario. This method of point-defense was one active means of hardening the target against the attack. Methods of passive defense also

showed promise, such as only permitting double-hull ships into a threat area or installing blast-resistant coating on ships' waterlines. Although both passive and active defenses would require some level of cost, they both served to minimize the damage resulting from a small boat suicide attack.

The TDSI-selected Sparviero hydrofoil was not cost-effective when used to randomly patrol the Straits (see Appendix I). Although this alternative would serve to indicate presence and could potentially deter some attacks, this effect was not evaluated in this study.

Although defeating a suicide boat attack in progress was very difficult, an increase in Sensors' ability to track small boats in the area of interest could give additional benefits. Intent or anomaly detection software could potentially detect trends or aberrant behavior by small boats, which could be the precursor to or preparation for an attack. Additionally, if SBAs were to become commonplace, being able to back-track to find the port of origin for attacking boats could allow resources to be focused in a region that could find terrorist bases, thereby halting attacks before they occur.

5.1.3.2 Recommendations

Due to the threat-specific nature of the defenses required for the SBA scenario and the rare occurrence of this type of attack, minimal resources should be dedicated to defending against this attack. Randomly on-loading Sea Marshal escorts on a small number of ships transiting the Straits of Malacca would serve to repel hostile boarding attempts, especially by pirates, which could also deter future terrorist SBA attempts. Another use of Sea Marshal escorts could be to capture pirates onboard merchant ships, and thereby deter pirate activity and attempt to gain intelligence on potential terrorist attacks.

More robust defense against future SBAs would be possible by installing Sensor systems that could track small boats in the area of interest. Once small boats were being tracked, anomaly detection software could be used to attempt to detect hostile activity, either by pirates or by terrorists. Once an area of concentrated hostile activity was discovered, then intelligence resources (especially HUMINT) could be focused to prevent future terrorist (or pirate) attacks.

5.2 SENSORS SYSTEM

5.2.1 Conclusions

In the first place, the study conducted by the Sensors Team indicated that there were insufficient current assets in the Straits of Malacca to effectively execute the MDP mission, as required. The "As-Is" search, track, classify, and identification capabilities were severely limited to an area that made it impossible to mount an effective response. As a result of this, it was determined that the existing "As-Is" architecture did not meet the requirements established for the MDP System.

For the proposed architectures, Alternative 1 provided an important (twofold) increase of Time-to-Go-1 (TTG1) compared to the current system, with a net savings over a period of ten years, while Alternative 2 also provided a more significant increase in TTG1 (almost tenfold), though at a substantially higher cost.

The physics-based modeling tools employed, Advanced Refractive Effects Prediction System (AREPS) and Target Acquisition Weapons Software (TAWS), allowed the Sensors Team to analyze sensor capabilities with a high degree of fidelity within the natural environment of the Straits of Malacca. The results of these low-level modeling findings were further used to graphically model the deployment of sensor arrangements for accurate determination of coverages and subsequent determination of inventory needs.

The previously described modeling efforts were complemented with extensive research of existing (and evolving) technologies. Based on all of these detailed studies, the following conclusions were drawn regarding current and future Sensor System capabilities:

Microwave Radar: Microwave radars were determined to be a "ready" solution to provide all-weather, continuous coastal surveillance in the Straits of Malacca. The technology is well-established and the relevant expertise is readily available, making it a quick, easy and affordable solution to implement a network of coastal surveillance radars. Although environmental limitations (particularly "ducting") were analyzed, the study indicated that the "height-of-the-eye" (height of the antenna) was the primary factor that limited the performance of the radar systems. Tethered aerostats were determined to be cost-effective platforms, supported by proven technologies.

Particularly, Medium Altitude and Endurance Aerostat Radar (MAEAR) is a mature technology. Operational availability issues, which seriously hampered the effectiveness of these systems for many years, were studied, modeled, and determined to be mostly solved. MAEARs were determined to be able to provide the required coverages out to 150 NM and beyond.

Ducting was determined not to be a critical issue for maritime radar surveillance performance. Although ducting seriously degrades the performance of radars in the air-search mode, there is not a corresponding degradation for surface radars. Ducting could only *extend* the usable ranges for maritime surveillance radars; however, since its occurrence its very unpredictable and only available for reduced periods of time, it should not be advisable to use those ranges as design parameters.

Deploying microwave radar installations along the Straits of Malacca would face other challenges that were not discussed in this report, such as (1) the electromagnetic interference from the high density shipping in the straits that would significantly impact the operation of a large network of radar installations, and (2) the vulnerability of static microwave radar installations to attacks, particularly attacks coordinated with maritime terrorism.

High Frequency Surface Wave Radar (HFSWR): HFSWR was also determined to be a mature technology. Improvements in signal processing techniques (under development) will enhance the detection and tracking performance out to the maximum required distances in the short term.

Although the studies showed that the ionosphere seriously affected the 3MHz to 5MHz band propagation, degrading its performance at night, the benefit of long range detection outweighed the limitations. Commercial pursuits included improved signal processing techniques for tolerance against interference and noise filtering to provide improvement in overall detection capability.

For long-range detection, beyond the 150 NM radius, it was more desirable to use the 3MHz to 5MHz band. For midrange surveillance, where range radius did not exceed 150 NM, the 10MHz to 18MHz band was considered. These higher frequencies, although more highly attenuated, were less susceptible to ionospheric conditions and provided better detection capability against smaller targets.

The prospect of using the HFSWR to detect surface targets at ranges out to 200 NM and beyond, working continuously 365 days of the year with low operating cost, was encouraging. However, it was necessary to take into account the decreased performance regarding targets of less than 1,000 tons where the sea conditions were not optimal and "crowding" occurred in the HF spectrum.

Electro-Optical/Infrared (EO/IR): As expected, weather played a critical role in performance for EO/IR Systems. Nevertheless, they were considered to be effective complementary augmentation assets to radar, particularly for the classification/ID mission, while ineffective as stand-alone detection and tracking systems. The effectiveness of fixed (tower-mounted) EO/IR assets was determined to be limited to their use in surveillance and monitoring applications in constrained areas, critical points and infrastructure. No sensible gain was obtained by increasing sensor height (contrast with radar).

Equatorial weather was relatively consistent and facilitated accurate electro-optical system modeling through a reduced "problem space." Analysis indicated that a good weather maximum distance for detection occurred in the visible spectrum sensors (TV at approximately ten NM for small craft). The best-performing sensors for foul weather were Long Wave Infrared (LWIR).

Automatic Identification System (AIS): The use of the Automatic Identification System (AIS) has been mandated by IMO and enforced by local authorities in the Straits of Malacca for over a year now. The requirement only covers large ships above a certain tonnage, though. Nonetheless, for the purposes of the MDP mission, AIS was determined to be a critical augmentation asset for the classification/ID function. The position accuracy and update rate of the information provided by the AIS System were determined to be acceptable for the input requirements established. The only caveat of AIS is that noncooperative vessels (and most small craft) are not "seen" by it, so it is not an effective stand-alone system. AIS base stations collocated with radar systems on aerostats extended the (VHF – Line of Sight) coverage considerably.

5.2.2 Recommendations

Based on the detailed studies and integrated analysis conducted in association with this MDP project, the following specific recommendations were proposed regarding current and future sensor systems capabilities:

- As shown, no single sensor can provide the needed capabilities. Accordingly, a multisensor approach should be implemented, exploiting the inherent capabilities of the different sensor packages used, to get multiple "looks" of the same COI as it moves through the area of regard.
- In synchronism with the previous idea, a layered approach should also be enforced. Increased demands on the Sensor System (detectability, accuracy, update rate, etc.) should be imposed gradually as the distance to critical points diminishes.
- Although commercial-off-the-shelf (COTS) technologies exist today which have the ability to meet the specified requirements for both detection and tracking and classification and identification, the following areas are worth being developed and explored for further improvements in capabilities:
    - While radar was generally regarded as a mature technology, evolving applications and advances in signal processing and software improvements are still needed, particularly in the HFSWR domain. Of specific note, efforts should also be invested in continuing developments that would increase the effective "height-of-the-eye." Particularly, high altitude (above 65,000 feet) platforms, like the untethered HAEAR Systems described in this study, should be monitored as feasible alternatives in the near future.
    - **Ducting:** Investigate exploitation of evaporation ducts using low or variable-height antennas, which could be used beneficially to extend the detection range of microwave radars.
    - **High Target Density/Mutual Interference:** Investigate the impact of electromagnetic interference from high-density vessel traffic on the operation of a large network of microwave coastal surveillance radars.

- **Frequency Diversity:** Investigate the feasibility of combining three different types of processing (frequency, polarization, and time) to enhance the detection of small surface targets in sea clutter.
- Development of combined TV/IR EO/IR Systems, which provide fused output to maximize detection capabilities for different environmental/target conditions.
- Application of UAV platforms for the MDP mission, particularly using EO/IR payloads for the classification/ID function.
- Extension of the AIS System to include smaller vessels.

- Continue to develop and explore the use of non-material procedural solutions (like enforcing security zones around high-value assets and restricted access to the sea lanes) to enhance the operational effectiveness of the Sensor System.

5.3 C3I SYSTEM

5.3.1 Conclusions

Based on the detailed studies conducted in association with this MDP project, the following conclusions were drawn regarding the C3I System's capabilities.

The other groups' systems represented performance parameter inputs to the C3I System. The C3I System performance was reliant on the contributed raw data at measurable levels of performance, linking their functions within the system of systems. Thus, the improved performance of the other systems contributed to the improved performance of the C3I System.

Network Centric Warfare (NCW) Systems with four C2 Centers, and nine fusion centers with 13 HUMINT/Intelligence nodes, promised the best performance. Although this C3I alternative resulted in the greatest cost, improvement to the C3I Systems provided cost-effective increases in performance when evaluated in the global context of the MDP Systems architecture. Having a communications and computer infrastructure that enabled a Common Operational Picture (COP) and increasing the number of Data Fusion Centers drove personnel as well as other system costs. Mission critical operating personnel accounted for roughly 85% to 99% of the total operating cost (TOC) for the notional C3I System alternatives.

NCW aided in the development and maintenance of COPs and Common Intelligence Pictures (CIPs), thereby creating situational awareness. Shared information, through the COP and CIP, enabled informed and timely decisions in the operational environment of the Malacca Straits.

The primary challenge at the onset of development was deriving a measure of performance that would serve as a guide for the modeling process. After discussions with stakeholders, it was determined that the U.S. Coast Guard Maritime Intelligence Fusion Center Pacific Area at Alameda, California performed similar functions and provided an acceptably analogous model, from which metrics could be derived based on proven operational capability. Research revealed that queuing theory could serve as an appropriate framework around which a model of a C2 network could be constructed.[1] Using common queuing system characteristics to outline the theory of C2 processes was straightforward. However, given the overarching goal of creating a C2 Center to monitor maritime traffic, a more detailed description of actual maritime C2 practices was needed to determine appropriate MOEs.

5.3.2 Recommendations

Based on the detailed studies and integrated analysis conducted in association with this MDP project, the following recommendations were proposed regarding the C3I System's capabilities.

- **Invest in a Network Centric Communications System.**

Aggregating information (i.e., data fusion), and then making it available through a COP was the critical enabler to the C3I System's capability. This improvement could only be accomplished through a robust, agile, and adaptable communications network. The communications network provided a "pipeline" for raw sensor data to be sent to the C2/Intelligence Centers.

- **Invest in HUMINT.**

Detecting a threat began with advanced planning, understanding an adversary's intentions, and observing a "trigger event." Technology could increase the quantity, accuracy

[1] Ralph S. Klingbeil, and Keith M. Sullivan, "A Proposed Framework for Network-Centric Maritime Warfare Analysis," *NUWC-NPT Technical Report*, 11, (15 July 2003): p. 447.

(e.g., vector information), and speed of information. However, highly trained and embedded "eyeballs and intellect" still proved to be a major asset in intelligence collection and exploitation.

- **Divide AOR into "data fusion cell" regions.**

Although the geographic region was constrained, the density of contacts in the Straits of Malacca made this problem a resolution issue. A single C2/Intelligence Center had only a handful of analysts to devote to a large AOR. Dividing the AOR into regions, and assigning those regions to data fusion cells, allowed the same number of analysts to concentrate on a smaller area; increasing awareness and reducing analysis time while providing a higher confidence factor. Within this recommendation is the core assertion that data fusion or aggregating information is an essential function of C3I Systems.

- **Risk Assessment Tools.**

Existing C2 Centers had no mission capability to assess the consequence of an attack. Creating a real-time risk assessment tool should be the focus of further research within C2 design.

Bringing together sensors, intelligence, and communications was a complex process with many unknowns. The use of systems engineering design processes to develop a comprehensive solution enabled adaptation of this solution to the changing requirements of MDP operations.

5.4 FORCE SYSTEM

5.4.1 Conclusions

One of the most significant findings to come out of the Force study was the realization that the only effective counter to a SBA was a Point Defense System. This Point Defense System could be employed onboard the target vessel, or it could be an escort vessel, but the security force had to be near the target to offer effective protection. The attempt to actively patrol the Straits would take more than 45 patrol craft, operating at all times, to maintain the minimum response time needed for visual engagement ranges. The added benefits of having a visible force in place at all times might outweigh the phenomenal costs associated with this type of employment pattern; however, this deterrent factor was not considered in this model, and therefore was not evaluated.

Another major finding was that the Sea Marshals currently being employed by the Singapore Port System were effective and should be improved on for even better performance. The existing capabilities seemed to be adequate for the current threat level, however, if hostilities and attack attempts began to rise, additional forces would be needed in theater. If this were to occur, the Force Group's findings would lead to the recommendation of using a harbor patrol boat to act as both a deterrent factor, as well as an engagement-capable platform.

Finally, the Force Group's studies led to the recommendation of using helicopters to transport the inspection teams out from a centralized staging location for all WMD inspections. This allowed for the use of existing infrastructure like barracks and support facilities already in place in Singapore. This option also allowed for moderating the number of teams on call, based on traffic patterns in the Straits, as well as desired inspection levels.

5.4.2 Recommendations

The major recommendations to come out of the Force Group's study was to implement some style of point defense (either active or passive) to counter the SBA threat, maintain the current Sea Marshal forces to counter SAW threats, and increase readiness to include helicopter-lifted inspection teams out to suspect WMD vessels. For the SBA threat, Sea Marshal escorts on ships transiting the Straits of Malacca should be an effective active defense, while blast-resistant hull coatings showed initial promise as a passive defense. For the SAW threat, one improvement over existing capabilities would be to increase the level of training and armament of the Sea Marshals. Significant improvement in the SAW threat scenario would be gained by implementing a method to detect hostile intent further from a critical area, either by speed zones, earlier boarding of Sea Marshals, staging area, etc. Detection of hostile intent at least ten NM from port would allow the Rapid Response Force to be effective in assisting the Sea Marshal team in retaking a SAW vessel.

5.5 LAND INSPECTION SYSTEM

5.5.1 Conclusions

The existing system used to inspect cargo containers was found to be inadequate in detecting WMDs or attempts to smuggle materials used for such weapons. This was primarily due to the tremendous volume of containers passing through a given port. The lack of dedicated

resources also limited the number of containers that could be inspected. Inadequacies were also identified in sensor detection capabilities. There was a lack of detectors that could address shielding concerns. Chemical and biological weapons that were sealed properly would not be detected until after an attack has occurred.

Delay costs due to container inspection, especially because of false alarms, would greatly influence the decision to implement an inspection regime. Dedicated resources would alleviate delays and minimize the impact of false alarms.

Modeling analysis showed that passive sensor probability of detection drove the system and was instrumental in identifying suspect containers as they moved through the port infrastructure. The false alarms associated with passive detectors also impacted the delay cost of containers. The best architecture performance was achieved through a layered defense of Port Centric (Alternative 1) and Trusted Agents (Alternative 2).

Employing effective supply chain security measures would reduce the delay cost by allowing cargo to flow unimpeded from manufacturer to shipper. Also, by increasing security measures across the supply chain, it would act to deter illicit trade, which might result in lower system costs.

5.5.2 Recommendations

Investment in passive sensor technologies would help maintain a constant flow of commerce that would be slowed down by intrusive, active inspections. Also, continued development of sensors with better penetration capabilities would help prevent harmful materials and potential WMDs from being placed into containers. In the existing system, only moderate levels of shielding would permit successful passage of WMDs through the supply chain. When active search was required, a method to decrease the amount of time it would take to actively search a container could minimize delay cost.

The number of inspection teams should be increased, requiring more inspectors in domestic and international ports. Also, countries not already using the Customs-Trade Partnership Against Terrorism (C-TPAT) would benefit from initiating the process. The program would require validation once certification had been granted. If the security measures were not tested, success could not be measured or a return on investment determined. The large

number of companies and personnel involved made the supply chain very vulnerable, since it could only be as strong as its weakest link. Strengthening each area throughout the supply chain would require incentives to industry to comply with costly, but necessary, standards.

5.6 SEA INSPECTION SYSTEM

5.6.1 Conclusions

One of the key insights was that the significant delay costs incurred on shipping made random inspections at sea inefficient. However, if C2 elements could get more data from the AIS, a better evaluation of each ship could be made, and in turn, inspection teams could be used more efficiently. Also, the deterrence factor of having the boarding teams could possibly justify their cost. Another factor that prevented the efficient use of inspection teams was the stacking configuration of containers onboard ships. Unless the container was on the end or somehow had enough room to access the container through the doors, inspection could only take place from the outside. This greatly limited an inspection team in the at-sea environment.

The current technology available for the handheld sensors used by the boarding teams was very costly. Handheld sensor technology had not advanced enough to be able to detect radiation sources with even a small amount of shielding from outside of the container. Also, for chemical and biological agents the technology was very poor in regard to contained agents. Therefore, the probability of detection for these sensors did not justify their cost. The use of "backpack" or other slim style sensor devices that would fit between containers and lowered down the stack was key to being able to detect hazardous material. Therefore, handheld sensor technology needed to be further developed.

The number of teams per shift had a significant effect on the delay cost. For Alternative 2, this happened to be the biggest factor. In order to reduce delay costs in shipping, decision makers must make sure they have the appropriate manning. When using too few inspection teams the delay costs become very large. The greatest driver on delay cost for Alternative 1 was the probability of random inspections. If random inspections were made without intelligence that would narrow down the number of ships, the inspection teams became overloaded and delay costs climbed. Therefore, intelligence information for decision makers was a key factor for reducing the total number of inspections.

5.6.2 Recommendations

Continued development of the sensor technologies to increase the probability of detection would make the at-sea inspections more efficient and less costly in terms of delay cost. Another driver of the high delay cost was inspection team manning—increasing the number of teams per shift would minimize the delay cost.

The selection process for the boarding team inspections required an efficient algorithm to select ships that should be inspected. The goal was to minimize the number of "good" ship inspections and inspect more "suspicious" vessels. To accomplish this, an algorithm should be developed to incorporate the AIS data into the inspection selection process. Simultaneously, the AIS data should be expanded to give decision makers more data for detailed analysis.

Finally, the Smart container devices would be excellent tools for shipping. The sensor mapping capabilities inherent in some of these devices was the key to localizing containers that had either been broken into or contained some type of radiological device. Smart container device technology should continue to be developed. Many of the devices the sea inspection team researched had the capability to add extra sensors for added security. These would, of course, use the same technology of the handheld sensor and should be more thoroughly developed as well.

Overall, the capabilities of any "At-Sea" Inspection System greatly depend on the sensors used for detection of chemical, biological, radiological, nuclear, or explosive material. Existing sensor technology would only detect chemical and biological agents if there were residue or spillage present. For explosive devices the technology that the Sea Inspection Group found was greatly dependent on the procedures used for taking samples. Newer, active interrogation-type technologies for explosive detection were present, but not developed enough for at-sea conditions. Sensor technology for radiological sources was very advanced, but still easily susceptible to defeat by shielding inside of the container. Without technology advances for each of these sensor technologies, Sea Inspection Systems could cause large delays in shipping and leave shipping susceptible and unprotected.

APPENDIX A: SEA 7 COHORT TASKING MEMO

Wayne E. Meyer Institute of Systems Engineering
Naval Postgraduate School

9 November 2004

Memorandum

From: Associate Director, Meyer Institute
To: SEA-7 Students

Subject: Overview, Expectations, and Deliverables for SEA-7 Integrated Project

1. The NPS Meyer Institute sponsors the biannual Systems Engineering and Analysis (SEA) Integrated Project, which serves as the capstone effort for SEA students. The Integrated Project in FY 05 concerns Maritime Domain Protection – countering terrorism from the sea and should include PACOM's Regional Maritime Security Proposal Initiative (RMSI), which proposes cooperation between various Southeast Asian countries to defeat terrorism and piracy conducted in PACOM's Maritime Domain. The SEA-7 Integrated Project is therefore titled *Maritime Domain Protection in PACOM*.

2. Consider the following to be the initial problem statement:

> **Design a conceptual System of Systems to defeat and prevent terrorism in the Maritime Domain. Design and assess integrated alternative architectures for sensor, communications, command and control, and reactive force for a coalition of nations, focusing on large ship security, and threats to and from large ships, in the Strait of Malacca. Additionally, design and assess alternative architectures for cargo inspection to include a total ship inspection sub-system that could detect and identify explosive and other dangerous materials so to prevent the use of a large cargo ship as a terrorist vehicle.**

SEA-7 should begin reviewing the national and theater maritime domain system for countering terrorism then may bound the problem space for the System of systems efforts by focusing strictly on one region such as the Strait of Malacca with input from PACOM as a key stakeholder. Additionally, while much of the challenge in realizing full international cooperation in the SE Asian region rests in the political and diplomatic arena, SEA-7 must remain outside of those two realms. The design process and eventual system designs must center on technical solutions, while addressing only generic organizational considerations. Make assumptions as necessary about the political and diplomatic arenas. SEA-7 must also consider the opposing aims of pirates and terrorists, and be prepared to discuss in the revised problem statement how these two separate groups could join forces. This will require the development of an appropriate operational scenario for the region, which must include guidance from key regional stakeholders, such as PACOM and others.

3. SEA-7 will break into 2 groups approved by the faculty. The first group will study the broader systems integration effort, focusing on system of systems and likely addressing command and control and reactive force architecture mentioned earlier. The second group will address a critical subsystem, potentially the specific systems engineering design of a total ship inspection capability. This capability includes the ability to search a large cargo ship for WMD or other explosives, as well as searching the outer hull of the ship for possible explosives. The design of appropriate robotic systems will be explored as a possible component of this system.

4. Both SEA-7 groups must thoroughly integrate engineering and OR students who are part of the Temasek Defense Systems Institute (TDSI) program. The 26 TDSI students, studying in 5 groups represented by different NPS curricula, will work closely with SEA-7 to establish a set of functional requirements (for each of the 5 groups) for a system that meets an operational need within the overall integrated project. Members of each TDSI group will then develop a conceptual design of that specific system that meets the agreed-upon functional requirements. Throughout this process, TDSI and SEA-7 students will meet regularly to update progress and address any needs for improving, or solely changing, requirements. In addition, SEA-7 students should recruit additional students from other curricula as necessary to help address the problem. These other curricula may include mechanical engineering, electrical engineering, information systems, defense analysis, national security affairs, combat systems, business management, financial management, operations research, and operational logistics, to name some.

5. SEA-7 students must complete this project by graduation day in June 2005. The tasks to be completed by SEA-7 include the integration of the work of others and the setting of foundations for some students who will continue related work after SEA-7 students graduate. Below are a summary of deliverables for the integrated project:

A. Prepare and deliver a high-quality briefing of about 2 hours duration, which describes the nature of the problem, the systems engineering design process, the results of various analyses and your conclusions. This briefing must clearly describe the interfaces and exchanges among the various student and faculty groups involved in related work. The briefing will be delivered and taped in about 2 June 2005 and it will likely be widely viewed.

B. Provide a complete written report of all work; the report will adhere to a typical technical report format. It will be complete, with consistent internal and external references. It will incorporate the written reports of the affiliated engineering teams, possibly as appendices. Provide a complete picture, including, as appropriate, how the work of others was in response to, or interfaced with, SEA-7; the incorporated reports of other students will give a complete view of their work.

C. Include an executive summary of no more than 5 pages. The executive summary will provide a clear picture of the nature of the task, as well as results and conclusions, emphasizing the essential elements of the work.

D. Prepare publishable papers and articles which will serve the purposes of 1) publicizing this work, 2) inviting discussion in professional circles of this important topic, 3)

demonstrating the ability to prepare publishable material and 4) provide an opportunity to be a published author. It is expected that 2 or 3 such papers/articles will be prepared for submission to a possible variety of publications, addressing some limited aspect of the overall effort, taking into account the subject matter of interest to the publication involved. Faculty advisors will provide leadership and critical guidance through the process of selecting a specific topic and targeting a particular journal or symposium. Some examples of what might be appropriate are:

1. A professional, operationally-oriented piece advocating some aspect of the project for adoption by the Navy/Marine Corps, for Naval Institute Proceedings.
2. A high-level, non-technical, but highly interesting piece for All Hands magazine.
3. A discussion of some portion of the analyses for submission to the journal of MORS, the Military Operations Research Society.
4. A paper with a technical/design approach to some aspect of one or more of the platforms envisioned in the final report, for submission to the American Society of Naval Engineers' ASNE Journal.
5. A paper dealing with some aspect of the utilization of systems engineering methods, such as the use of EXTEND®, or your development of your functional flow diagram, etc., for submission to the International Council on Systems Engineering (INCOSE) for their periodical, Systems Engineering.

E. Provide a listing and description of desirable follow-on work to be undertaken by the SEA curriculum students who follow, with support as feasible, and by students in the TDSI program. These descriptions cover the nature of the problem remaining to be solved or the issue requiring further examination and will provide sufficient background to relate the needed further work to the work done as part of your project. These follow-on work packages should be identified and recorded as some as the need becomes apparent; they should be discussed well in advance with faculty advisors to permit an assessment of their suitability.

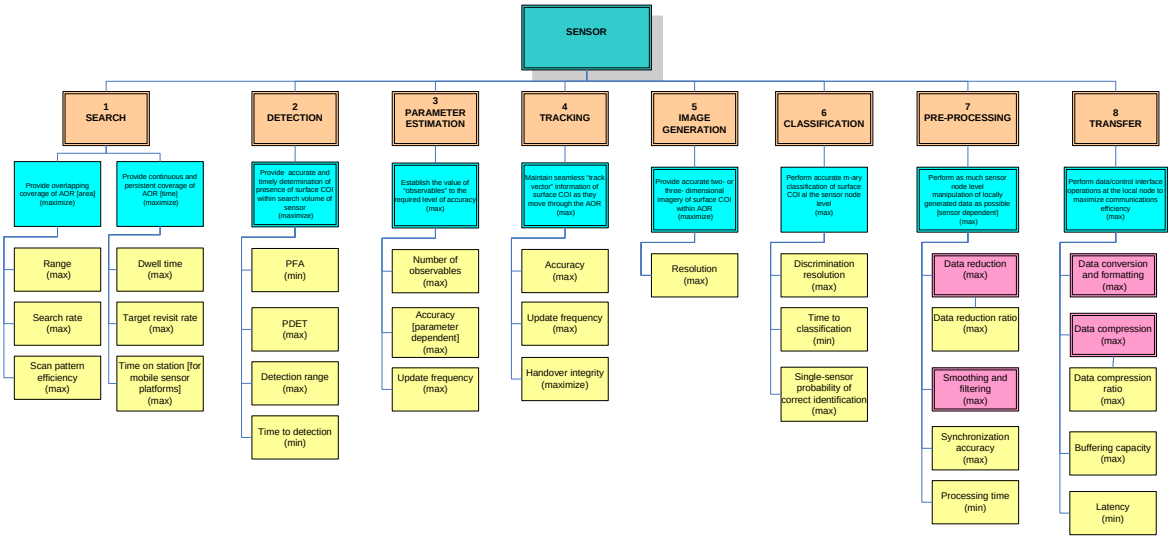
6. Professors Olwell, Paulo, and Vaidyanathan will be the final authority as to whether or not the project is satisfactorily completed and will be the faculty members who assign Pass or Fail grade. They will also assess the quality of the proposed paper or article, giving some appropriate weight to the faculty member working with each student-author team. They will accept input and opinions concerning the total project work from other involved faculty members, but the final assessment will be theirs.

7. SEA-7 has an exciting challenge ahead. The successful design of a Maritime Domain Protection System-of-Systems is important to our nation's security, yet it is an extremely complex endeavor. SEA-7 students must combine their professional experience with the knowledge gained through SEA core courses in order to thoroughly address all relevant aspects of Maritime Domain Protection. Additionally, SEA-7 students must follow the Systems Engineering Design Process learned in SI4001, as well as the project management tools in SI 3002 in order to ensure that the final systems designs have the capability to meet the

performance needs of the customer (DoD and PACOM), and does so within schedule and budget.

/s/ David H. Olwell

APPENDIX B: SENSORS SYSTEM GROUP OBJECTIVE HIERARCHY



APPENDIX C: FORCE SYSTEM GROUP OBJECTIVE HIERARCHY

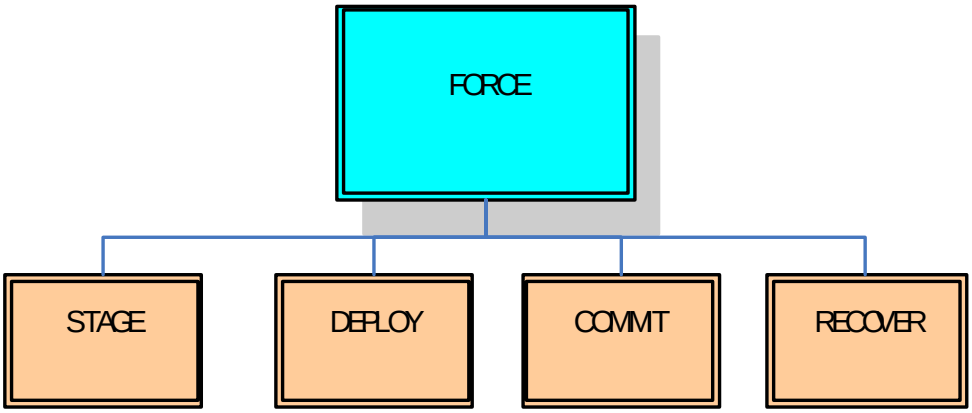


Figure 142. Force Objective Hierarchy Top Level Functions

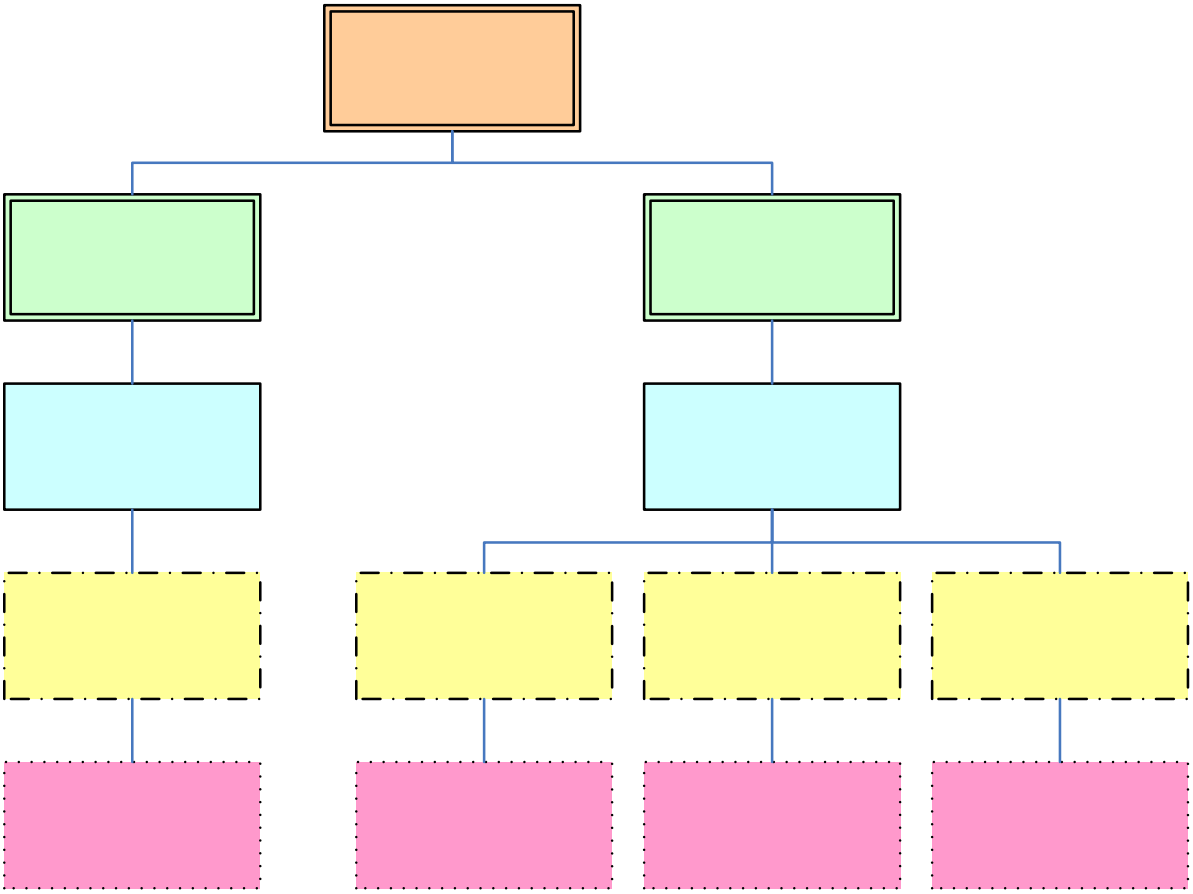


Figure 143. Stage Function Hierarchy

Plan

Choose Optimum Response

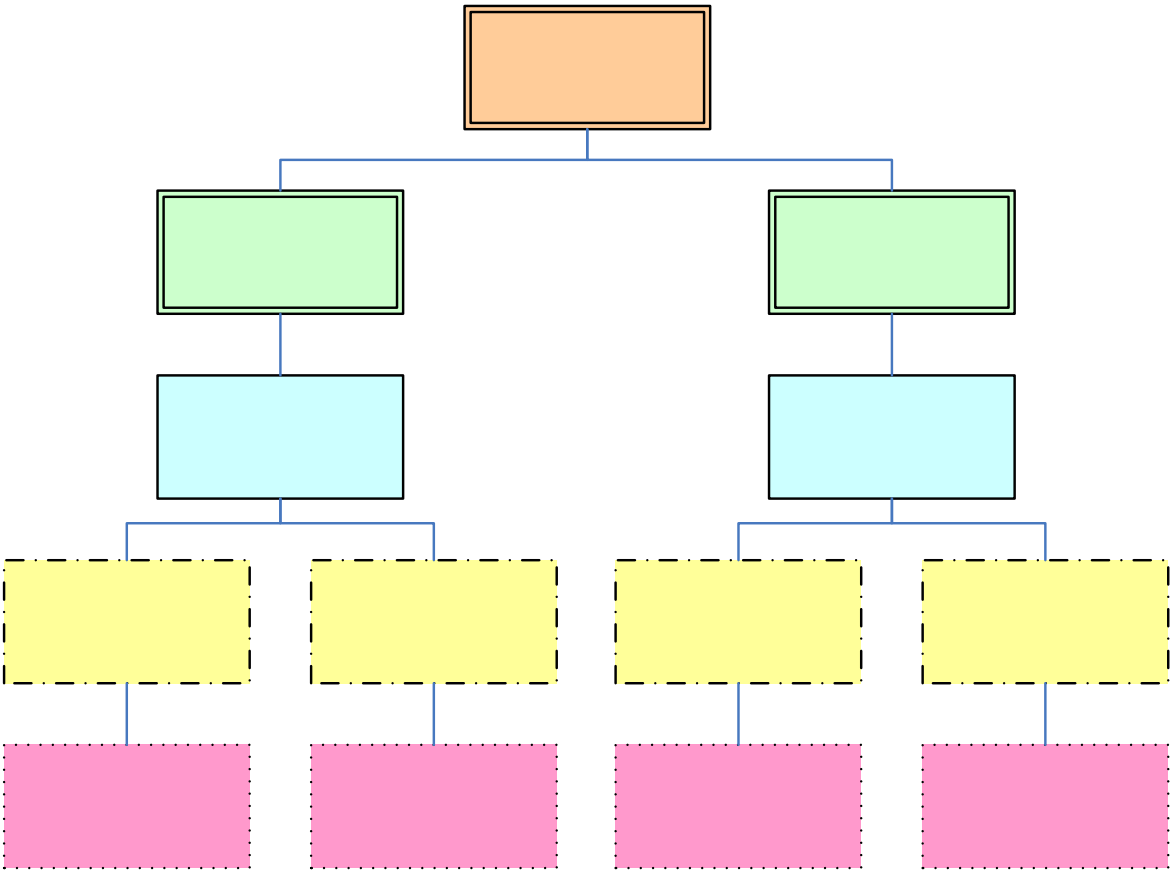


Figure 144. Deploy Function Hierarchy

Embar

Get Reaction
onboar
Transporta

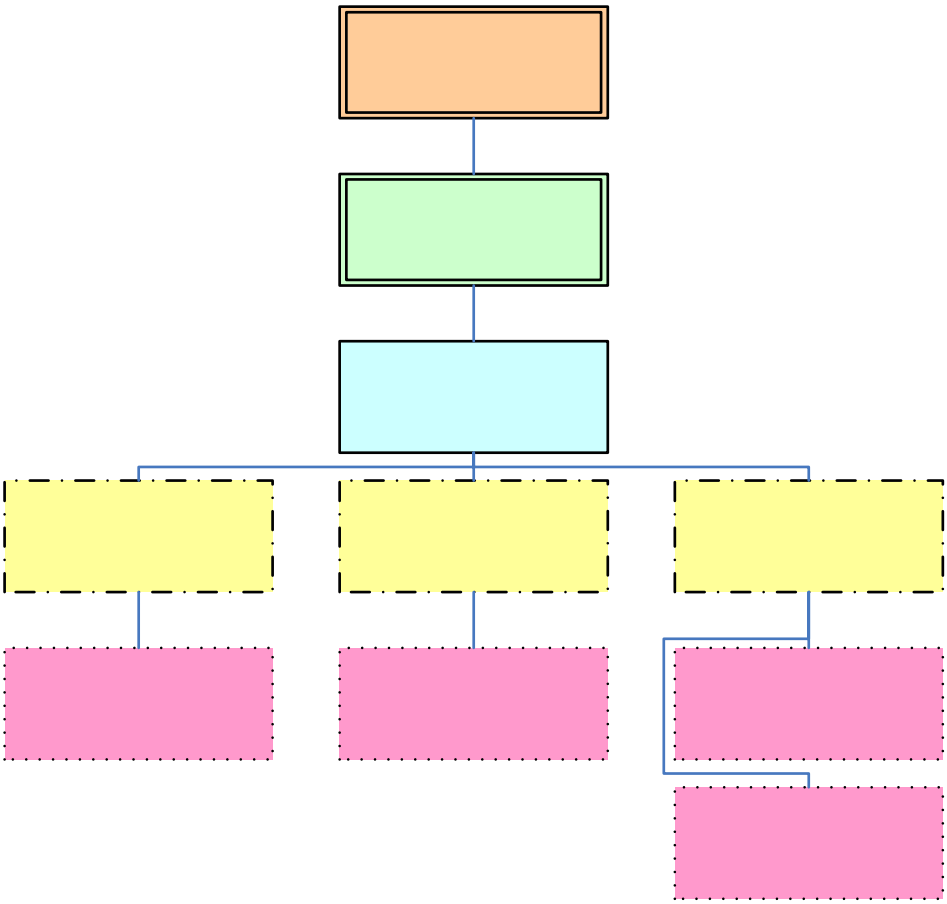


Figure 145. Commit Function Hierarchy

Eliminate Thr

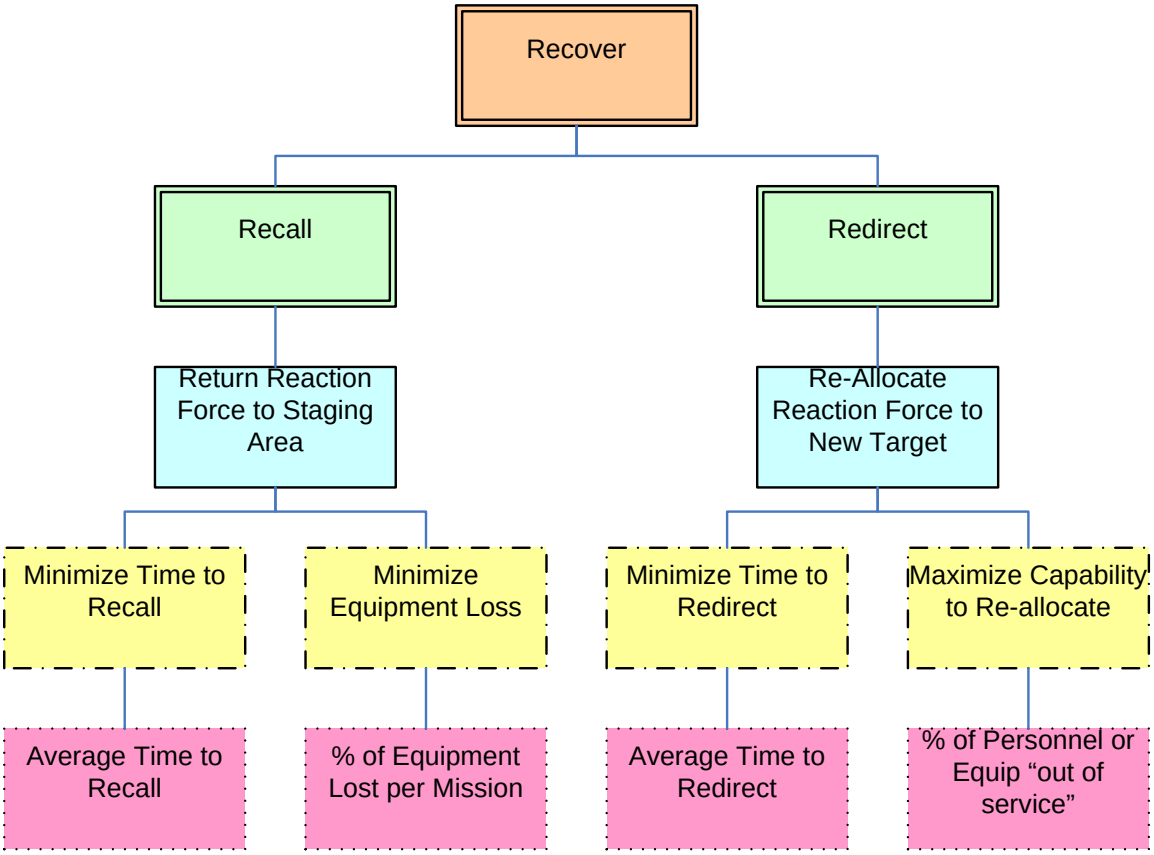


Figure 146. Recover Function Hierarchy

APPENDIX D: LAND SYSTEM GROUP OBJECTIVE HIERARCHY

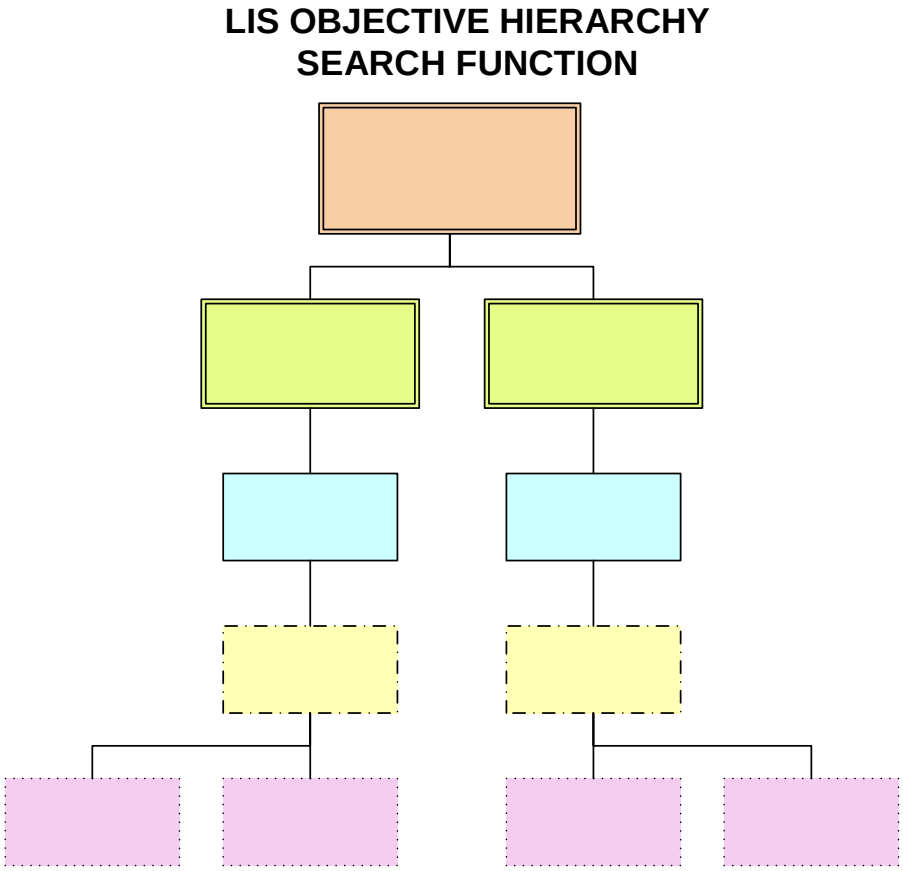


Figure 147. Search Function

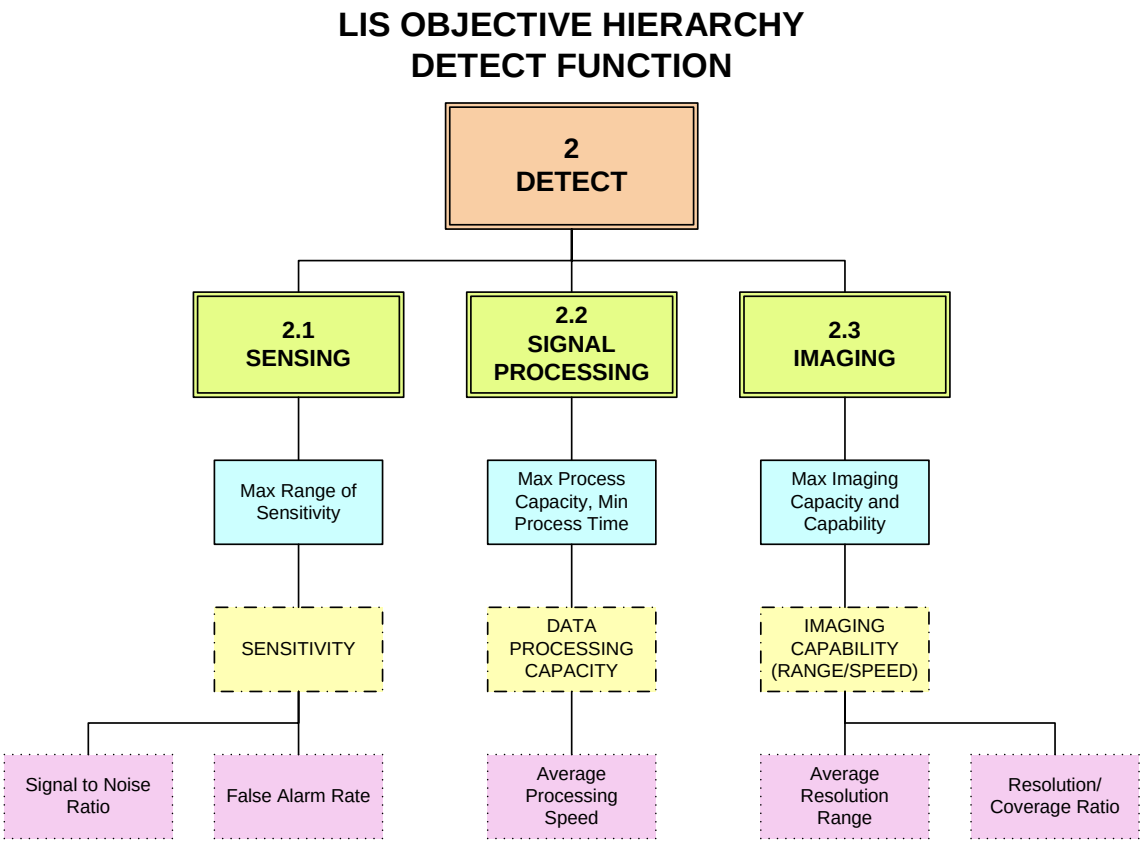


Figure 148. Detect Function

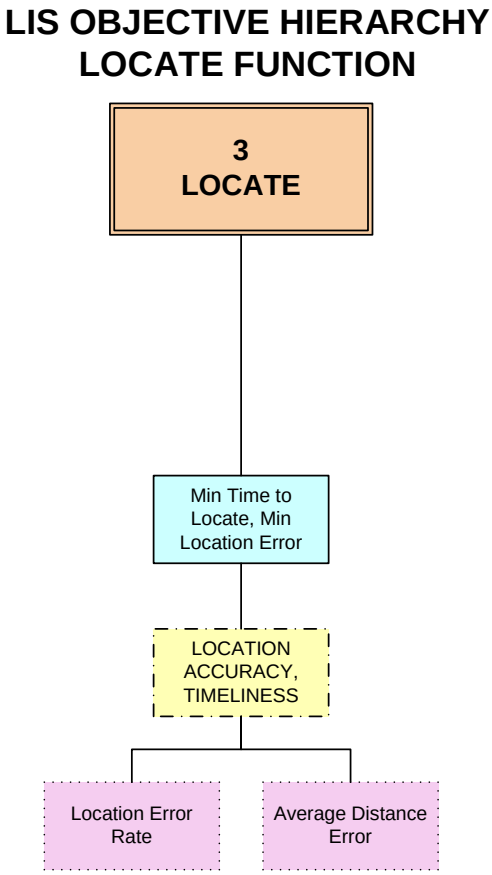


Figure 149. Locate Function

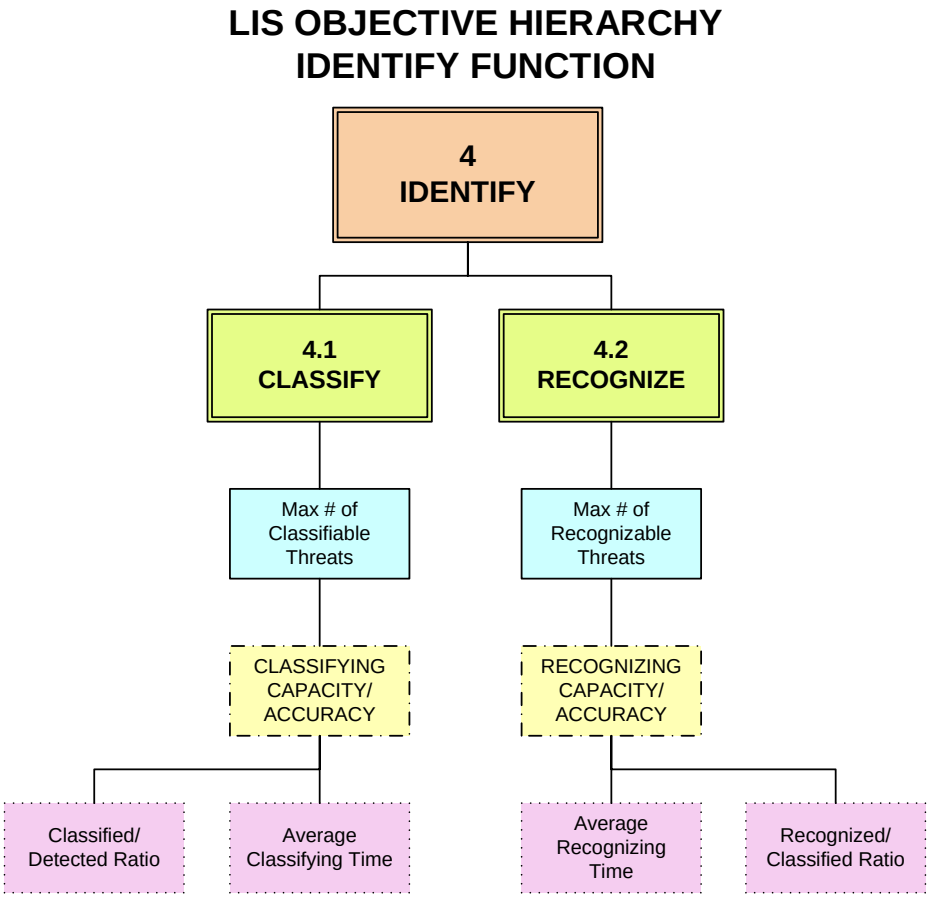


Figure 150. Identify Function

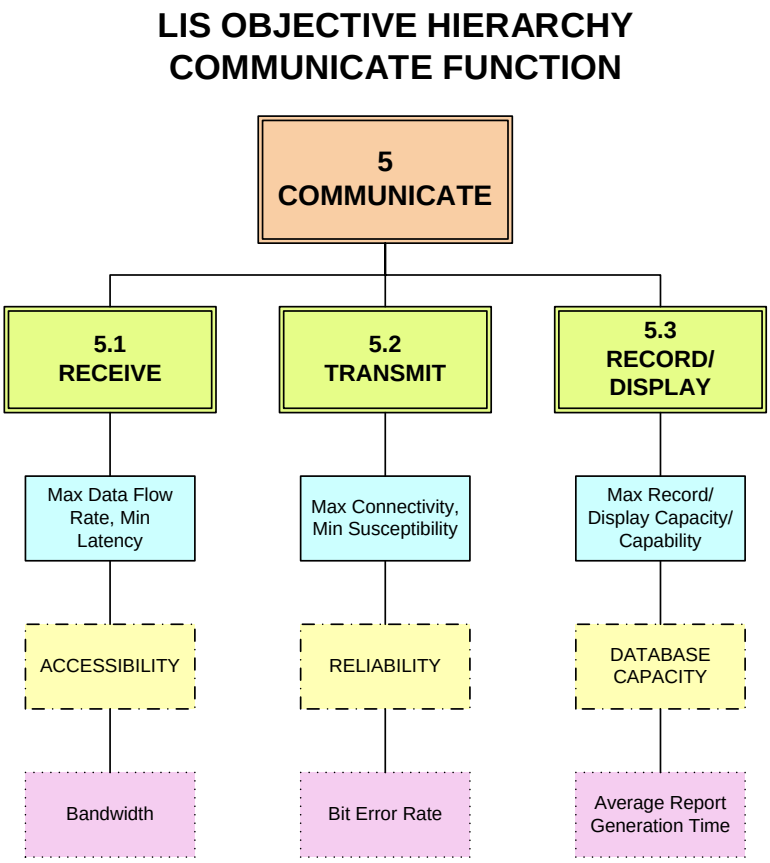


Figure 151. Communicate Function

APPENDIX E: SEA INSPECTION SYSTEM GROUP OBJECTIVE HIERARCHY

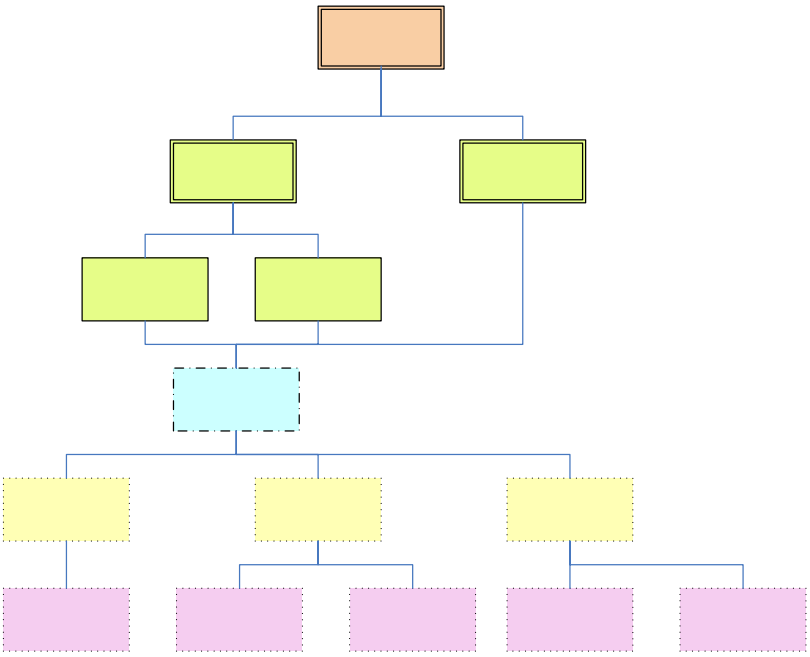


Figure 152. Search Function

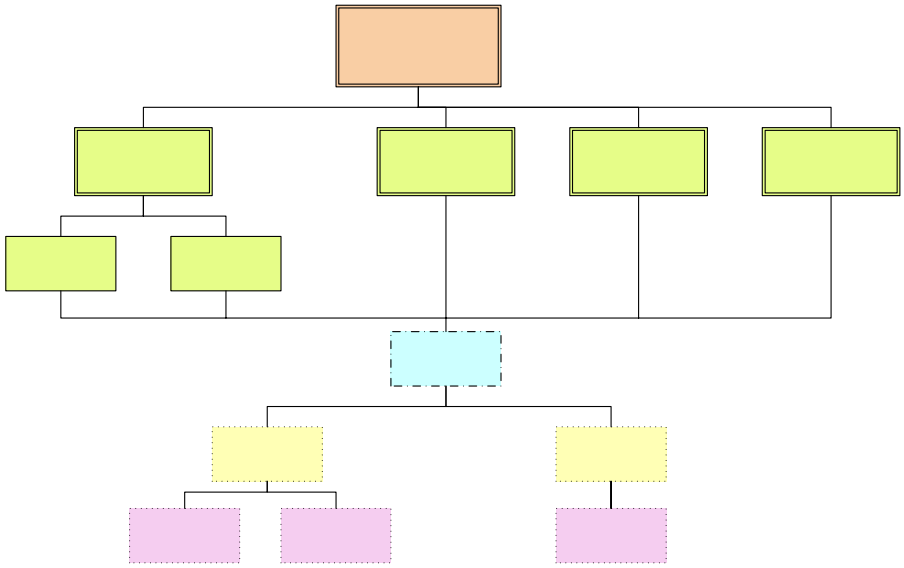


Figure 153. Detect Function

2.1 RADIATION

Gamma

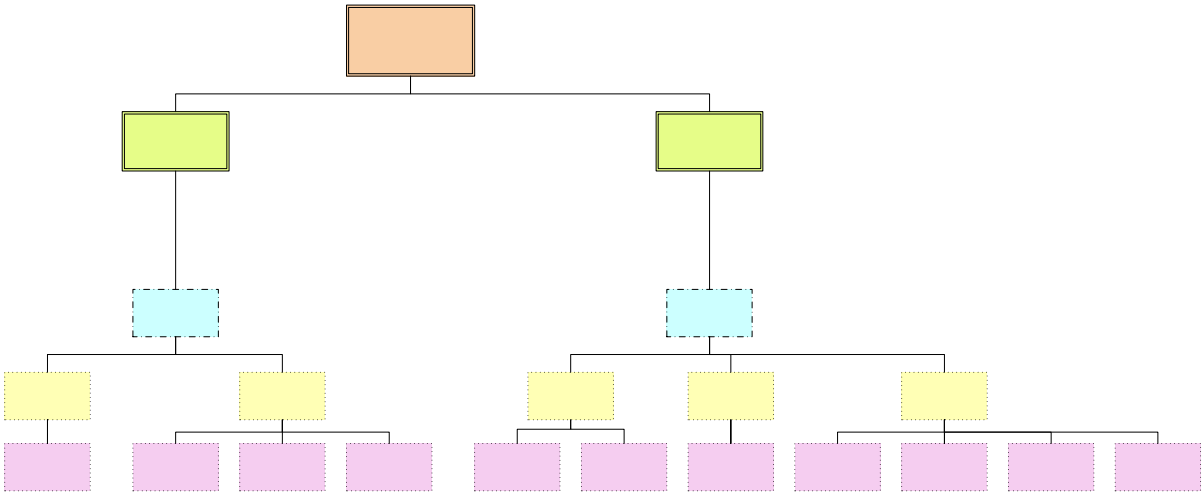


Figure 154. Locate Function

3.1 Automated

Maximize Signal Processing Efficiency

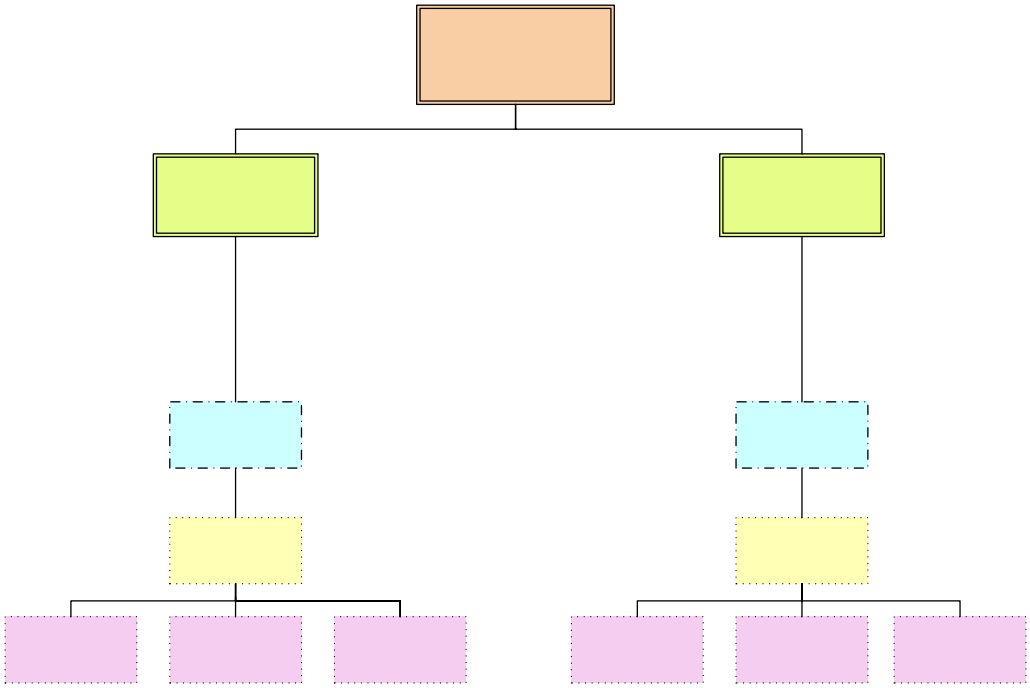


Figure 155. Identify Function

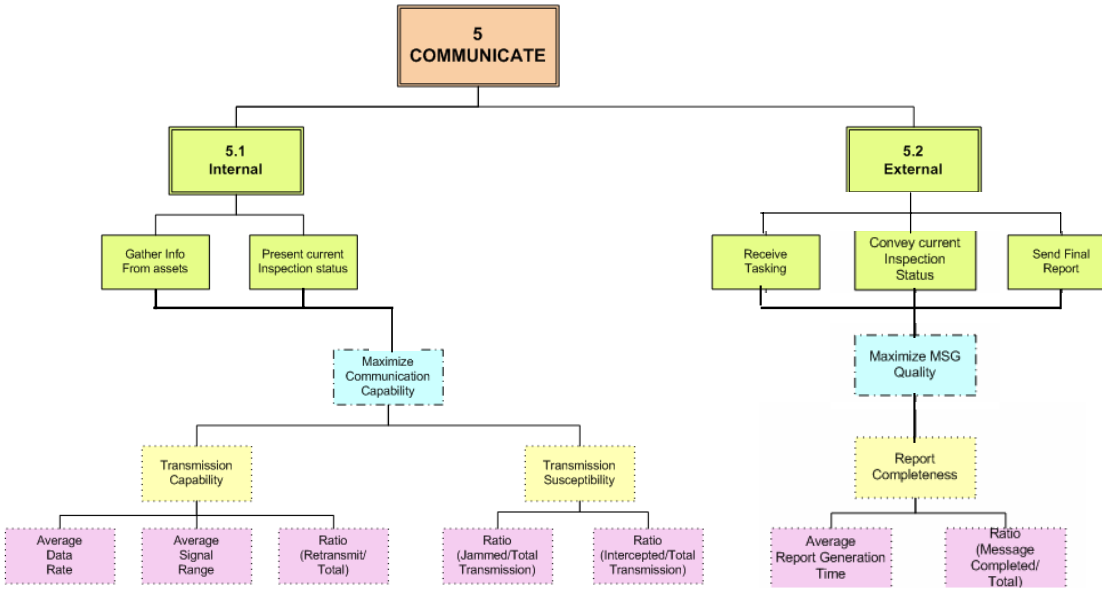


Figure 156. Communicate Function

APPENDIX F: SONAR FEASIBILITY STUDY

Feasibility Study of SONAR for the MDP mission

Although SONAR is generally regarded as a poor means of detection and tracking, it was nonetheless evaluated for applicability under its own merit within the expected environment in the Straits of Malacca.

As part of the area surveillance requirements for the Maritime Domain Protection (MDP) project for SEA-7, the applicability and capability for subsurface acoustic systems was investigated.

Feasibility of SONAR

The highest influence regarding the use of SONAR is, as expected, noise. The high traffic volume, high traffic speeds, constrained passages, high rainfall rates, and shallow waters are converging influences. The Straits of Malacca is probably the noisiest open water marine environment in the world.

Assumptions

The assumptions taken for the feasibility evaluation of sonar in the application of this project are as follow:

- Underwater mines are not considered for this project.
- Terrorists do not have the means to acquire or operate a normal-sized[1] submarine.
- Automatic Identification System[2] is in place for the consideration of this project.
- Merchant shipping is expected to be making way at speeds of more than 10 knots when traveling along the strait.

Geographical Consideration

- Length of the strait is approximately **485 nm.**
- Width is **1.3 nm** at its narrowest (Phillips Channel).
- The shallowest depth of water route is about **27 m**
- More than **50,000 vessels a year**, carrying a third of world trade & half of its oil supplies.
- Also frequented by many other vessels (barter traders, tugs, fishermen & pleasure crafts).
- Some **900 commercial vessels** passing through each day.
- **Extra 858 nm** around it. The closure of the Straits of Malacca would immediately raise freight rates worldwide.

Figure 1 – Straits of Malacca

Environmental Conditions

Coastal waters are normally a noisy environment because shipping lanes often parallel coastlines. In the southern portion of the straits, the land masses of Indonesia and the Malaysian Peninsula narrow the shipping channel down as noted before. Additionally, the limited depth

[1] At least 80 m in length and capable of reaching 10 knots underwater.
[2] All ships of 300 GRT or more provide their position, identification, course and speed to the relevant maritime authorities.

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[2] All ships of 300 GRT or more provide their position, identification, course and speed to the relevant maritime authorities.

significantly contributes to high noise levels. Wind speeds also affect the noise level over a wide frequency range. The increase of level with wind speed was found to be 7.2 dB[3] per wind speed doubled, or an increase of intensity slightly greater than the square of the wind speed. Like most underwater sound parameters, ambient noise is eminently characterized by variability. Much of this variability arises from changes in the dominant sources of noise, such as changing wind speed and amount of shipping. The high probability of rain (about 1 in every 4-5 days) in the Strait of Malacca further worsens the already extremely high ambient noise within the strait.

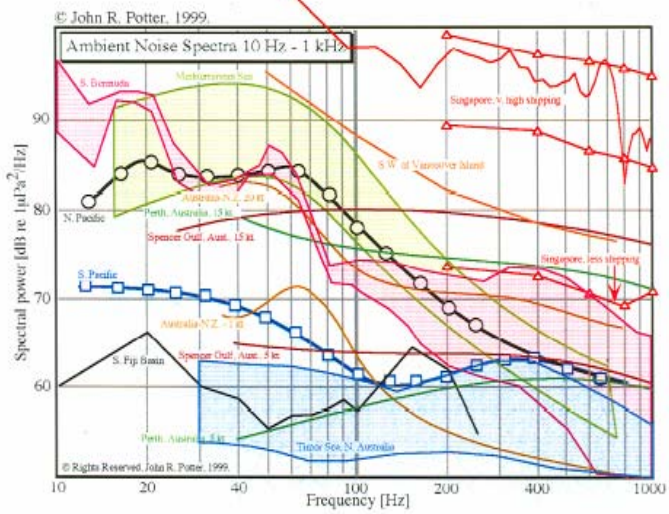

Figure 2 – Indication of the ambient noise level along Singapore Strait and Strait of Malacca

Threats

Mainly unconventional, typically small groups of attackers in high-speed vessels armed with hand-held weapons:

- Armed with AK-47, M-16 assault rifles
- Commence with the attackers approaching suddenly at high speed towards their chosen target.
  - They would then board the vessel forcibly, unafraid to use their weapons as necessary.
  - Attackers may choose to escape with the valuables onboard.
    - Kidnap the crew for ransom.
    - Hijack the vessel for sale or other commercial purposes.
- Terrorists may possess the ability to attack shipping from underwater. Either as divers or even through the use of small submersible vessels.

[3] Demonstrated by Piggot over a 1-year period on the Scotian shelf in water about 150 ft (50 m).

- Air threat in MS is assessed to be limited.
- Sub-surface Threat – Most likely originate from pre-laid mines
  - Very difficult for a small underwater vehicle to emulate a relatively slow surface speed of 10 knots.
  - Even if the underwater vehicle is able to achieve this speed, it needs to be big enough to house sophisticated equipment amounting to that of a submarine.

Figure 3 – Possible threats in the strait

Using Sonar for Detection

$SL - 2TL + TS = RL + DT$ (Active Sonar Equation)
$SL - TL = NL - DI + DT$ (Passive Sonar Equation)

Nominal Values of Target Strength[4]

Target	Aspect	TS, dB
Submarine	Beam	+25
	Bow-stern	+10
	Intermediate	+15
Surface ships	Beam	+25 (highly uncertain)
	Off-beam	+15 (highly uncertain)
Torpedoes	Bow	-20
Unsuited swimmers	Any	-15

Example:

Active Sonar System:	Power output of 1,000 watts at a frequency of 8 kHz
DI:	20 dB, uses a pulse length of 0.1 second, with a receiving bandwidth of 500 Hz
Target:	Beam-aspect submarine at a depth of 40 m
Detection:	Required 50 per cent of the time, using incoherent processing, with a probability of 0.01 percent of occurrence of a false alarm during the echo duration.

Calculations

The active-sonar equation, solved for TL, is

$TL = \frac{1}{2}(SL + TS - NL + DI - DT)$

[4] Duplicated from *Urick* page 324.

SL[5] = 221 dB
TS[6] = 25 dB
NL[7] = + 80 dB
DI = +20 dB
Using d = 15, DT = 5 log (15 x 500/0.1) = +24 dB.

Therefore, TL = ½ (221 + 25 – 80 + 20 - 24) = 81 dB
Range[8] corresponding to this value of TL is 5,000 yd, i.e. 2.5 nm.
The passive sonar equation, solving for SE=DT and a Probability of detection equal to 50% (P_{det}=0.5) is

NL = 90 dB
SL = 100 dB
DI = +10 dB
Using PL = 10 log (R), cylindrical spreading in shallow water

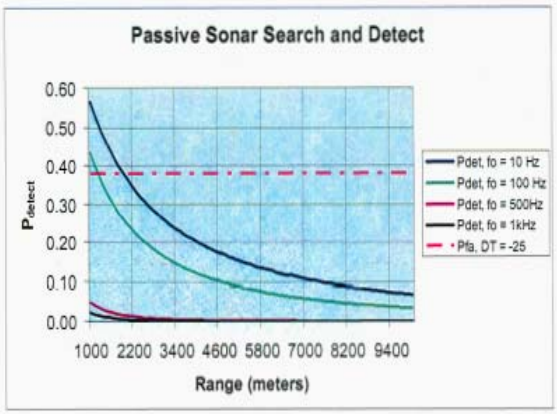

Figure 4 - Detection Frequencies and Probabilities

Assessment from Calculation

- The above calculations are meant to show that the effectiveness of sonar detection (for both active and passive) is very dependent on NL (or Noise Level), which is expected to be extremely high and variable in the strait.

- This hypothetical calculation made use of conservative estimates. For example, it is assuming the beam aspect of an underwater contact that is the size of a submarine. The real threat (for both surface and subsurface) is expected to be a lot smaller of considerably lesser TS (or Target Strength). Hence, the expected range of detection is probably even smaller.

- With the short range of detection estimated and to cater for margin of redundancy, the number of systems required to cover the entire strait (of about 485 nm in length and 1.3 nm at the narrowest) would be extremely high.

Feasibility of Sonar for Support of Mission

Effectiveness for Detection and Identification

There is no doubt that sonar systems can be used to detect contacts of interest within the strait. However, due to the number of contacts within the strait and their similarities, it is almost

[5] Using Fig. 4.4 from *Urick*, page 75.
[6] Using Table 9.3 from *Urick*, page 324.
[7] Using Fig. 2 very conservatively.
[8] Using Fig 6.7d from *Urick*, page 156, for a layer depth of 150 ft and assuming the transmission is the same as that for a source depth of 100 ft.

impossible to use sonar systems for identification purposes even with finger-printing of signatures. The use of signatures may be possible to identify most merchant ships, but this capability may be redundant as the Automatic Identification System (AIS) has already been implemented for all ships more than 300 GRT. With an extensive deployment requirement and an equally extensive maintenance program to keep systems working, it is opined that sonar systems may not be cost-effective for detection and identification purposes except in specific small areas to act as an alternative (or complement) to other systems.

Assessment of Underwater Threat

The geographical, environmental and depth factors of the straits makes it very challenging for underwater attacks to be carried out from smaller or midget submarines. Ruling out underwater mines, it is opined that the underwater threat is limited to divers with divers' propulsion vehicles. Since it is expected that most merchant ships would be traveling at speeds of 10 knots or more along the straits, it is assessed that underwater attacks are almost impossible while these vessels are making way. The underwater threats are thus limited to areas close to ports where vessels are expected to pick up pilots or in anchorage areas.

Conclusion

It has been shown that the environmental domain is a very challenging one for sonar systems within the Straits of Malacca. The density and profile of shipping in the straits also serve to minimize the detection and identification usefulness of sonar systems. Though opined to be not cost effective to cover the entire strait, sonar systems may still be used in areas close to ports and anchorage areas to act against underwater threats.

It is therefore, recommended that all search and detection uses of SONAR be regarded as infeasible and not considered among the selected alternatives.

References:

- Presentation on "Role of Automatic Identification System in Enhancing Maritime Security" by Nyberg Magnus from Saab TransponderTech AB, Sweden
- Straits Times articles:
  - "Pirate Attacks in Region's Waters Double" by K.C. Vijayan
  - "3-Nation Patrols of Strait Launched" by K.C. Vijayan
- Presentation on "Atmospheric and Ocean Effects on RF/EO Propagation" by Kenneth L. Davidson, Naval Postgraduate School
- "Introduction to Underwater Acoustics - *The Science of Sound"* by Dr Matthias Hoffmann-Kuhnt, Acoustic Research Laboratory, TMSI-NUS
- "Principles of Underwater Sound (3rd Edition)" by Robert J. Urick
- "Shallow-Water Acoustics" on *Physics Today* (Oct 2004) by William A. Kuperman and James F. Lynch

APPENDIX G: SENSOR SYSTEM GROUP "AS-IS" SURVEY

EXISTING SENSOR SYSTEMS IN THE STRAITS OF MALACCA

BACKGROUND

The Straits of Malacca is a narrow stretch of waterway between Peninsular West Malaysia and the Indonesia island of Sumatra. It forms the main ship passageway between India Ocean and the Pacific Ocean linking India, Indonesia and China.[1] According to International Maritime Organization, at least 50,000 ships sail through this strait every year. They transport approximately 30% of the world trade goods and 80% of Japan's oil needs. As the Straits are only 1.5 nautical miles wide at their narrowest point, Phillips Channel in Singapore Straits forms one of the world's significant sea traffic bottlenecks with potential for collisions, grounding and oil spills.[2] Hence, a few initiatives or systems have been implemented to manage and enhance navigational safety and minimize environmental pollution risk.

CURRENT INITIATIVES

The key systems currently in place in Straits of Malacca include:

(1) Vessel Traffic Services (VTS): The purpose of a Vessel Traffic Service (VTS) is to provide active monitoring and navigational advice for vessels in particularly confined and busy waterways. There are two main types of VTS, surveillance and non-surveillance. Surveillance systems consist of one or more land-based sensors (i.e. radar, AIS and closed circuit television sites), which output their signals to a central location where operators monitor and manage vessel traffic movement. Non-surveillance systems consist of one or more reporting points at which ships are required to report their identity, course, speed, and other data to the monitoring authority. They encompass a wide range of techniques and capabilities aimed at preventing vessel collisions, rammings, and groundings in the harbor, harbor approach and inland waterway phase of navigation. They are also designed to expedite ship movements, increase transportation system efficiency, and improve all-weather operating capability.[3]

(2) Electronics Navigation Charts - Electronics Chart Display and Information System (ENC – ECDIS): A system involves the automated collection, processing

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1 Nationmaster.Com, "Encyclopedia: Straits of Malacca", http://www.nationmaster.com/encyclopedia/Straits-of-Malacca.html (Accessed 31 Mar 05).

2 South Asia Analysis Group, "Straits of Malacca: Security Implications", http://www.saag.org/papers11/paper1033.html (Accessed 31 Mar 05).

3 US Coast Guard Navigation Center, "Vessel Traffic Services", http://www.navcen.uscg.gov/mwv/vts/vts_home.htm (Accessed 2 Apr 05).

and display of the ship's navigation and other sensor data in order to maximize watch bridge efficiency and navigational safety.[4]

(3) Differential Global Position System (DGPS): It is a radio navigation system that receives satellite generated positioning information. This system calculates real – time corrections to that information based on its known positioning and then transmits those corrections over select marine radio beacon transmitters to users located in the transmitter's coverage area.[4]

(4) STRAITREP: A joint Indonesia – Malaysia – Singapore mandatory ship reporting system in the Straits of Malacca and Singapore. It requires vessels using the Malacca and Singapore Straits to provide a report to the Vessel Traffic Services (VTS) Authority in Klang, Johore and Singapore. The STRAITREP consists of eight items including information on the vessel's name, position, course, speed, notification and description of hazardous cargo, sustained defects or damage and notification and description of pollutions or dangerous cargo lost overboard. The report is currently made by voice via very high frequency (VHF) radio channels.[5]

(5) Radar System: A sensing system to detect and track the movement of vessel entering and exiting the Straits of Malacca. Due to lack of information, the team assesses that the radar network is being deployed to support STRAITREP and Automatic Identification System (AIS).

(6) Ship Routing System: A shipping system of one or more routes or routeing measures aimed at reducing the risk of collision; it includes traffic separation schemes, two- way routes, recommended tracks, areas to be avoided, inshore traffic zones, roundabouts, precautionary areas and deep-water routes.

(7) Global Maritime Distress & Safety System (GMDSS): It provides the communication support needed to implement the search and rescue plan. This system, is based upon a combination of satellite and terrestrial radio services, and has changed international distress communications from being primarily ship-to-ship based to ship-to-shore (Rescue Coordination Center) based. The GMDSS provides for automatic distress alerting and locating in cases where a radio operator doesn't have time to send an SOS or MAYDAY call, and, for the first time, requires ships to receive broadcasts of maritime safety information which could prevent a distress from happening in the first place.[6]

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4 Koji Sekimizu, Jean-Claude Sainlos, James N. Paw, "The Marine Electronic Highway in the Straits of Malacca and Singapore – An Innovation Project for the Management of Highly Congested and Confined Waters", International Maritime Organization, July 2001.

5 Joshua Ho, "Operationalising the Regional Maritime Security Initiative", IDSS Commentaries (www.idss.edu.sg) 18/2004, 27 May 2004.

6 US Coast Guard Navigation Center, "GMDSS Overview", http://www.navcen.uscg.gov/mwv/vts/vts_home.htm (Accessed 2 Apr 05)

To summarize, the existing facilitates and information technologies that are in place along the Straits of Malacca and Singapore for maritime safety and environment protection and management are summarized as followed:[4]

Facility and Information Technology	Coverage in the Straits			
	Indonesia	Singapore	Malaysia	Straits - Wide
VTS	x	x	x	x
Radar System		x	x	x
ENCs	x	x	x	
DGPS Broadcast Systems		x		x
STRAITREP	x	x	x	x
Ship Routing System	x	x	x	x
GMDSS	x	x	x	x
GIS – based Environmental Database	x	x	x	x

Besides the abovementioned existing systems to ensure navigational safety, other new or in progress initiatives have been initiated to address the alarming increasing piracy attacks, threats of terrorist acts and enhance maritime safety in the Straits of Malacca are:

(1) The Marine Electronic Highway (MEH) is envisioned to be a regional network of marine information technologies linked through the ENCs – ECDIS. The availability of differential global positioning system (DGPS) with accuracy of 1 to 5 meters enhances the navigational accuracy of ENCs – ECDIS, especially in congested and confined waters. From a technical standpoint, the MEH has two components, namely, maritime safety and environmental protection and management. Within maritime safety, three categories are recognized i.e. navigational safety, precision navigation and emergency response. For environmental protection and management, four categories are identified that have a bearing on marine and coastal environments: environmental monitoring, protection and management, emergency response and risk/ damage assessment.[4]

(2) Automatic Identification System (AIS): The International Maritime Organization mandated AIS, to be installed on larger ships of above 300 gross tons by December 2004 which will provide and receive ship identity and positional information to shore stations, ships and aircraft; it will monitor and track ship, as well as exchange data with VTS Authority. As the AIS report is generated automatically, AIS – equipped ships will also have a concealed alert system that can send a covert signal or message to the VTS Authority should an emergency occur on board.[5]

(3) Straits Patrolling: Due to sovereignty issue, instead of a joint patrol, a trilateral coordinated patrol by Indonesia, Malaysia and Singapore at Straits of Malacca was launched in July 2004 to deter piracy and terrorist attacks.[7] [8]

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7 Mushahid Ali, Jeffrey Chen, "Maritime Security Cooperation in the Malacca Straits : Prospects and Limits", IDSS Commentaries (www.idss.edu.sg) 23/2004, 1 July 2004.

(4) Regional Maritime Security Initiatives (RMSI): The United States (U.S) is concerned over the movement of cargo relating to Weapon of Mass Destruction (WMD) through the Straits of Malacca. The RMSI is part of the U.S Proliferation Security Initiative (PSI) in its global war on terrorism. In South East Asia, Australia and Singapore are participants in this initiative.[2] It consists of three components: a sea picture of the traffic in the Malacca and the Singapore Straits, a decision making structure to decide on actions to take with respect to clandestine activity that is occurring and a standby maritime force to act on that decision. The RMSI may leverage on existing systems or arrangements.[5]

CURRENTLY OPERATIONAL SYSTEMS

To support the STRAITREP system which is a tripartite joint mandatory ship reporting system in the Straits of Malacca and Singapore, the shore-based facilities have been erected to facilitate communication and provide sensor coverage capabilities along the congested and busy narrow waterway.

Based on literature research, both X-band and S-band radars have been installed at 12 designated locations in Malaysia and Singapore waters. Moreover, only VHF (Very High frequency) equipment is used to establish communication between the VTS authorities and the vessels using designated frequency channels.[9]

On the other hand, the AIS system automatically captures and broadcasts data such as vessel's position, speed, name, call sign, course over ground and cargo type. The control centre will immediately get these data without the need for extensive radio communication. The purposes for the implementation of the AIS in Straits of Malacca include:[10]

- Form an integral part of the mandatory strait reporting (STRAITREP) system and the proposed Marine Electronic Highway project.
- Provide weather data (such as wind speed and direction, air temperature, sea current levels and tidal height and direction) to vessels.
- Monitoring the movement of hazardous cargo and to control commercial fishing operations in territorial waters.
- Use to investigate an accident, oil spills and other incidents at sea.
- Provide as a useful tool in search and rescue operations.

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8 Warships Magazine, "War on Terror Update Oct 2004", http://www.warshipsifr.com/pages/terrorism_special12.html (Accessed 1 Apr 05).

9 Mandatory Ship Reporting Systems: Resolution MSC.73(69); Annex 10 adopted may 1998.

10 Maicons Technology, "Automatic Identification System", http://www.maicons.com.my/ais_malacca.html (Accessed 27 Apr 05).

Figure 1: Sensor Location in Malacca Straits.

Figure 2: Sensor Location in Singapore Straits.

For the STRAITREP system, redundancy has been incorporated into the current system design. The objective is to avoid any irretrievable breakdown of equipment which will hinder the functioning of the services provided by the respective Vessel Traffic Services (VTS) authorities i.e. Klang, Johore and Singapore. The identified critical equipment and power sources are duplicated and the facilities are provided with emergency generating sets as well as with Uninterruptable Power Supply (UPS) units. In addition, a maintenance team is available 24 hours a day to attend to any breakdown. If any one of the station fails, the adjacent station has the capability to provide the necessary coverage.[10]

The northeastern coast of Indonesia is filled with mangrove swamps and it is sparsely populated with no major economical activities. As such, the team perceives Indonesia will not have any economical interest to monitor the sea traffic conditions along the Straits of Malacca. This is the most likely reason that there is no fix shore-based radar installation found on the coast along the Straits of Malacca.

As there is no detailed description of the specific type of radar used for coastal surveillance, the team assesses that the following coastal radar systems (with specifications cited at the end of this paper) can be deployed for surveillance purposes:

- ARGOS-73 Coastal Surveillance Radar
- Score Coastal Radar
- Signaal Coastal Radar System (SCORADS)
- EL/M-2226 Coastal Surveillance Radar
- TRS 3415 SURICATE Coastal Surveillance Radar

To maintain a secured sea lane in the Straits of Malacca, a coordinated joint sea patrolling among the three nations was initiated. Besides the information on the fixed radar installations, a list of radar and electro-optics systems that have been deployed by the Indonesia, Malaysia and Singapore Navies have been consolidated from Jane's Defense publications as summarized in the table below. Their specifications are appended at the end of this paper for references.

Table 2: Platform Sensor Systems.

S/No.	Sensor Type	Indonesia	Malaysia	Singapore
	RADAR			
1	DA05 Naval Surveillance Radar	x	x	
2	DA08 Naval Surveillance Radar		x	
3	Herakles Multifunction 3-D Radar			x
4	RAN 11L/X and 12L/X Naval Radar		x	
5	Scout Naval Radar	x		
6	VARIANT Naval Surveillance Radar	x		
7	EL/M-2228X Surveillance and Gunnery			x

S/No.	Sensor Type	Indonesia	Malaysia	Singapore
	Radar (SGR)			
8	Strut Curve/Strut Pair Search Radar	x		
9	Sea Giraffe 50/150 Naval Radar		x	x
10	United Kingdom Type 1006	x		
11	Sperry Marine Surveillance and Navigation Radar	x	x	x
12	AN/SPS-67(V) Search Radar		x	
13	APS-504(V) Radars	x		
14	AMASCOS 100 Maritime Patrol System	x		
15	Ocean Master Radar	x		
16	Seaspray 3000 Maritime Surveillance Radar		x	
17	AN/APQ-122(V) Multimode Radar	x	x	x
18	AN/APS-138 Airborne Early Warning (AEW) Radar			x
19	AN/APS-128/-128 Model D Maritime Surveillance Radar	x	x	x
20	AN/APS-133(V) Multimode Radar	x		
21	AN/APS-134(V) Maritime Surveillance Radar			x
22	APS-143B(V)3 Ocean Eye™ Sea Surveillance Radar		x	
23	Side-Looking Airborne Modular Multi-mission Radar (SLAMMR)	x		
	EO/IR			
24	BAE Systems Sea Archer 30 (GSA8)			
25	Elop Multisensor Stabilized Integrated System (MSIS)			
26	Thales IRSCAN			
27	Thales, Spar Aerospace SIRIUS			
28	The Boeing NMMS			
29	The Boeing Thermal Imaging Surveillance System (TISS)			

For the Electro-Optics and Infrared (EO/IR) systems, the deployment information on the specific type of sensor by each of the three navies is not specified in any publications. However, based on the operation experiences gained by a few of the Singapore Navy Officers who have patrolled along the Straits of Malacca, the abovementioned EO/IR sensors systems will have the most probable capability to perform their intended functions in the spectral band of 3 – 5 μm and 8 – 12 μm in the typical equatorial climatic conditions.

By observation of the shore-based radar systems, they utilize two bands of different frequency ranges. For the platform radar systems, both single and double frequency bands are being used. A close inspection reveals that the I-band ranging from 8 – 10 GHz is the most commonly used as compare to other frequency bands i.e. D (1 – 2 GHz), E (2 – 3 GHz), F (3 – 4 GHz), G (4 – 6 GHz) and H (6 – 8 GHz).

The historic data or statistics shows that approximately 50000 vessels pass through the Straits of Malacca annually. Thus, on the average, about 137 vessels will transit through the busy and narrow passage daily. This may imposes a requirement to have a good resolution sensor system to detect the presence of vessels especially when two or more vessels are in close proximity range. Hence, the use of two different frequency bands will provide long range detection (by the lower frequency range) and give better resolution (by the higher frequency range) relatively.

ANNEX A

SPECIFICATIONS

1. DA05 Naval Surveillance Radar[11] :

Antenna: Horn fed parabolic reflector
Beamwidth: Vertical $cosec^2$ up to 40°; azimuth 1.7°
Polarization: Linear and circular, selectable
Transmitter: E/F band (2 – 4 GHz) tunable coaxial magnetron, with selectable frequencies
Peak Power: 1.2 MW
Range: 135 km on a fighter
Pulse Length: 1.3 and 2.6 μs
PRF (Staggered): 1000 and 500 Hz
System Weight: 3273 kg

Used by:
Indonesia: 'Amad Yani' (six ships) and 'Fatahillah' (three ships) class guided missile frigates
Malaysia: 'Musytari' class offshore patrol vessel (two ships)

2. DA08 Naval Surveillance Radar[11] :

Antenna: Horn fed parabolic reflector
Polarization: Linear and circular, selectable
Beamwidth Azimuth: 1.55°
Beamwidth Elevation: $cosec^2$ up to 40°
Rotation Speed: 10/20 rpm (Version 1); 15 rpm (Version 2)
Processing: MTI (Version 1); FFT (Version 2)
Stabilization: Roll and Pitch
Transmitter: F-band coherent (3 – 4 GHz) TWT system
Power Output: 145 kW peak; 5 kW average
PRF: 500/1000 Hz (Version 1); 2400 Hz (Version 2)
Detection Range (2 m^2 RCS target): 125 km (FFT Version); 185 km (MTI Version)
Resolution: 90 m (Range); 1.55° (Bearing)
Weights: Total top weight 1100 kg; remainder 3253 kg

Used by:
Malaysia: 'Leiku' class guided missile frigates (two ships) and 'Kasturi' class guided missile corvettes (two ships)

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11 Martin Streetly, "Jane's Radar and Electronic Warfare Systems 2004 – 2005", Naval / Coastal Surveillance and Navigation Radars.

3. Herakles Multifunction 3-D Radar[11] :

Frequency: E/F-band (2 – 4 GHz)
Angular Coverage: up to 70° (Elevation); 360° (Azimuth)
Range: up to 200 km
Track Capacity: > 200
Rotation Speed: 60 rpm

As of 2003, Herakles was reported as having been selected for installation aboard six 'La Fayette' (Project Delta) class frigates being procured by Singapore during the period 2004 to 2008

4. RAN 11L/X and 12L/X Naval Radar[11] :

Frequency: D- (1 – 2 GHz) and I-band (8 – 10 GHz)
Antenna: Roll and Pitch stabilized
Rotation Rate: 15 and 30 rpm
Polarization: Linear and Circular
I-band Transmitter: Frequency tunable
I-band Receiver: Image suppression, mixer, log receiver, Dicke-fix, autogate, automix
D-band Transmitter: Frequency diversity, waveform coding
D-band Receiver: double frequency conversion, coherent limiting, dual-channel Doppler processing, code matched filtering, azimuth correlation
Range (on a fighter size air target): low altitude (I-band) more than 37 km; medium altitude (D-band RAN 11L) more than 22 km; medium altitude (D-band RAN 12L) more than 26 km
Range Accuracy: 45 m (I-band); 160 m (D-band)
Angular Accuracy: 0.2° (I-band); 1.5° (D-band)

Used by:
Malaysia: 'Laksamana' class frigates (four ships – RAN 12L/X radar)

5. Scout Naval Radar[11] :

Frequency: I-band (8 – 10 GHz)
Transmitter Power: 1 mW, 10 mW, 100 mW or 1 W (Operator Selectable)
Antenna Gain: 30 dB
Antenna Rotation Speed: 24 rpm
Sweep Repetition Frequency
Number of Range Cells: 512
Range Scales: 1.4, 2.8, 5.6, 11.1, 22.2 and 44.5 km
Range Cell Size: 3, 6, 12, 24, 48 and 96 m
Range Resolution: 9, 18, 36, 72, 144 or 288 m (range scale dependent)
Power Requirements: 115 V (60 Hz, 1-phase, 700 VA approx load)

Dimensions (w x h x d): 420 x 460 x 300 mm (Processor); 1933 x 608 x 400 mm (Antenna Assembly)
Weight: 15 kg (Processor); 65 kg (Antenna Assembly)

6. VARIANT Naval Surveillance Radar[11] :

Antenna: Double pill-box
Beamwidth: Elevation 14°; Azimuth 1.8°(G-band)
Rotation Speed: 14 and 28 rpm
Frequency: G- (4 – 6 GHz) and I-band (8 – 10 GHz)
Transmitter: TWT
Average Power: 200 W
Operating Modes: G-band only; I-band only; G- and I-bands; low probability of intercept
Pulse Length: 10 μs (short); 16 and 25 μs (long)
Processing: Digital pulse compression; FFT Doppler processing; automatic tracking
Instrumented range: 60 km air; 70 km surface

Used by:
Indonesia: 'Todak' class large patrol craft

7. EL/M-2228X Surveillance and Gunnery Radar (SGR)[11] :

Frequency: I-band (8 – 10 GHz)
Transmitter: TWT
Range: 50 km (fighter size air target); 100 km (instrumented); radar horizon (surface targets)
Fall of shot measurement accuracy: 10 m (range); 2.5 mrad (bearing)
Scan Rate: 12 or 24 rpm
Stabilization: 20° Roll and Pitch
Antenna type/ weight/ location: Cosec^2 (up to 30° in elevation) reflector/ 220 kg/ masthead

Used by:
Singapore: 'Fearless' class patrol craft

8. Strut Curve/Strut Pair Search Radar[11] :

The radar designated by NATO as 'Strut Curve' is an F-band (3 – 4 GHz) medium range general purpose search radar that provides both air and surface search facilities. An elliptical lattice reflector is used, illustrated by a horn feed carried by a boom projecting from the lower edge of the scanner. Range performance against a 2 m^2 aircraft target at medium altitude is approximately 111 km with a likely maximum range of 278 km.

A version of this radar – known to NATO as 'Strut Pair' – makes use of two 'Strut Curve' antennas mounted back-to-back.

Used by:
Indonesia: 'Kapitan Patimura' class corvettes and 'Frosch I/II' class landing ships

9. Sea Giraffe 50/150 Naval Radar[11] :

Operating Frequency: G-band
Output Power: 60 kW; Average Power 1200 W
Antenna Rotation Rate: 60/30 rpm
Instrumented Range: 25, 50, 100 and 150 km
Tracking Capacity: > 30 (air target – auto initiation); > 50 (surface targets – mutual initiation)
Antenna sidelobe levels: - 45 dB
Beamwidth Bearing: 1.8°
Elevation Coverage: 0 - 70°
Accuracy: 20 m (range); 0.3° (azimuth)

Used by:
Malaysia: 'Lekiu' class frigates (two ships – Sea Giraffe 150)
Singapore" 'Victory' class corvettes (six ships – Sea Giraffe 150)

10. United Kingdom Type 1006[11] :

It is a I-band (8 – 10 GHZ) navigation and surface search radar.

Used by: Indonesia survey ship 'Dewa Kembar' and the replenishment tanker 'Arun'

11. Sperry Marine Surveillance and Navigation Radar[11] :

Indonesia:
'Fatahillah' and 'Van Speijk' class frigates. Both use Solid State series type 1229 which employs 30 cm PPI displays, operate in I-band (8 – 10 GHz), have 20 kW outputs and are equipped with 2.7 m antenna.

'Dagger' FACs. It uses Solid State series type 1226 which employs 30 cm PPI displays, operate in I-band (8 – 10 GHz), have 20 kW outputs and are equipped with 1.83 m antenna.

'Singa' class FACs and 'Kapap' class large patrol craft. Both use Type 2459 F/I radar (3 – 4 and 8 – 10 GHz) that is fitted with a combined F/I band antenna and which can utilize a variety of transceiver and display

units. A variant known as 2459 FID incorporates a D-band (1 – 2 GHz) identification friend-or-foe sub-array.

Malaysia:
'Lekiu' class frigates. It uses a I-band radar with a 2.7 m antenna incorporate with an air search capability which can detect targets traveling at speeds up to 1111 km/h at ranges of up to 74 km.

'Kasturi' class corvettes, 'Musytari' class off-shore patrol vessels and 'Mahamiru' class minehunters. All use Solid State series type 1226 which employs 30 cm PPI displays, operate in I-band (8 – 10 GHz), have 20 kW outputs and are equipped with 1.83 m antenna.

Singapore:
'Swift' class coastal patrol craft. It uses Solid State series type 1226 which employs 30 cm PPI displays, operate in I-band (8 – 10 GHz), have 20 kW outputs and are equipped with 1.83 m antenna.

12. AN/SPS-67(V) Search Radar[11] :

Frequency: 5.4 – 5.8 GHz
Azimuth Beamwidth: 1.5°
Elevation Beamwidth: 12° (-67(V)1); 31° (-67(V)2&3)
Pulsewidth: 0.1; 0.25; 1.0 μs
Peal Power: 280 kW
Scan Period: 2/4 s (-67(V)2&3); 4 s (-67(V)1)
Instrumented Range: 104 km
Track Initiation: Automatic (SPS-67(V)3)
Track File Size: 128 (SPS-67(V)3 – expandable, claimed > 24 dB improvement over preceding models, coherent receive auto clutter lock digital moving target indication)
MTBF: > 600 hr
MTTR: < 0.5 hr

Used by:
Malaysia: Tank Landing Ship 'Sri Inderapura'

13. APS-504(V) Radars[12] :

Frequency: 8.9 – 9.4 GHz (transmit, 16 sub-frequencies); 9.345 GHz (weather mode); 9310 (receive) – 9375 (transmit) GHz (beacon mode)
PRF: 320 – 2 , 230 Hz (mode dependent)
Transmitter Power: 6.6 kW (peak)
Pulse Length: 0.2 – 30 μs (mode dependent)

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12 Martin Streetly, "Jane's Radar and Electronic Warfare Systems 2004 – 2005", Airborne Surveillance, Maritime Patrol and Navigation Radars.

Pulsewidth: 0.032 μs (compressed search receive – 10 μs transmit); 0.2 μs (search and compressed search receive – 30 μs transmit); 0.5 μs (receive, beacon); 2 μs (transmit, beacon); 5 μs (weather); 10 μs (transmit, search); 30 μs (transmit, search)
Gain: 33 dBi (one – way, mimimum)
Beamwidth: 2.4° (azimuth, one – way, maximum); 6.7° (elevation, one – way, maximum)
Scan Rate: 7.5, 15, 30, 45, 60, 90 and 120 rpm (automatic selection)
Azimuth Sidelobes: 27 dB (close-in, one – way, mimimum); 40 dB (beyond 55°, one – way, minimum)
Antenna Stabilization: ±20° (Pitch and roll, 2-axis pedestal, up to 30 rpm scan rate, 0° tilt)
Receiver Noise: 5 dB (maximum)
TWS: up to 20 targets (search and beacon modes)
Range Scales: 5, 11, 22, 46, 93, 185 and 370 km
Modes: MPA search, ground stabilized search, weather/weather contour and beacon
Power: 28 VDC, 115 VAC (3-phase, 400 Hz)

Used by: Indonesia Boeing 737-2X9 Surveillers (4 x APS-504(V))

14. AMASCOS 100 Maritime Patrol System[12] :

The AMASCOS 100 configuration is designed for a range of tasks including Exclusive Economic Zone (EEZ) control, fisheries protection, maritime traffic surveillance, anti-smuggling, anti-piracy and anti-drug patrols, immigration control, pollution monitoring, Search And Rescue (SAR) and sovereignty patrols executed by coastal surveillance services, customs services and / or armed forces. As such, the suite is generally installed aboard lightweight aircraft and is operated by one or two operators working in collaboration with the host aircraft's flight crew. A typical AMASCOS 100 application weighs a maximum 250 kg and is suitable for installation aboard both fixed-wing aircraft and land or ship-based helicopters.

Used by: Indonesia – The supply of AMASCOS 100 suite including Ocean Master radars and Chlio Forward Looking Infra Red (FLIR) for use aboard six IPTN NC-212 Aviocar maritime patrol aircraft and three NBO 105 helicopters.

15. Ocean Master Radar[12] :

Frequency: I/J-band (8 – 20 GHz)
PRF: 300 Hz – 125 kHz

Transmitter Output: 100 W (Ocean Master 100 – average); 400 W (Ocean Master 400 – average)
Detection Range: 200 m (mim); 370 km (max)
Range Resolution: 3 m (min)
Track-while-Scan: up to 32 targets (automatic)
Antenna Stabilization: 2-axis (±20% roll; ±10% pitch)
Antenna Tilt: -29 to +4°
Antenna Rotation Rate: 6 – 30 rpm (automatic selection by mode)
Antenna Gain: 30.5 – 34 dB
Power requirement: 115 VAC (400 Hz)
Power Consumption: 2 kVA (Ocean Master 100); 3.8 kVA (Ocean master 400)
Interfaces: ARINC 429; MIL-STD-1553B; RS-422; video
Options: 48 cm (19 in) display; IFF compatibility; datalink, ES, IFF, FLIR, sonics and video recorder interfaces, ISAR target classification
Dimensions: 375 x 300 x 415 mm (MMI); 415 x 275 x 320 mm (Ocean Master 100 transmitter); 555 x 200 x 340 mm (exciter/ receiver/processor unit); 566 x 208 x 260 mm (Ocean Master 400 transmitter); 660 x 350 mm antenna option); 940 x 350 mm (antenna option); 1800 x 300 mm (antenna option)
Weight: 8 kg (MMI control panel); 15 kg (660 x 350 mm antenna option); 16 kg (approx – 940 x 350 mm antenna option); 18 kg (MMI display); 27 kg (exciter/receiver/processor unit and 1800 x 300 mm antenna option); 29 kg (Ocean Master 100 transmitter); 39 kg (Ocean Master 400 transmitter)

Unidentified Ocean Master variants for installation aboard six (?) NC-212-200 maritime patrol aircraft and three NBO-105S over-the-horizon targeting helicopters of the Tentara Nasional Indonesia – Angkatan Laut (Indonesian National Defence – Navy)

16. Seaspray 3000 Maritime Surveillance Radar[12] :

Frequency: I-band (8 – 10 GHz)
Peak Power: 90 kW
Transmitter: High speed, spin tuned magnetron
Pulse widths: 2 (selectable)
PRF: 4 (selectable)
Coverage: 360°
LRUs: 6
Weight: 90 kg
Target Illumination: Monopulse lock-follow
Features: CFAR and operator selectable scan-to-scan integration
Options: Operator selectable circular polarization; antenna size (up to 1 m diameter); display types

Used by: Malaysia Navy

17. AN/APQ-122(V) Multimode Radar[12] :

I-/low J-band (8 to 12 GHz) and K-band (20 to 40 GHz) navigation and mapping radar. The full set of APQ-122(V)8 operating modes is as follows:

- Terrain-Following (TF)
- Terrain-Avoidance (TA)
- Terrain-Following / Terrain-Avoidance (CS)
- Long range ground map
- Weather detection
- Beacon
- Precision ground map (PGM)
- Simultaneous TF/PGM, TA/PGM, CS/PGM

Used by: Indonesia, Malaysia and Singapore Air Force

18. AN/APS-138 Airborne Early Warning (AEW) radar[12] :

Frequency: UHF band (0.3 to 1 GHz)

APS-138 was followed by the 1987 vintage APS-139 variant that has been characterized as a 'relatively modest' improvement over its predecessor and appears to have been an attempt to improve the radar's capability against low radar cross section targets such as cruise and anti-shipping missiles.

Used by: Singapore (four E-2C Group 0s with APS-138)

19. AN/APS-128/-128 Model D Maritime Surveillance Radar[12] :

Frequency: I-band (9375 MHz)
Frequency Agility: 85 MHz peak/peak
Power Output: 100 kW peak
Pulse Width: 2.4 and 0.5 μs
PRF: 400, 1200, 1600 Hz
Noise Figure: GAS-FET 3.5 dB low noise RF amplifier
Antenna Rotation Rate: 15 rpm (sector scan selected from the 60°- 360° arc); 15 – 60 rpm (continuous)
Bright Display: High ambient light, 875 line high resolution
System Weight: 91.8 kg with 20 cm display

Used by: Indonesia, Malaysia and Singapore Air Forces

20. AN/APS-133(V) Multimode Radar[12] :

Fequencies: I-band (9375±5 MHz – transceiver, weather/map modes; 9310±5 MHz – receiver beacon mode)
Power Output: 65 kW peak (nominal)
Range: 560 km
Antenna: 76 cm parabola with 3 pencil beams and CSC $cosec^2$ fan beam
Antenna Scan Angle: 180° (±90°)
Weight: 53.6 kg

Used by: Indonesia Air Force

21. AN/APS-134(V) Maritime Surveillance Radar[12] :

Three modes of operation are available:

- Periscope target detection in sea clutter using fast scan (150 rpm), high pulse repetition frequency (PRF – 2000 pulses/s) and high resolution with display ranges selectable up to 59 km
- Maritime surveillance out to 278 km with high resolution, low PRF (500 pulses/s) and medium scan speed (40 rpm)
- Long range search and navigation out to 278 km with medium resolution, low PRF and slow scan (6 rpm)

Transmitter frequency: I-band (9.5 – 10 GHz modes a and b; 9.6 – 9.9 GHz mode c)
Power Output: 500 W (average); 500 kW peak
Antenna Beamwidth: 2.4° (azimuth); 4° (elevation)
Polarization: Vertical

Used by: Singapore's Fokker Maritime Enforcer Mk 2 maritime patrol aircraft.

22. APS-143B(V)3 Ocean Eye™ Sea Surveillance Radar[12] :

Frequency: 9.25 – 9.7 GHz (450 MHz agility)
Transmitter: Helix traveling wave tube type
Power Output: 260 W (average, nominal); 500 W (average, max); 8 kW (peak, min)
Pulse Width: 0.1, 10, 23.4 or 40 μs
Weighted Compressed Pulse Width: 100 ns (search modes)
Waveform Generation: digital synthesis
PRF: Multiple
Receiver Noise: 2.5 dB (max)
Receiver Bandwidth: Matched to Pulse-width
Antenna: Cooperate fed planar array
Antenna Bandwidth: 500 MHz
Antenna Gain: 31 – 34 dB (antenna dependent)

Antenna Polarization: Horizontal (vertical option)
Antenna Stabilization: ±30° (pitch and roll)
Sector Scan: 45° - 350° or continuous 360° (operator selectable)
Detection: 1 m^2 RCS target (typical – range in excess of 56 km (30 nm), low altitude operation, Sea State 3)
Range: in excess of 370 km (max)
Display Range Resolution: 18.5 m (1 m - imaging)
Search Range Resolution: < 3 m
Azimuth Accuracy: 0.5° or better
Programmable Video Resolution: CCIR-601, RS-170/343, VGA and XVGA
Operating Modes: ISAR, range profiling, range zoom, return-to-ship, search, SLAR, spotlight SAR, strip map SAR, color weather and air-to-air
Power Requirement: 28V (12 A); 115 VAC (400 Hz, 3-phase)
MTBF: 800 hrs (helicopters); 1400 hrs (fixed-wing aircraft)
Weight: 82 kg

Used by: four Super King Air 200TB maritime patrol aircraft of the Malaysia Air Force

23. Side-Looking Airborne Modular Multi-mission Radar (SLAMMR)[12] :

Side looking long range surveillance radar

Used by: Indonesia Air Force's three Boeing 737-2X9 Surveiller combined maritime patrol/transports.

24. BAE Systems Sea Archer 30 (GSA8)[13] :

Director
Height: 1100 mm
Swept Radius: 465 mm
Weight: 270 kg (incl sensors)
Pointing Accuracy: better than 3 m at 10 km in sea State 5
Elevation motion: 110° (-35 to +75°)
Training motion: 610° (±305°)
Elevation Velocity: 90°/s
Training Velocity: 90°/s
Elevation Acceleration: 150°/s sustained until max velocity is reached
Training Acceleration: 150°/s sustained until max velocity is reached

Thermal Imager
Wavelength: 8 – 12 μm
Output: CCIR 625 line 50 Hz
Field of View: 17 to 3° (diagonal)

---

13 Martin Streetly, "Jane's Electro-Optic Systems 2001 – 2002", Ship Weapon Control Systems: Fire Control.

Magnification: x3.6 to x20
Detector: SPRITE
Cooling: Integral Stirling Engine

TV Camera
Type: Charge Coupled Device (CCD)
Output: CCIR 625 Line 50 Hz
Field of View: 17 to 3° (diagonal)
Magnification: x3.6 to x20
Lens Max Aperture: f1.4

Laser Range Finder
Wavelength: 1.54 µm
Beam Divergence: 1.5 mrad max
Pulse Repetition Frequency: 12.5 Hz
Peak Power: 10 MW
Range Resolution: 5 m

25. Elop Multisensor Stabilized Integrated System (MSIS)[13] :

Line of Sight Stabilization: 20 µrad
Elevation Motion: -35 to +85°
Training Motion: x360°
Slewing Rate: 60 and 90°/s
Reporting Accuracy: 0.8 mrad Sea State 3
Tracking Accuracy: better than 150 µrad
Weight: Turret 60 kg; Total System 100 kg
Turret Dimension: 780 mm (h) x 600 mm (d)

Thermal Imager
Spectral Band : 8 – 12 µm or 3 – 5 µm
Cooling : Integral Stirling Engine

Laser Range Finder
Wavelength : 1.064 µm or eye-safe

TV Camera
Type : BW CCD

26. Thales IRSCAN[14] :

Detection Capability : Typically 20 km (For incoming aircraft and supersonic missiles); typically 12 km (For subsonics missiles)
Target Designation Accuracy: < 1 mrad

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14 Martin Streetly, "Jane's Electro-Optic Systems 2001 – 2002", Ship Weapon Control Systems: Infra-Red Search and Track.

Internal Track Capacity: > 500 tracks real time
Alert Generation: Automatic alert generation on 32 tracks, classified threatening
False Alert Rate: < 1 false alert/hr
Elevation Coverage: 14.6°
Scanning Speed: 78 rpm
Spectral Band: 8 – 12 μm
Detector: 1024 elements staggered line array (CMT plus COMS readout technology)
Detector Cooling: Closed-Cycling Stirling
Power Requirements: 115 V, 60 Hz; 3-phase 115 V; 60 Hz; 1 phase anti-condensation heating
Max Power Consumption: 4.55 kW

27. Thales, Spar Aerospace SIRIUS[14] :

Detection Range : Typically 35 km (Supersonic sea-skimming missiles); typically 21 km (Subsonics sea-skimming missiles); typically 30 km for fighter aircraft
Elevation Coverage: 3.8°
Scanning Speed: > 60 rpm
Spectral bands: 3 – 5 μm, 8 -12 μm
Detectors: 300 x 10, 300 x 8 elements
Cooling: Closed-cycle Stirling
Weight Stabilized Sensor Head: 180 kg
Weight Below-desk Equipment: 830 kg
Power Consumption: 8 kVA

28. The Boeing NMMS[15] :

System Weight: 113.4 kg

Turret
Weight: 72.57 kg
Diameter: 64.77 cm
Stabilization: 2 axis, < 20 μrad jitter
Azimuth: ±190°
Elevation: ±30°

TV Camera
Type: Silicon Vidicon
Frequency Range: 0.65 – 0.9 μm
Output: 875 line video
Field of View: 2° narrow, 8° wide

15 Martin Streetly, "Jane's Electro-Optic Systems 2001 – 2002", Ship Weapon Control Systems: Surveillance.

Thermal Imaging Sensor
Type: 120 element MCT scanning
Spectral band: 8 – 12 μm
Field of View: 3° narrow, 10° wide

29. The Boeing Thermal Imaging Surveillance System (TISS)[15] :

System Weight : 363 kg

Turret
Weight: 70 kg
Diameter: 44.45 cm
Width: 52.07 cm
Stabilization: 2 axis, < 15 μrad jitter
Azimuth: ±270°
Elevation: +75, -35°

TV Sensor
Type: Low-light silicon CCD
Spectral range: 0.65 – 0.95 μm
Output: 875 line video
Field of View (h x v): 1.6 x 1.2° (Narrow); 6 x 4.5° (Wide)

Thermal Imaging Sensor
Type: 480 x 512 staring InSb
Spectral Band: 3 – 5 μm
Target Temperature Range: -60 to +100°C
Field of View (h x v): 1 x 1° (Narrow); 2.9 x 2.9° (Wide)

Laser Range Finder
Type: Class 1A eye-safe Nd: YAG
Wavelength: 1.54 μm
Range: 20000 m
Durability: 10^6 shot life

30. ARGOS-73 Coastal Surveillance Radar[11] :

Frequency: S-band (2 – 4 GHz)
Range: in excess of 139 km (fighter aircraft sized target)
Coverage: up to 35° (elevation)
Accuracy: 0.3° (angular); 50 m (range)
Antenna: cosecant squared reflector
Rotation diameter: 5.2 m
Scan Rate: 10 rpm
Polarization: Linear / Circular

Dimensions (HxWxD): 1750 x 1460 x 663 mm (Tranmsitter); 1950 x 827 x 566 mm (receiver); 4980 mm (antenna height, including SLS and pedestal)
Weight: 440 kg (receiver); 700 kg (transmitter); 1300 kg (antenna assembly)

31. Score Coastal Radar[11] :

Antenna: 4.8 m parabolic reflector
Gain: 42 dB
Azimuth Beamwidth (3 dB): 0.55°
Elevation Beamwidth (3 dB): 2.7°
Polarization: circular, fixed
Rotation Speed: 11 rpm
Frequency: I-band
Compressed Pulse: 0.02 μs
Range: 93 km (2.5 m^2 RCS fighter at low altitude); 130 km (fast patrol boat)

32. Signaal Coastal Radar System (SCORADS)[11] :

Frequency: G-band (4 – 6 GHz)
Peak Power: 2000 W
Antenna Gain: 40 dB
Beamwidth: 0.75° (Azimuth); 2.75° (elevation)
Scan Rate: 10 rpm
Sidelobe Levels: -40 dB (peak)
Uncompressed Pulse Length: 10 μs (surface mode); 24 μs (air mode)
Compressed Pulse Length: 550 ns
PRF: medium (air mode); low (surface mode)
Max Range: 105 km (surface); 120 km (air)
Altitude: 3048 m
Accuracy: 0.25° (Azimuth); 50 m (Range)
Resolution: 2° (Azimuth); 100 m (Range)
Capability: 400 tracks / scan
Dimensions / Weight: 4980 x 4815 x 3126 mm / 2950 kg (antenna / transmitter unit); 745 x 1496 x 445 mm / 160 kg (receiver / processor cabinet); 750 x 555 x 650 mm / 50 kg (local control workshop)

33. EL/M-2226 Coastal Surveillance Radar[11] :

Frequency: 8 – 12 GHz
Azimuth Beamwidth: 1.5°
Elevation Beamwidth: 2.6°
Detection Range (Sea State 3) : > 20 km (rubber boat) ; > 60 km (patrol craft)
Track / Target Capability: > 100

34. TRS 3415 SURICATE Coastal Surveillance Radar[11] :

Antenna: 4.4 m
Gain: 40 dB
Azimuth Beamwidth: 0.6°
Elevation Beamwidth: 4°
Cosec^2: - 30°
Rotation Speed: 11 rpm
Range: 83 km (2.5 m^2 target); 114 km (10 m^2 target)
Polarization: Circular or Linear (switchable)
Transmitter: I/J-band (8 – 20 GHz) TWT
Compressed pulse: 20 ns

Over time, SURICATE is understood to have been procured by 'several' European and Asian customers.

APPENDIX H: TDSI FORCE GROUP FINAL REPORT

NAVAL
POSTGRADUATE
SCHOOL

MONTEREY, CALIFORNIA

THESIS

MARITIME DOMAIN PROTECTION

Force Group

by

Er, Kim Hua

How, Yew Seng

Lukacs, John,

Quek, Chin Khoon,

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December 2005

Advisor: Papoulias, Fotis

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Month Year	SEA 7-TDSI Integrated Project Report 2005

4. TITLE AND SUBTITLE: Title (Mix case letters)	5. FUNDING NUMBERS
MARITIME DOMAIN PROTECTION,Force Group	
6. AUTHOR(S)	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Naval Postgraduate School Monterey, CA 93943-5000	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
N/A	

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Distribution Statement (mix case letters)	

13. ABSTRACT (maximum 200 words)

Three possible scenarios have been presented for analysis within the SEA-7 Integrated Project namely:

1) Small Boat Attack (SBA)

2) Ship As a Weapon (SAW)

3) Weapon of Mass Destruction (WMD)

Each of these scenarios are discussed in detail to provide baseline knowledge as well as to establish conditions for victory and measures of effectiveness.

The Top Level requirements have been promulgated by the MDP group leaders, and are discussed and analyzed for their relevance to the Force group. These form the overall integrated project requirements. Each of these situations are further analyzed to determine the Second Level and Third Level requirements for the Force Weapon System component of the Integrated Project.

The proposed deployment strategy presented by the MDP group leaders are studied, specifically considering the zonal patrol

strategy for the minimum requirements necessary to achieve the performance and effectiveness measures that were developed.

Having agreed on a set of necessary specifications for the weapon system platform, several possible alternative vehicles are presented and discussed. Each are evaluated against the scenarios, the MOEs, and the MOPs to determine the best solution for the project.

Finally, a discussion of further analysis, evaluation, and alternatives for future implementation is presented.

14. SUBJECT TERMS			15. NUMBER OF PAGES 33
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

Prescribed by ANSI Std. 239-18

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PROJECT TITLE

Integrated Project (TDSI Force System)

NAVAL POSTGRADUATE SCHOOL
June 2005

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12. Janes Fighting Ships 2003-2004

EXECUTIVE SUMMARY

Three possible scenarios have been presented for analysis within the SEA-7 Integrated Project namely:

1) Small Boat Attack (SBA)

2) Ship As a Weapon (SAW)

3) Weapon of Mass Destruction (WMD)

Each of these scenarios will be discussed in detail to provide baseline knowledge as well as to establish conditions for victory and measures of effectiveness.

The Top Level requirements have been promulgated by the MDP group leaders, and will be discussed and analyzed for their relevance to the Force group. These will form the overall integrated project requirements. Each of these situations will be further analyzed to determine the Second Level and Third Level requirements for the Force Weapon System component of the Integrated Project.

The proposed deployment strategy presented by the MDP group leaders will be studied, specifically considering the zonal patrol strategy for the minimum requirements necessary to achieve the performance and effectiveness measures that were developed.

Having agreed on a set of necessary specifications for the weapon system platform, several possible alternative vehicles will be presented and discussed. Each will be evaluated against the scenarios, the MOEs, and the MOPs to determine the best solution for the project.

Finally, a discussion of further analysis, evaluation, and alternatives for future implementation will be presented[1].

[1] Executive summary adapted from the SEA7-TDSI Integrated Project, Spring 2005.

1.0 INTRODUCTION

1.1 Overview

The Straits of Malacca and the waters off Indonesia are one of the most heavily trafficked and pirated waters in the world. Large merchant ships transport trillions of dollars worth of international trade through these waters every day, making it a key arterial of the global economy[2].

The United States Pacific Command commissioned an initiative to study methods of coordinating the efforts of Southeast Asian countries to fight Maritime Piracy in the Straits of Malacca, envisioning joint patrols and shared intelligence efforts. The NPS Meyer Institute has sponsored the biannual Systems Engineering and Analysis (SEA) Integrated Project, of which the Temasek Defense Systems Institute is a supporting partner to investigate and design an initial proposal incorporating Sensors, Intelligence, Command and Control, and Weapon Systems in support of that initiative.

The problem statement for the Systems Engineering Integrated Project defines the methods that will be utilized to study the system. The objective of this Integrated Project was to design a conceptual system of systems to defeat and prevent terrorism and piracy in the Maritime Domain.[3]

The Maritime Domain Protection Group was tasked with analyzing user requirements to include a complete examination of the threat and concept of operations resulting in the development of threat scenarios, and to design and assess integrated alternative architectures for a coalition of nations, focusing on large ship security in the Straits of Malacca.

1.2 Current Situation

In 2003, the International Maritime Bureau, a London based agency that monitors piracy, indicated the number of piracy attacks increased 20 percent from 2002.[4] They also reported the highest number of piracy-related killings in the first half of 2004, even though actual numbers of piracy attacks declined from 234 to 182 for corresponding period in 2004 and 2003.[5] The IMB also stated that the

---

[2] Patrolling Malacca Straits a Sticky Issue, Matthew Clark, http://www.globalpolicy.org/empire/intervention/2004/0609malacca.htm, 09 June 2004

"Problems affecting safe navigation in the ... [straits] will remain of international concern because, according to the International Maritime Organization (IMO), at least 50,000 ships sail through the narrow channel every year. They transport about 30 percent of the world's trade goods and 80 percent of Japan's oil needs."

[3] SEA-7 Initial Problem Statement and Tasking List, 27 Oct 2004

[4] "Maritime Piracy Increasing", Nancy-Amelia Collins, http://www.iwar.org.uk/news-archive/2004/01-28-2.htm, 28 Jan 2004

[5] Piracy Primer, USCINCPAC Virtual Information Center, 01 Oct 2004

waters off the Straits of Malacca are particularly dangerous, ranking second in the world by number of attacks.[6]

On 20 July 2004, the three countries bordering the Straits of Malacca launched a trilateral arrangement for coordinated patrols of the straits and intelligence sharing.[7] The plan calls for 3 or 4 ships on a 24 hour a day patrol of the straits, and a 24 hour a day information center. It is unclear whether the new initiative will have any effect in stemming piracy in the region. Indonesian Navy Colonel Sulistyanto said "Our three nations need more assets, personnel and intelligence building. The policy and budgeting must change".[8] In addition, one of the key features of the program is the maintaining of territorial sovereignty – "Coordinated Patrols" are not allowed to cross into the territorial waters of another country, as "Joint Patrols" would be.

Some countries have expressed reluctance in allowing foreign navies to operate within territorial waters, even if the aim was specifically to fight terrorism. Malaysian Deputy Prime Minister Najib Razak said "What we should avoid is the presence of foreign forces in Southeast Asia to help us deal with this threat, not because we distrust those outside the region, but because foreign military presence will set us back in our ideological battle against extremism and militancy."[9]

Singapore has expressed significant support for US involvement in the region. In the International Conference on Asia in June 2004, Singapore proposed the idea of U.S Marines helping to patrol the straits. Singapore is also a participant of the Regional Maritime Security Initiative of the U.S. Malaysia and Indonesia are reluctant at best to see US involvement. Admiral Bernard Kent Sondakh, Chief of Indonesian Navy, said "Indonesia deems it not necessary to include troops from outside countries, including United States, to be involved in safeguarding the strategic waterway".[10]

Therefore, while Defense Secretary Donald Rumsfeld "was very cautious in suggesting the involvement of U.S troops in securing the straits, but nevertheless making it very clear that the

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[6] "Maritime Piracy Increasing", Nancy-Amelia Collins, http://www.iwar.org.uk/news-archive/2004/01-28-2.htm, 28 Jan 2004

[7] "Malacca Strait: Target for Terror", Ioannis Gatsiounis, http://www.atimes.com/atimes/Southeast_Asia/FH11Ae02.html, 11 August 2004

[8] "Malacca Strait: Target for Terror", Ioannis Gatsiounis, http://www.atimes.com/atimes/Southeast_Asia/FH11Ae02.html, 11 August 2004

[9] Patrolling Malacca Straits a Sticky Issue, Matthew Clark, http://www.globalpolicy.org/empire/intervention/2004/0609malacca.htm, 09 June 2004

[10] "Straits of Malacca : Security Implications", C.S.Kuppuswamy, http://www.saag.org/papers11/paper1033.html, June 18 2004, (Quoting The Jakarta Post of June 17, 2004)

country has strategic interest in the channel"[11], it is critical that any proposed solution involve the regional military powers to a substantial degree. Currently, neither Malaysia nor Indonesia have the ability or desire to effectively carry out the surveillance of the straits and ensure security of this waterway. Hence, US military involvement will be required to some degree.

[11] "Straits of Malacca : Security Implications", C.S.Kuppuswamy, http://www.saag.org/papers11/paper1033.html, June 18 2004, (Quoting The Jakarta Post of June 9, 2004)

2.0 THREAT SCENARIOS

The scenarios, designed early in the systems engineering development process, were to encompass current and potential threats to the maritime domain in the Straits of Malacca. In depth research and analysis was conducted to study the potential terrorist threats to shipping within the Straits of Malacca.

Based on the analysis, three major threats were identified to be the most predominant. These were:

1) Small boat attack against a large merchant ship

2) A ship as a weapon attack against a major port facility

3) The smuggling of Weapons of Mass Destruction (WMD) into the region

In terms of the likelihood of the threats, the small boat attack has the highest probability of occurrence; however the consequences of such an attack would be low. The ship as a weapon threat, though having a lower probability of occurrence, is deemed a significant threat as it has a higher economic and social impact to the country. Documented evidence exists that shows terrorists have embarked onto merchant ships and have taken over the controls of a ship for brief periods of time in an attempt to learn its maneuvering characteristics. The third threat of smuggling in WMD has the least probability of occurrence but the consequences of a detonation of these weapons near a port facility would be catastrophic.

2.1 Scenario 1 – Small Boat Attack (SBA)

In the scenario of the small boat attack, a 7m boat fitted with a 75hp outboard motor carries a payload of 1,000lbs of TNT. The payload may be remotely detonated. The small boat exits from a cove near Pulau Assan and rapidly approaches the sea lanes at 30kts to engage a merchant ship. Within the 2nm radius from the merchant ship are 7 large ships and 34 small ships. The small boat is unresponsive to VHF hails.

The objective of the defence strategy put in place for the small boat attack threat would be to neutralize the small boat prior to 35m (threshold) from the merchant ship. The defensive engagement may commence at 250m from the merchant ship.

2.2 Scenario 2 – Ship as a Weapon (SAW)

This scenario depicts a 113m ship loaded with 5,200m^3 of compressed propane gas heading towards Singapore with the intent of ramming the Mobil Oil facilities off Pulau Pesek. The complexity of this scenario is enhanced when the attack is envisaged to occur at night. Prior to the attack, a check on the ship's manifest revealed no discrepancies; the ship was responsive to hails and accepted the pilot onboard at normal pilot pickup point. At the initial entry into Singapore, the ship follows all standard navigation restrictions. However as it approaches the Selat Jurong channel the ship accelerates towards the Mobil Oil facilities and Singapore Harbour Control looses communication with the pilot.

In this scenario, the objective of the defence strategy would be to neutralize the threat at no less than 50m from the pier. It is preferable to neutralize the threat at greater than 500m from the pier as the defensive engagement is to commence from 2000m.

2.3 Scenario 3 – WMD Threat (WMD)

The third scenario pertains to the transportation of WMD on board a typical merchant ship. The scenario assumes that the illicit cargo is unknowingly loaded at the port of Shanghai, China in a shipment of 32, 40ft shipping containers carrying Apple Ipods to Savannah, GA. The merchant vessel on its course to Savannah, GA is to pass through the Straits of Malacca.

The objective in this scenario is to stop the ship 1000m from the port. An inspection team is to board the ship and to isolate the illicit cargo.

The focus of the Force Group report will be on addressing the threat posed by the small boat attack. The ship as weapon scenario was not considered as there are capabilities within the US and Singaporean defense force to combat this situation. The force objective for the scenario comprising the ship with the weapon of mass destruction is to transport the inspection team to the designated ship.

3.0 INTEGRATED PROJECT REQUIREMENTS

3.1.1 Top Level Requirements

In view of the threat scenarios anticipated, the design and implementation of the collective systems to mitigate the attacks under each scenario, will be defined as the System. Three levels of requirements governing the System, in response to the respective scenarios are specified. The top-level requirements **[1]** are the overall requirements for the entire System. These requirements are applicable to all participating groups (of the Integrated Project Team) including but not limited to the Sensors, C3I, Inspection and Force Groups. The second and third- level requirements are Force Group specific requirements, in setting the force response architecture and specification.

The top-level performance requirements for successful defeat of the threats are:

a) For a Small Boat Attack (SBA) scenario, the System shall achieve 80% or higher probability of success in stopping a small boat attack on large commercial ships.

b) For Ship As Weapon (SAW) scenario, the System shall achieve 90% or higher probability of success in stopping ships that are used as a weapon for attacking port facilities.

c) For Weapon of Mass Destruction (WMD) scenario, the System shall achieve 90% or higher probability of success in keeping ships laden with chemical and biological threats, away from ports and 60% or higher probability of success for ships laden with nuclear or radioactive threats.

In addition to performance requirements, the other key requirements are:

d) The System shall be operable and be able to achieve the required probability of successful defeat of threats, at all times, both day and night, and under all weather conditions in the stipulated region of operation.

e) The System shall be interoperable with external systems that are engaged in the same operation.

f) The damage, assessed in monetary value, of as a result of one attack under any of the above listed scenarios shall not exceed $10M.

g) The Platform shall be operable in five years from June 2005.

3.1.2 Second Level Requirements

Using the top level requirements, the next level or the second-level requirements were generated by the Force Group. These requirements specify the roles and characteristics of the System elements necessary to meet the top-level requirements. The key second-level requirements, covering all the three attack scenarios, are:

a) The System shall comprise platforms ("Platform") and operators that form the response team in defeating or mitigating any attacks under the listed scenarios.

b) The Platform shall perform the roles of a transporter, escort ship, patrol ship and fast attack ship.

c) The Platform shall be able to transport an inspection team of at least 8 persons with hand portable inspection equipment and weapons, of combined total weight not exceeding 1600 kg, in responding to the WMD scenario.

d) The Platform shall be equipped to attack identified surface targets of at least seven meters in length, in view of the required probability of success in defeating attacks under the SBA and SAW scenarios, for the System.

e) The Platform shall be able to defend its crew and itself against small arms threat.

f) The Platform shall be operable and sustainable for at least 24 continuous hours under non-emergency conditions.

g) The Platform shall be operable and sustainable for at least one engagement under any of the listed attack scenarios.

3.1.3 Third Level Requirements

a) The Platform shall be designed with the capability to engage a small boat traveling at 30 knots over a minimum distance of 2 nautical miles, in the small boat attack scenario. This engagement can comprise the use of the Platform and its weapons.

b) The Platform crews shall be provided with the means to approach and board a suspected ship from the Platform, such as for inspection purpose.

c) The Platform shall have weapons with the ability to disable the movement of any suspected ship, when required. Such weapons shall have Non-Line-of-Sight engagement capability.

d) The Platform shall be suitable for operating with good maneuverability in high density traffic such as in the Malacca Straits.

e) The Platform shall be equipped with communication system that has the ability to integrate with the System's C3I network, to be able to locate threats beyond Line-of-Sight (LOS).

f) The Platform design shall take into consideration the use of Commercial-Off-the-Shelf (COTS) and existing systems wherever possible, with the aim of achieving more cost effective solutions.

4.0 FORCE SYSTEM OBJECTIVES

4.1 Force Functions

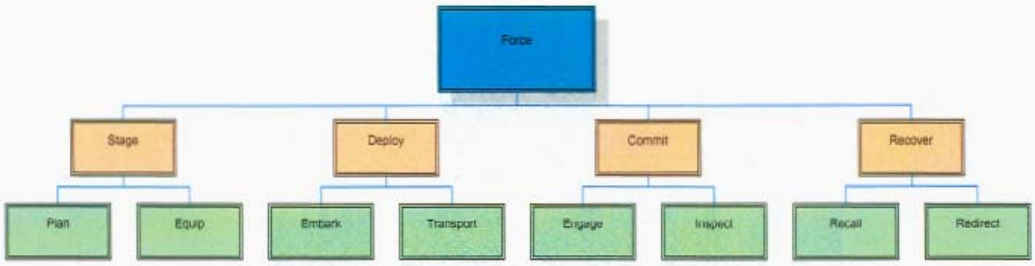

Figure 1: Force Operational Functions

The operational functions of the Force Group cover the domains of Stage, Deploy, Commit and Recover.

4.1.1 Stage

Planning of patrol operations, maintenance of equipment in an operational status, and the equipping of systems for both patrol and engagement requirements.

4.1.2 Deploy

Embarkation of armament systems, as well as the transportation of those systems to situations that potentially require intervention.

4.1.3 Commit

Employment of equipment and armament systems in acts of physical intervention, as well as the capabilities to conduct physical inspections of suspected hostile forces.

4.1.4 Recover

Recalling and redirecting the systems after engagement to ensure that all systems are operational and functional

4.2 TDSI Force Function Emphasis

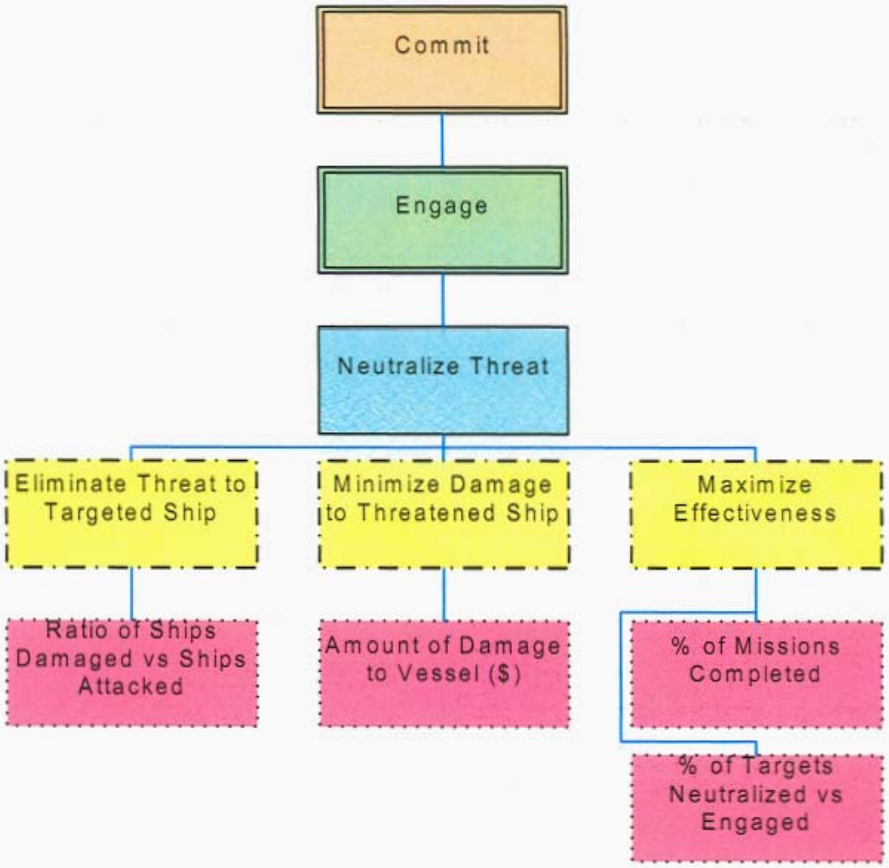

Figure 2: TDSI Force Function

The TDSI Force Group will be primarily concerned with the provision of the Commit function. Hence, the TDSI Force Group will select a suitable patrol craft to be implemented in a zonal concept that ensures maximum coverage and protection against the potential threats in the Malaccan Straits.

The sequence of evaluating the Commit function involves firstly the elimination of the threats to the targeted ship, followed by minimizing the damage to threatened ship should an engagement be involved, and finally to maximize the effectiveness of the patrol boats against these threats in engagements.

The assessment criteria employed includes the ratio of ships damaged vs the ships attacked in the first instance, the amount of damage to the vessels in the second instance, and the percentage of missions completed as well as the percentage of targets neutralized vs those that are engaged in the third instance.

5.0 DEPLOYMENT STRATEGY

5.1 Full Escort

The full escort strategy provides protection coverage for merchant ships throughout their passage in the Straits of Malacca. Merchant ships are placed in linear convoys surrounded by one patrol ship each at the front and end of the convoy, and at least 2 other boats on either side of the convoy. In essence, a minimum of 6 boats is required to cover half of the Malaccan Straits.

When a merchant ship needs to adjourn to a port of call, it will break away from the escorted convoy. One of the side flanking patrol boats will then escort the merchant ship to its desired port of call before rejoining the rest of the patrol boats to escort the remaining boats in the detail to their desired port of calls.

Hence, the role of the four side-flanking boats is to accompany merchant ships to their port of calls while the front and back patrol ships will always stay with the convoy.

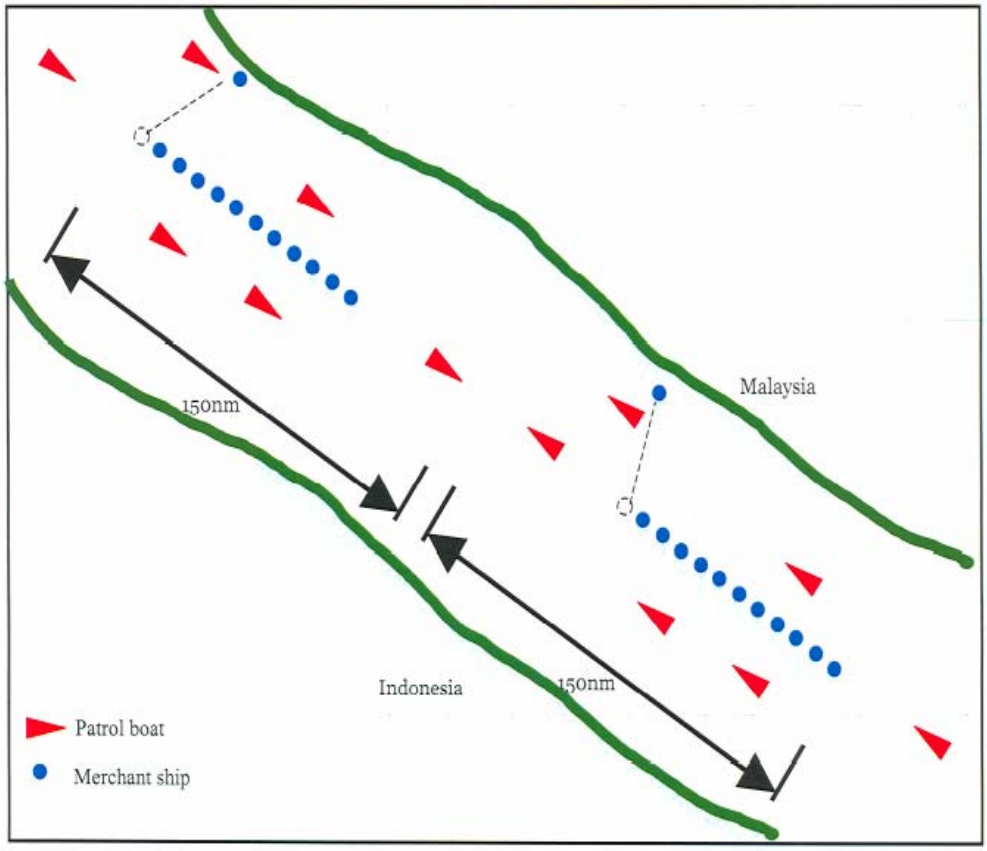

Figure 3: Full Escort Strategy

5.2 Harbor Escort

The harbor escort strategy similarly employs the concept of organizing the merchant ships into linear convoys. One patrol boat each is placed at the front and rear of the convoy, while one patrol boat each is placed to flank both sides of the convoy.

However, instead of having patrol boats breaking off from the convoy, small coastal boats will be deployed from the harbor as the convoy passes near to the port of call. Hence, those merchant ships that are advancing to a certain port of call will be met and escorted by these small coastal boats that originate from their docking wharves near the port of call.

Hence, fewer patrol boats are required, but there will be a need to tap into the resources of existing harbors and port of calls to provide such small coastal boats for the escorting purpose.

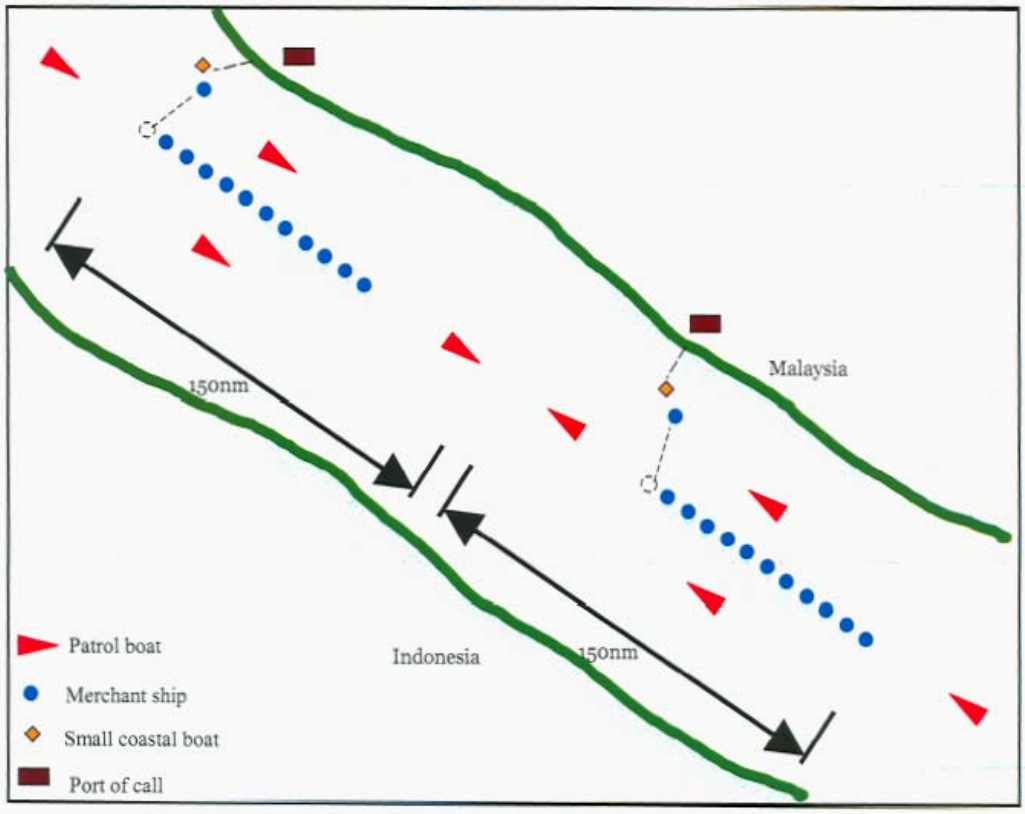

Figure 4: Harbour Escort Strategy

5.3 Zonal Patrol

The zonal patrol strategy requires approximately five patrol boats each to protect 150 nm of the Malaccan Straits. The patrol boats employ an ellipsoidal patrol route and merchant ships pass along the middle of this ellipsoidal coverage zone. They are supported by a HSV Mothership.

The patrol boats must be able to respond as quickly as possible to any attacks on these merchant ships since they will not have dedicated escorts for the merchant ships. The patrol ship that is nearest to a point of possible hostility will be activated to protect the merchant ship. Hence, the speed and weapon range that the patrol boats possess must be adequate for this strategy to be implemented.

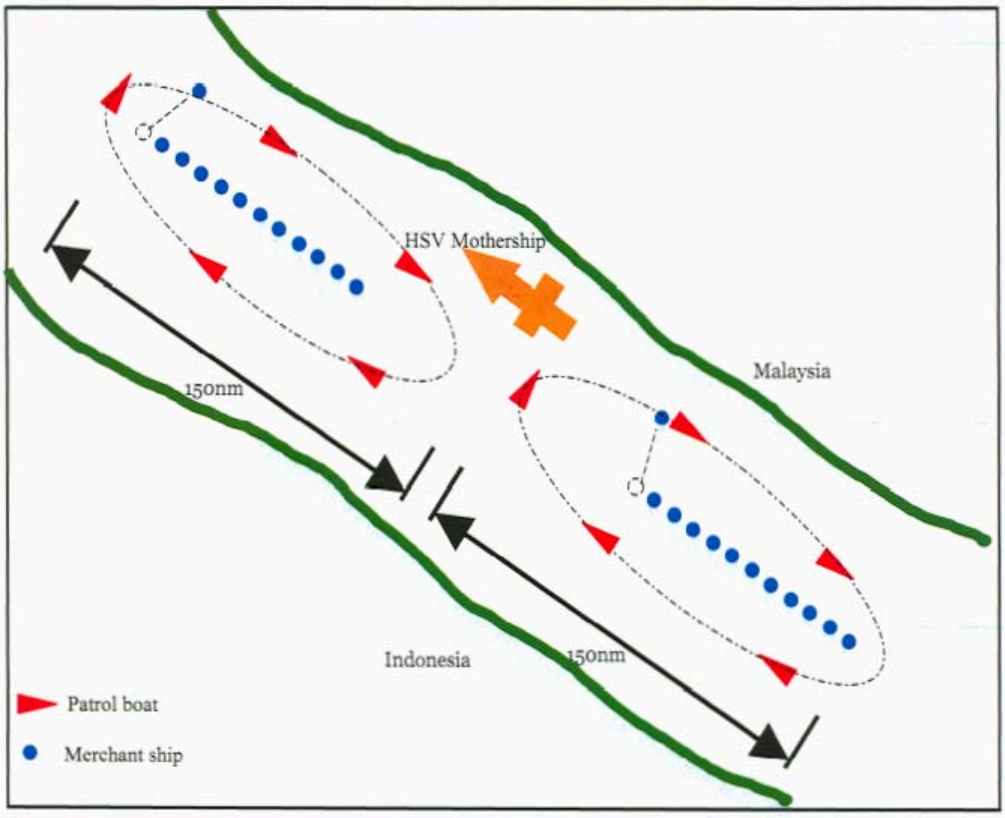

Figure 5: Zonal Patrol Strategy

The zonal patrol strategy was finally chosen because of the ease of implementation and also it requires possibly the least number of ships as well as integration. The huge number of merchant ships passing through the Straits of Malacca makes the implementation of a convoy system more difficult. Since the feasibility of the zonal patrol strategy hinges on the number of ships, ship speed and weapons range of the patrol boat, these parameters would be investigated in greater detail.

6.0 ZONAL PATROL ASSESSMENT

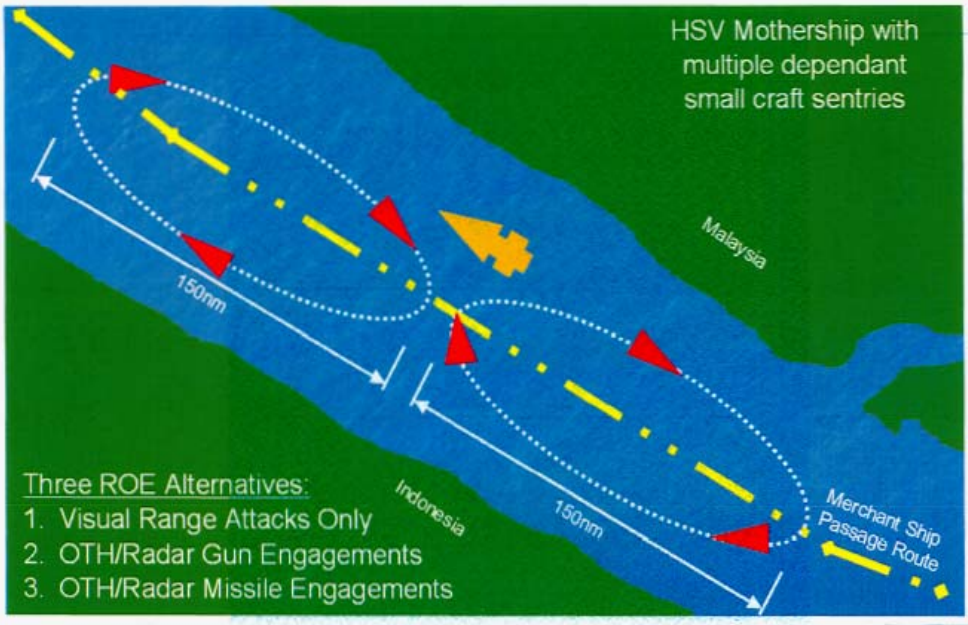

Figure 6: Zonal Patrol Assessment

The given requirement is to be able to begin the engagement at a distance of 2 nautical miles away from the merchant ship upon identification. The target ship is estimated to be traveling at an average speed of 30 knots which is a reasonable assumption for the speed of a small boat.

The response time needed by the platform to neutralize the target is calculated as follows:

$$t = \frac{\text{Distance between target and merchant ship}}{\text{Speed of target}} = \frac{2\ nm}{30\ knots} = 4 \text{ mins}$$

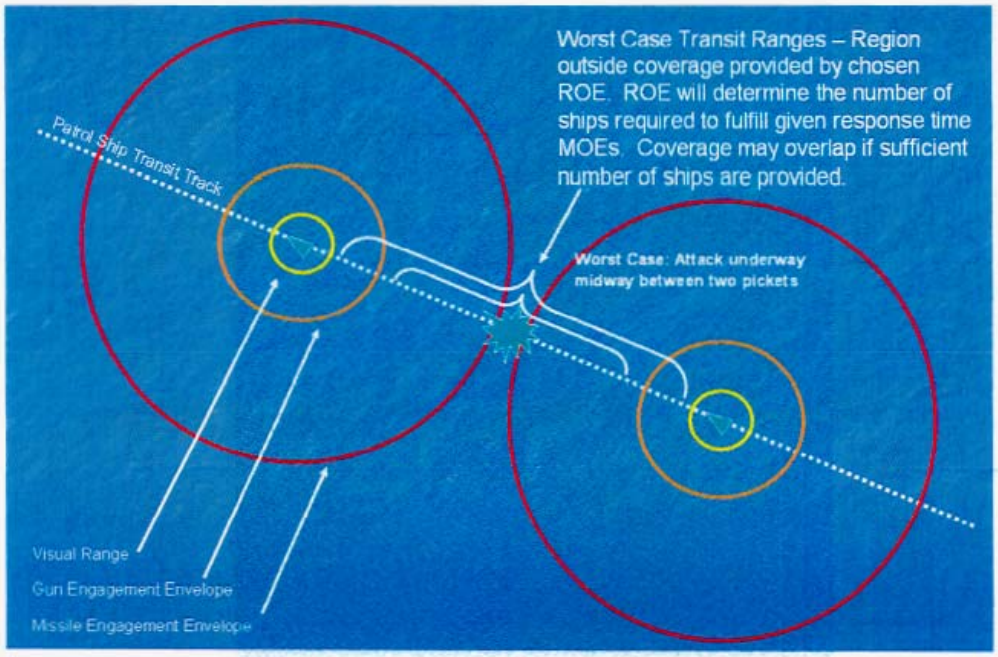

Figure 7: Worst Case Scenario Assessment

The worst case scenario happens when the attack occurs exactly at the midway between two patrol ships because that is when the maximum response time is needed to neutralize the target. This analysis will be based on the worst case scenario.

Three possible engagement ranges, based on the predetermined Rules of Engagement (ROE) are analyzed for defeating the target, namely:

- Visual Range (5.23 nm)
- Gun Engagement (9 nm)
- Missile Engagement (30 nm or 50 nm)

Based on the above three ranges, a study was carried out to determine the optimum number of ships in order to meet the required response time of 4 minutes based on the engagement envelop and three different speeds of the patrol ships. The results are presented in the **Table 1** below:

Number of Ships	Visual Range (~5nm)				76mm (9nm) - Flight Time at 960 kts = 0.25 min			
	Worst Case Range (nm)	Response Time at 30kts (min)	Response Time at 40kts (min)	Response Time at 50kts (min)	Worst Case Range (nm)	Response Time at 30kts (min)	Response Time at 40kts (min)	Response Time at 50kts (min)
3	47.10	94.21	70.66	56.52	43.33	86.67	65.00	52.00
4	34.02	68.04	51.03	40.82	30.25	60.50	45.38	36.30
5	26.17	52.34	39.26	31.40	22.40	44.80	33.60	26.88
6	20.94	41.87	31.41	25.12	17.17	34.33	25.75	20.60
7	17.20	34.40	25.80	20.64	13.43	26.86	20.14	16.11
8	14.40	28.79	21.59	17.27	10.63	21.25	15.94	12.75
9	12.21	24.43	18.32	14.66	8.44	16.89	12.67	10.13
10	10.47	20.94	15.71	12.56	6.70	13.40	10.05	8.04
11	9.04	18.09	13.56	10.85	5.27	10.55	7.91	6.33
12	7.85	15.71	11.78	9.42	4.08	8.17	6.13	4.90
13	6.85	13.69	10.27	8.22	3.08	6.15	4.62	3.69
14	5.98	11.97	8.98	7.18	2.21	4.43	3.32	2.66
15	5.24	10.47	7.86	6.28	1.47	2.93	2.20	1.76
16	4.58	9.17	6.87	5.50	0.81	1.63	1.22	0.98
17	4.01	8.01	6.01	4.81	0.24	0.47	0.35	0.28
18	3.49	6.98	5.24	4.19				
19	3.03	6.07	4.55	3.64				
20	2.62	5.24	3.93	3.14				
21	2.25	4.49	3.37	2.70				
22	1.91	3.81	2.86	2.29				
23	1.60	3.19	2.39	1.92				
24	1.31	2.62	1.97	1.57				
25	1.05	2.10	1.58	1.26				

Number of Ships	Missile (30nm) - Flight Time at 580kts = 3.1 min				Missile (50nm) - Flight Time at 580kts = 5.2 min			
	Worst Case Range (nm)	Response Time at 30kts (min)	Response Time at 40kts (min)	Response Time at 50kts (min)	Worst Case Range (nm)	Response Time at 30kts (min)	Response Time at 40kts (min)	Response Time at 50kts (min)
3	22.33	44.67	33.50	26.80	2.33	4.67	3.50	2.80
4	9.25	18.50	13.88	11.10	-10.75			
5	1.40	2.80	2.10	1.68				
6	-3.83							

Table 1: Optimization of number of ships

Sample calculations for obtaining the total respond time for each ROE are as follows:

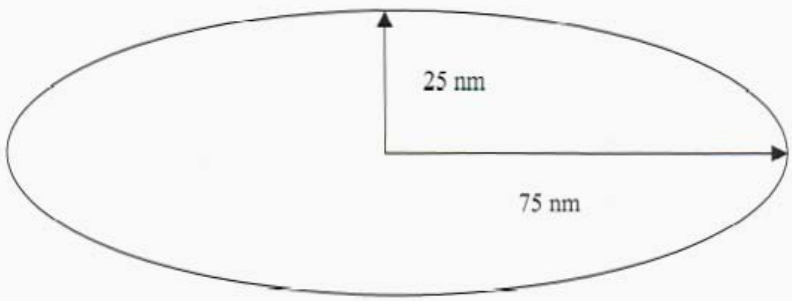

Figure 8: Area of Protection

Circumference of area of patrol (ellipse) = $2\pi(r_1 + r_2/2) = 314nm$

Visual Range

Engagement Range = 5.23 nm

Number of ships (50 knots) = 19

Speed of projectile = 1768 knots

Distance between ships = $\frac{\text{Circumference of Patrol Path}}{\text{Total No. of Ships}} = \frac{314}{19} = 16.5\ nm$

Distance to go = Distance Between Target and Ship - Enagement Range = $\frac{16.5}{2} - 5.23 = 3.02nm$

Response time, t = $\frac{\text{Distance To Go}}{\text{Speed of Ship}} = \frac{3.02}{50} = 3.64$ min

Gun Engagement

Engagement Range = 9 nm

Number of ships (50 knots) = 13

Speed of gun = 1768 knots

$$\text{Distance between ships} = \frac{\text{Circumference of Patrol Path}}{\text{Total of Ships}} = \frac{314}{13} = 24.2\ nm$$

$$\text{Distance to go} = \text{Distance Between Target and Ship - Enagement Range} = \frac{24.2}{2} - 9 = 3.1nm$$

$$\text{Response time, t} = \frac{\text{Distance To Go}}{\text{Speed of Ship}} = \frac{3.1}{50} = 3.69 \text{ mins}$$

$$\text{Projectile flight time, t} = \frac{\text{Firing Range}}{\text{Speed of Projectile}} = \frac{9}{1768} = 18\text{scc}$$

Total respond time, t = $t_1 + t_2$ = 3.69 + 0.3 = 3.99 mins

Missile Engagement

Engagement Range= 50 nm

Number of ships (50 knots) = 3

Speed of missile = 580 knots

$$\text{Distance between ships} = \frac{\text{Circumference of patrol path}}{\text{Total No. of Ships}} = \frac{314}{3} = 104.6\ nm$$

$$\text{Distance to go} = \text{Distance Between Target and Ship - Enagement Range} = \frac{104.6}{2} - 50 = 2.3\ nm$$

$$\text{Traveling time of ship, } t_1 = \frac{\text{Distance To Go}}{\text{Speed of Ship}} = \frac{2.3}{50} = 2.8\text{mins}$$

$$\text{Missile flight time, } t_2 = \frac{\text{Distance between target \& ship}}{\text{Speed of missile}} = \frac{50 \text{ nm}}{580 \text{ knots}} = 5.17 \text{ mins}$$

Total respond time, t = $t_1 + t_2$ = 2.8 + 5.17 =7.97 mins

Missile Engagement

Engagement Range = 30 nm

Number of ships (30 knots) = 5

Speed of missile = 580 knots

Distance between ships= $\frac{\text{Circumference of patrol path}}{\text{Total Ships}} = \frac{314}{5} = 63$ nm

Distance to go = Distance Between Target and Ship - Enagement Range= $\frac{63}{2}$-30=1.5 nm

Traveling time of ship, $t_1 = \frac{\text{Distance To Go}}{\text{Speed of Ship}} = \frac{1.5 \text{ nm}}{30 \text{ knots}}$ =2.8 mins

Missile flight time, $t_2 = \frac{\text{Distance between target \& ship}}{\text{Speed of missile}} = \frac{30 \text{ nm}}{580 \text{ knots}} = 3.1$ mins

Total respond time, t = $t_1 + t_2$ = 2.8 + 3.1 =5.9 mins

Clearly, there are a series of solutions depending on the ROE chosen. The option of utilizing missile to engage the target will require the least number of ships because of its extended engagement range as compared to the other two. It may not always be practical to do so against a small boat, since this would be overkill. However, this option is necessary when there is a need for an extremely short response time.

Measures of Performance

- Speed
- Response Time
- Payload
- Weapon System Compatibility

	Semi-Planing Monohull No.1	Semi-Planing Monohull No.2	Catamaran	Hydrofoil
Calm Water Speed (knots)	35.8	45.7	46.3	46.9
Speed in Waves * (knots)	*34.0*	*44.0*	*45.0*	*46.0*
Payload Weight * (long tons)	*30*	*30*	*30*	*30*
Range at Speed in Waves * (nautical miles)	*750*	*750*	*750*	*750*
Displacement (long tons)	189	324	309	149
Installed Power (hp)	11,192	30,662	13,932	6,571
Engines	6 T800	6 LM 1600	6 T800	6 T800
Fuel Carried On Board (long tons)	46	100	39	18
Length (ft)	126	151	159	127
Beam (ft)	25	30	51	32
Hullborne Draft (ft)	9.4	11.2	7.3	17.5
Rough Order of Magnitude Cost, for ship alone.	$3.3M	$8.3M	$5.1M	$2.4M

* : input parameters (values in italics).

Table 2: Comparison of Potential Ship Hull Designs

8.0 FORCE SYSTEM

8.1 Assumptions

The following assumptions are made in the analysis of each option available.

- Complete Intelligence regarding all attack scenarios
- Accurate Position Information will be provided by the C4I group
- No Simultaneous / Coordinated Attacks will be conducted
- There are no Escort Duty requirements for the patrol ships
- Weapon system Probability of Hit and Probability of Kill are not considered

8.2 Patrol Ships

The requirement for 24/7 patrols on a long term basis combined with the extremely short response time drove the initial choice of platform. Several alternatives were considered and rejected prior to the choice of a ship as the basis platform:

1. Helicopter – Rejected. The time required to get a helicopter in the air upon notification of an attack is longer than the four minutes allowed, even if the vehicle is on a standby alert. The combination of aircrew briefing, rotor spin-up, in-flight tests, all required before the transit to the attack site can even occur, requires significantly more time than available. Overcoming those deficiencies requires a helicopter to remain airborne 24/7, which is not economically feasible due to aircraft and aircrew endurance requirements[12].
2. Unmanned Aerial Vehicles – Rejected. The project guidelines call for a system to be in place within five years. UAVs are a tested product within the surveillance community, but have not yet been proven as a weapon carrying platform. This may be an option for future work, but is not feasible for a short-term solution.
3. Ground-based weapon systems – Rejected. The number of independent systems required to completely cover the area of regard is very large. Each weapons placement site will require the government to allocate sufficient amounts of land, a security perimeter which must be

[12] § 135.265 Flight time limitations and rest requirements: Scheduled operations. http://www.faa.gov/regulations_policies/faa_regulations/ . The maximum flight times according to this regulation are: (1) 1,200 hours in any calendar year; (2) 120 hours in any calendar month; (3) 34 hours in any 7 consecutive days; (4) 8 hours during any 24 consecutive hours for a flight crew consisting of one pilot; and (5) 8 hours between required rest periods for a flight crew consisting of two pilots qualified under this part for the operation being conducted.

continuously monitored by armed personnel, and a large enough maintenance force to be able to travel to the site (vice bringing the equipment back to a central repair facility). Additionally, no visible presence within the area of regard is a psychological loss to the system.

The choice was then made to look at possible patrol ships. Four options were chosen that met the design criteria – two mono-hulls, a catamaran, and a hydrofoil – from which the final design will be selected.[13] The hierarchy of design criteria was implemented as follows:

1. Meet capability requirements. The patrol ship must be able to carry the required weapon system (preferably the chosen ship will already have a comparable system onboard), be able to achieve the required speeds, and have the range and capacity to carry the inspection team over long distances.

2. Maximize Speed and efficiency. The driving requirement of the project is the response time. Economic realities mean that there will not be a sufficient number of ships to ensure complete continuous coverage of the entire area of regard. It is therefore critical, overridingly so, that the ship has a maximized sustainable top speed.

3. Minimize the size. The presence of a "mothership" in the given design criteria allows the patrol ship to forgo many normally required features – such as sufficient crew rest areas, large maintenance equipment, and long-term storage facilities. These will be provided by the large "mothership" as necessary. Smaller sized ships may also lead towards a less expensive ship and possibly a faster ship, though not necessarily.

4. Range is irrelevant as long as the minimum requirement is met. A minimum range of 750 nm was established as the requirement determined by the given design criteria. Each patrol ship will transit roughly a 300 nm loop while on patrol and will travel roughly 300 nm while transporting inspection teams round-trip. Therefore, the 750 nm range will allow for two un-refueled transits of either type with a small reserve to spare. However, the proposed ship only has met this criteria – extra range will not influence the selection unless a tie-breaker is needed.

5. There was no preference for ship hull design. The hull-form of the ship will have no effect on the design selection.

[13] The details of the Tenix, Hayabusa, Skjol and Sparviero classes were taken off the internet. Refer to reference page for details.

Proposed Ships

	Tenix Fast Attack Craft	Hayabusa Class	Skjold Class	Sparviero Class
Build	Monohull	Monohull	Catamaran	Hydrofoil
Length by Beam, ft	151 by 28	164 by 28	155 by 44	71.5 by 23
Speed, knots	34	44	45	46
Range, nm	2000 at 15 knots	Estimated 800	800	1200 at 8 knots
Displacement, tons	205	200	270	50
Compliment	37	21	15	11

Table 3: Specifications of Proposed Ships

The platform selected as the patrol ship for this design was the Sparviero class hydrofoil. The ship currently exists in two navies, the Italian and the Japanese. Each navy has a different missile system onboard and a different caliber of main battery – thereby demonstrating it's compatibility with multiple weapon systems. The range and compliment of the Sparviero make it capable of fulfilling the mission requirements. Additionally, it is the fastest, most efficient, and smallest of all of the options.

8.3 Gun

The guns are a necessary component of the platform's weapon systems as they are to engage targets which are within the platform's line of sight. The guns are generally subdivided into the offensive and defensive categories. The offensive guns are to take on and stop identified enemy targets and is usually expected to engage at ranges less than 8nm. The defensive guns are employed to protect the platform during close-in inspection or interrogation of suspected targets.

8.3.1 OTO Melara 76mm

The OTO Melara 76mm is the most widely used gun system. The latest versions are currently being offered for implementation into the US Navy Littoral Combat Ship programme as well as the US Coast Guard's Project Deepwater[14].

The light weight rapid-fire 76mm gun is suited for installation on small combat vessels. The unmanned 76mm Above Deck (AD) mounting is compatible with the Hydrofoil platform and is designed for engagement of surface targets.

The automatic loading system and supporting equipment may be installed in the appropriate deck space. The mounting is 3.6m in diameter at its base, 8.2m long and 2.5m high with a swept radius of 6.4m. The lower part of the mounting contains the magazine, servo mechanisms and hydraulic gear, is 1.2m high, while the revolving turret is 1.3m high and 2.8m across. The empty weight is 5.5tonnes.

The 76mm AD has an elevation range from -10° to 70° with an elevation speed of 35°/s. The training speed for the gun is 60°/s and is has a firing rate of 120rounds/min. With a muzzle velocity of 910m/s the gun has an engagement range of 8.5nm thus being able to engage a target within 17s. This OTO Melara 76mm gun is proposed as the offensive gun systems for the platform.

OTO Melara 76mm Gun[15]

Elevation	-10° to 70°
Training speed	60°/s
Elevation speed	35°/s
Weight (unloaded)	5.5 t
Muzzle velocity	910 m/s
Rate of fire	120 rds/min
Range	8.5 n miles

Table 4: Specifications of OTO Melara 76mm Gun

[14] In July 2003 General Dynamics Ordnance and Tactical Systems announced it had signed a letter of intent for co-operation in the sale of the 76 mm Super Rapid gun and DART ammunition to the US Navy. This is being offered for the Littoral Combat Ship (LCS) as well as for the US Coast Guard's Project Deepwater new generation of cutters. Referenced from Janes Naval Weapon Systems.

[15] Janes Naval Weapon Systems **[3]**

8.3.2 M2 .5Caliber Machine Gun

The M2 .50 Cal machine gun is already in use on various naval mounts. The gun provides automatic weapon suppressive fire for offensive and defensive purposes and is effective against both personnel and small boats.

The M2 is capable of single shot as well as automatic fire with a 550 rounds/min cyclic firing rate. The maximum range of the M2 is 4.22nm and with the use of night vision scopes, the M2 is able to operate effectively during night operations.

In addition to being placed on mounts, the M2 is also crew transportable over short distances. This feature would complement the on board inspection of suspected targets. The M2.50 Calibre Machine Gun is proposed as the defensive gun system for the platform.

M2 .5Caliber Machine Gun[16]

Length	1.56m
Weight	38 kg
Max Range	6.8 km
Cyclic rate	555 rounds/min

Table 5: Specifications of M2.5Caliber Machine Gun

[16] Federation of American Scientist. http://www.fas.org/man/dod-101/sys/land/m2-50cal.htm [4]

8.4 Missiles

Missile System

A missile system is assessed to be mandatory to engage targets at long ranges with short response time. Current operational missile systems were short listed for comparison. A suitable missile system will be selected based on the following criteria:

1. Range
2. Speed
3. Size
4. Integration with selected platform

Missile	*Range (km)*	*Speed (Mach)*	*Length (m)*	*Diameter (cm)*	*Weight (kg)*	*Launching modes*
Penguin SSM	27	0.8	3	28	340	Fire & Forget
Otomat	***60***	***0.9***	***4.46***	***46***	***770***	***Fire /Track Fire & Forget***
RBS 15	150	0.8	4.35	50	598	Fire & Forget
Gabriel, II	26	0.7	3.41	34	520	Fire & Forget Fire/Track

Table 6: Missile parameters comparison[15]

Based on previous calculations the missile must have an engagement range of at least 30 nautical miles (48 km).

It can be seen from **Table 6** that Otomat is superior in terms of range, speed and has multiple launching modes which are critical parameters in meeting the operational requirements. One main disadvantage is its size which will take up more space on board the platform. The RBS 15 is superior in terms of speed but it has only one launching mode. The Fire and Forget mode requires a substantial amount of preparation time prior to fire which may not be that suitable for time critical targets.

Another main advantage of the Otomat missile system is that over 1000 Otomats have been well deployed to date within the Italian navy and one of the ships that has been equipped with the Otomat system is the Sparviero class therefore this would significantly ease integration. The other missile systems have not been integrated with the Sparveiero class and could pose integration problems.

Otomat is also an all weather long range missile system with OTHT (over-the-Horizon Targeting) capability to comply with coastal attack mission. Furthermore, missiles can be launched at any direction without imposing ship's maneuvering constraints.[17]

Hence, the Otomat is the preferred missile system as compared to the rest based on its speed, range capability and most important of all it is a proven system that has integrated well with the Sparviero class ships.

Otomat Missile Performance Evaluation

A performance evaluation is necessary to ensure that the actual response time of the combination of selected platform and missile system meets the operational requirement. An iteration process is carried out to determine the actual number of ships required.

i) Number of Sparviero ships: 4

Engagement Range= 36 nm

Speed of Sparviero class ships: 46 knots

$$\text{Distance between ships} = \frac{\text{Circumference of patrol path}}{\text{Total no. of Ships}} = \frac{314}{4} = 78.5 \text{ nm}$$

Distance to go =

Distance Between target and Sparveiro Ship - Enagement Range = $\frac{78.5}{2}$ - 36= 3.25 nm Traveling time of ship before launching missile,

$$t_1 = \frac{\text{Distance between target \& ship}}{\text{Speed of ship}} = \frac{3.25 \text{ nm}}{46 \text{ knots}} = 4.23 \text{ mins}$$

$$\text{Missile flight time, } t_2 = \frac{\text{Distance between target \& ship}}{\text{Speed of missile}} = \frac{36 \text{ nm}}{579 \text{ knots}} = 3.73 \text{ mins}$$

Total response time = $t_1 + t_2 = 3.25 + 3.73 = 6.98$ mins

The combination of 4 ships and the Otomat missile system will be not able to meet the operational requirement of 4 minutes.

---

[17] Reference to http://www.mbda.net/eotomat.html [6]

ii) Number of Sparviero ships: 5

Engagement Range= 36 nm

Speed of Sparviero class ships: 46 knots

$$\text{Distance between ships} = \frac{\text{Circumference of patrol path}}{\text{Total no. of Ships}} = \frac{314}{5} = 63 \text{ nm}$$

With 5 ships, the missile can be launched directly as the distance between the target and the ship is within the engagement range of the missile. The computation is shown below.

Distance to go =

$$\text{Distance Between target and Sparveiro Ship - Enagement Range} = \frac{63}{2} - 36 = -4.5 \text{ nm}$$

Total Respond time = missile flight time,

$$t = \frac{\text{Distance between target \& ship}}{\text{Speed of missile}} = \frac{31.5 \text{ nm}}{579 \text{ knots}} = 3.2 \text{ mins}$$

9.0 FURTHER WORK RECOMMENDED

The following options may be considered for future work or additional consideration if some specific requirements were lifted.

- Design a smaller or cheaper missile with the same range capability and response time that is suitable for littoral environment.
- Evaluate the use of armed Unmanned Aerial Vehicles as primary vehicle for surveillance and engagement. Possible weapon systems include Hellfire Missile or Laser Guided Bombs onboard Predator-sized airframe.
- More detailed analysis of Probability of Hit or Probability of Kill within the designed system.

10.0 CONCLUSION

The selected design comprises the Sparviero class hydrofoil with an Otomat Missile system. Complementing the missile system will be the Oto Melara 76mm gun and the M2 .50cal machine gun. The patrol ship is to operate in conjunction with a High Speed Vehicle to provide for logistics and minor maintenance requirements.

The combination of two groups of five ships on continuous patrols over two 150nm stretches and the use of the Otomat missile system will be able to meet the operational response time, from the received order to the conclusion of the engagement, of four minutes.

APPENDIX I: SENSOR SYSTEM GROUP RELIABILITY ANALYSIS

Sensor System Reliability, Availability & Maintainability (RAM) Analysis

INTRODUCTION

In the Maritime Domain Protection (MDP) system, the sensors assumed the role of "eyes," searching, tracking, classifying, and identifying surface contacts within the Straits of Malacca or Area of Regard (AOR). In order assure adequate sensor capability has been 'designed in' to meet the MDP mission, the Sensors group performed a Reliability, Availability, and Maintainability analysis regarding the proposed architectures.

The primary sensors used in the system were Microwave Radars and High Frequency Surface Wave Radars (HFSWR) augmented by Electro-Optics and Infrared (EO/IR) sensors. All of these sensors were integrated and installed along the Straits of Malacca and Straits of Singapore. In addition, the use of airborne assets and mobile land platforms fitted with both microwave radars and EO/IR sensors provided an enhanced overall maritime picture. The consideration of airborne assets included but was not limited to, Maritime Patrol Aircraft and Helicopters, Unmanned Aerial Vehicles (UAV), Aerostats, and Low Earth Orbit (LEO) Constellation of Satellites.

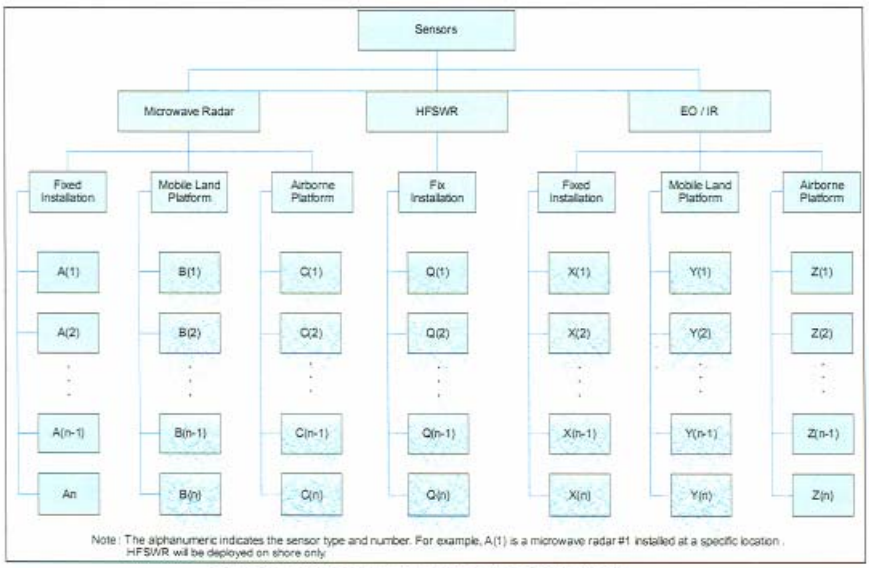

Figure 1. Sensor System Architecture.

The sensor system architectures considered included both land and airborne systems.

OBJECTIVE

The objective of this analysis was to determine and analyze the sensor system's operational availability based on the proposed operational and maintenance support concepts highlighted in the following paragraphs.

ASSUMPTIONS

The following assumptions were made for the RAM analysis:

- The systems operate in steady state conditions (of the bathtub curve) and independently of each other.
- For each specific sensor type deployed in Singapore, Malaysia and/or Indonesia, the same sensor model was utilized. As such, similar sensors had identical reliability.
- The airborne and mobile land platforms were assumed to be operational and available when their service was required.
- All spares required to support the maintenance tasks were assumed to be available when needed. (i.e. no logistic delays)
- All maintenance crews were well trained and equipped with necessary tools and manuals.
- At each maintenance level, the facilities had all the necessary resources to support the maintenance tasks (i.e. power supply, overhead crane, special test Equipment, etc.)
- The Mean Down Time (MDT) of the system was calculated as the summation of the mean administration, transportation and repair times.
- For each fixed installation, there was at least one operator manning the station.

OPERATION SCENARIO

The requirement for the sensor system was to provide continuous 24 hour coverage under all weather conditions in the Straits of Malacca with a detection probability of at least 90%. In order to provide the desired detection probability, the MDP system needed to be operational with a high system uptime. Due to the crucial role that the sensor system must perform, it was assumed that the system had an availability of at least 99%.

Under Sensor System Design Alternative 1, Microwave Radars and HFSWR, the primary sensor coverage in Straits of Malacca was provided by microwave and HFSWR radars mounted on fix installations i.e. towers, prepared grounds, etc. To enhance sensor

coverage in the AOR, the primary sensors were supported by either air platforms or mobile land platforms or both.

Fixed installation sensors such as the microwave radars and HFSWRs were deployed along the coastlines of the AOR. Approximately fourteen shore based Microwave Radars (MR) and four HFSWR were required to covered the Malacca Straits and an additional four HFSWR installed in the eastern part of Singapore were needed to provide complete coverage of the strait's South China Sea entrance.

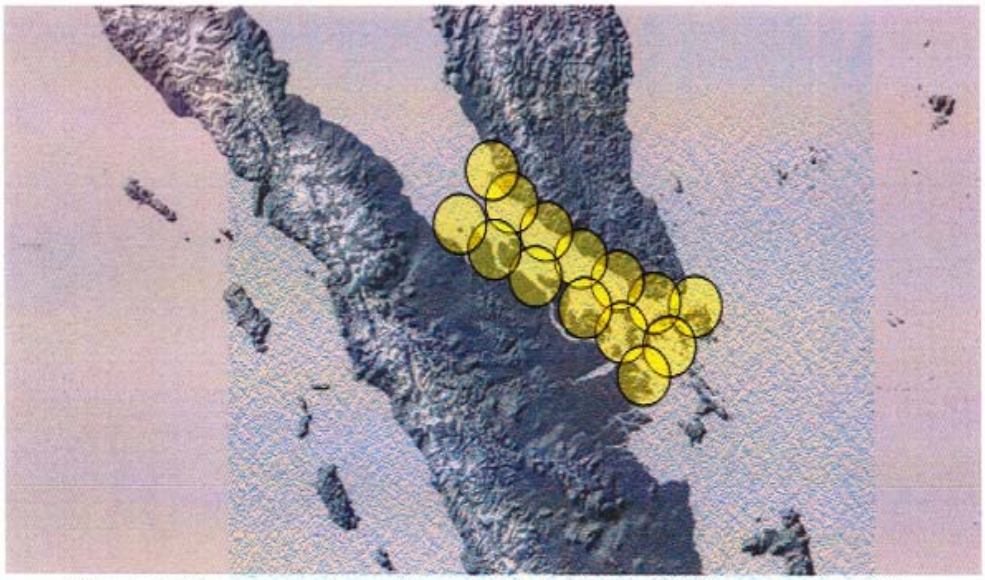

Figure 2 Microwave Radar (Fix Installation/ Coastal) Coverage in AOR.
The critical portion of the AOR requires no less than fourteen tower mounted microwave radar installations to meet the MDP mission requirements.

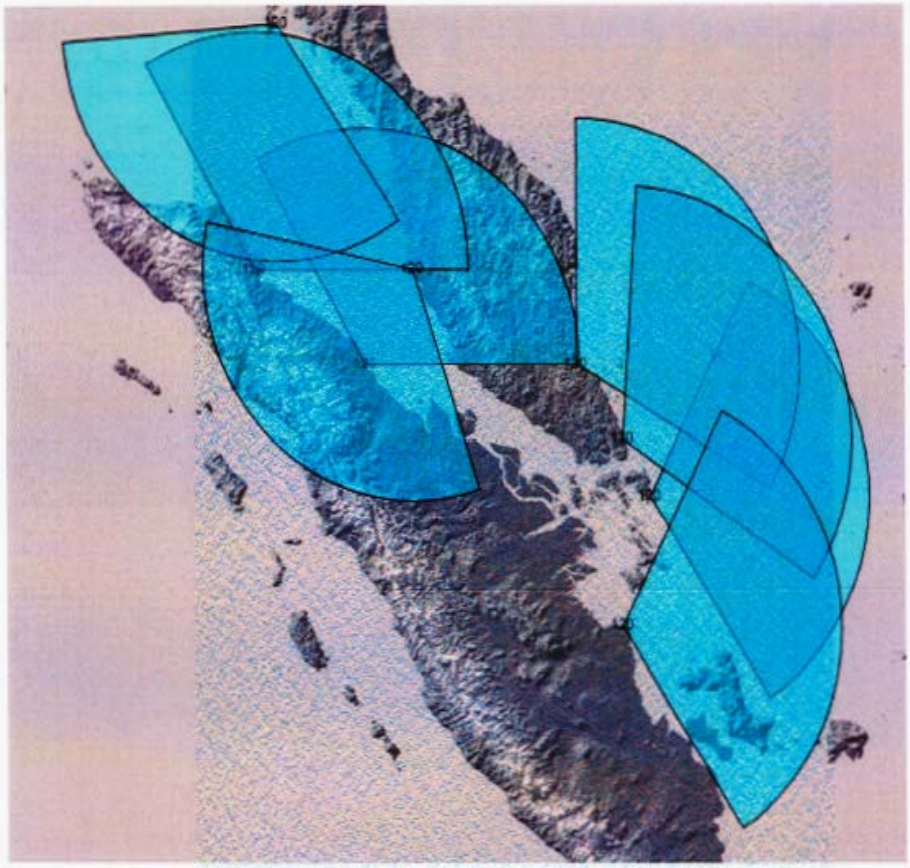

Figure 3 HFSWR (Fix Installation/Coastal) Coverage in AOR.

The long and medium range portions f the AOR requires no less than eight High Frequency Surface Wave Radar (HFSWR) installations to meet the MDP mission requirements.

An aerial sensor coverage plan for air deployment is shown below. It was assumed that for every two hour time window, there would be one airborne asset covering the north-eastern approach (from Port Klang to George Town) to the Malacca Straits and another airborne asset deployed at the eastern approach (from Singapore to South China Sea) covering the Singapore Straits. In addition, it was assumed there would be one airborne platform providing coverage from Singapore to Port Klang.

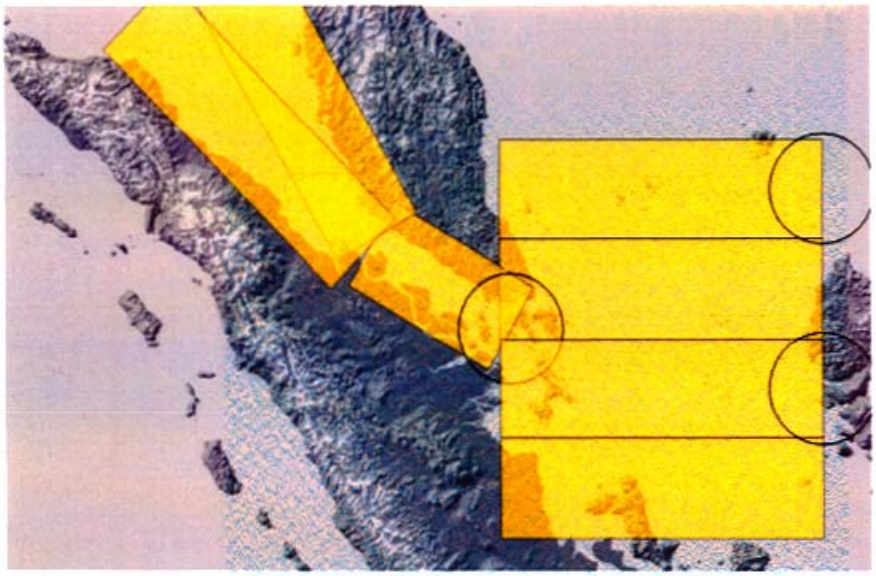

Figure 4 Aerial Sensor Coverage in AOR.

The infrequent equipment failure and weather induced down time associated with tethered aerostats requires MPA augmentation to facilitate long range microwave radar, EO/IR, and AIS coverage.

The launching of the air assets mounted with Microwave Radar and EO/IR sensors from George Town, Melaka and Singapore provided complete coverage of Areas A, B and C respectively.

Direct sensing support was provided by properly deployed mobile land units. Areas with high economic value along the stretch of coastline from Johor to Kelang such as busy cities and ports were considered prime targets. Thus, all additional land based mobile patrolling units were confined to this region. The mobile units supported the ground based microwave radars situated along this stretch of coastline, which were positioned approximately 100 km apart.

It was farther assumed that each mobile land platform mounted with sensors patrolled the Malaysian coastline at an average speed of 50 km/h for duration of 2 hours, traversing toward an adjacent fixed microwave installation during one duty cycle. During the next duty cycle, the land platform reversed direction and patrolled toward its origin. The same approach was adopted on the Indonesian coastline. With 7 ground based radar stations on each littoral state's coastlines, a total of 14 mobile platforms were required.

Time (hrs)	0000-0200	0200-0400	0400-0600	0600-0800	0800-1000	1000-1200	1200-1400	1400-1600	1600-1800	1800-2000	2000-2200	2200-2400
Air Assets	3	3	3	3	3	3	3	3	3	3	3	3
Land Platforms	14	14	14	14	14	14	14	14	14	14	14	14

Table 1 Number of assets required for each window timeframe.

The maximum number of required assets based on a 2-hour sensing window is shown in the timetable.

MAINTENANCE SUPPORT CONCEPT

A 3-level Maintenance Concept was adopted for the sensor systems composed of an Organization Level (O-level), an Intermediate Level (I-level), and a Depot Level (D-level). At the O-level, maintenance task performed by first line maintenance crews was restricted to modular part replacement and minor repair tasks not exceeding more than one hour. This approach allowed for a fast turn around time in bringing the system up to operational status. For maintenance tasks taking between one to four hours and/or tasks requiring special support or test equipment (STE), l-level by base maintenance crews were tasked. These tasks may include removal, repair, and installation, check out, and functional test. If the repair was beyond the I-Level capability, the job was passed to the D-level support. The D-level maintenance was contracted to the Original Equipment Manufacturer (OEM) or an Approved Contractor.

	Organization	Intermediate	Depot
MTTR (hrs)	less than 1	1 to 4	> 4

Table 2 Proposed Maintainability Guidelines.

The Mean Time To Repair (MTTR) at each maintenance level is shown above .

At the O-level, the corrective maintenance tasks were conducted on site where the system i.e. on-system remove & replace. The maintenance tasks were performed by the operators who doubled up as maintenance crews. For I-level repair jobs, the repair was conducted off site i.e. off-system repair. Cases were the entire system needed to be

brought back to the O-level or contractor facilities to have the system diagnosed and repaired or to conduct further failure investigations were classified as D-level repair jobs.

For I-level maintenance, there were five maintenance sites: Singapore, Melaka, Kelang, George Town and Mersing. There were no I-level maintenance sites situated in Indonesia as it was assumed that Indonesia would not have any economical interest on the sensor's operation status. As such, all the sensor system installations mounted on Indonesia's coastline and the mobile land platforms were maintained by Singapore and Malaysia authorities. Access to the sensor systems in Indonesia was made possible by floating platforms.

Considering the distance between the sensor system and the geographical location of the I-level maintenance base, the maintenance of each sensor system was assigned to a specific maintenance base.

Sensors	Singapore	Melaka	Kelang	George Town	Mersing
MR1	-	-	112	-	-
MR2	-	-	24	-	-
MR3	-	-	125	-	-
MR4	-	-	70	-	-
MR5	-	93	-	-	-
MR6	-	46	-	-	-
MR7	-	95	-	-	-
MR8	-	28	-	-	-
MR9	93	-	-	-	-
MR10	-	93	-	-	-
MR11	139	-	-	-	-
MR12	20	-	-	-	-
MR13	79	-	-	-	-
MR14	65	-	-	-	-
HFSWR1	-	-	-	278	-
HFSWR2	-	-	-	325	-
HFSWR3	-	-	139	-	-
HFSWR4	-	-	-	139	-
HFSWR5	-	-	-	-	46
HFSWR6	-	-	-	-	93
HFSWR7	139	-	-	-	-
HFSWR8	278	-	-	-	-

Table 3 Sensor Installation/Service Center Matrix

The estimated distance between the I-level maintenance base and the sensor systems is tabulated in the table below. Note that distances only appear for the sensor and its specific I-level maintenance base. Note: Distances are specified in kilometers (km).

For Depot maintenance, it was assumed that the system would be sent to the OEM in the United States of America (USA) for repair. It was further assumed that the most difficult depot level tasks took up to 30 working days (with 8 working hours per day) to get the system to full operational status. Taking into consideration the transportation and administration time, the Mean Down Time (MDT) was limited to no more than 60 days i.e. 1440 hours turn around time.

MODELING APPROACH

The MDP sensor system was modeled using the K of N system modeling technique. At the microscopic level, each specific sensor type was modeled to determine its effect on operational availability when only K of the N systems were operating. Since each specific sensor type could also be viewed as operating independently, the effect on the overall system availability was assessed at the macroscopic level when full sensing capability was not in place.

In general, the system's success probability, which is the probability of at least K of N successes, was clearly governed by the Binomial Probability Law defined as the following [1] :

$$A_{system} = \sum_{x=k}^{N} \frac{N!}{x!(N-x)!} (A)^x (1-A)^{N-x}$$

RELIABILITY

Reliability was defined as the duration or probability of failure-free performance under the stated conditions.[2] Considering steady state operating conditions, the reliability of the system was modeled using exponential distribution i.e. constant failure rate.

It was assumed the data or information captured by each sensor was independently fed back to the command center regardless of the mode of deployment. In

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1 Paul Kales, *Reliability for Technology, Engineering and Management* (Prentice Hall Inc., 1998).

2 Professor Thomas Hoivik, OA4603 Test & Evaluation, Edition 7. (Naval Postgraduate School, CA,USA, 2005).

this case, the sensors for each specific sensor type were modeled as a K of N system. Note that if K=N, then the entire system could be modeled as a series system. If K=1, then parallel models could be applied.

S/No.	Sensor Systems	Typical MTBF Values (hrs)
1.	Ground Radar	20000
2.	Airborne / Coastal Radar	10000
3.	EO / IR (Air)	2500
4.	EO / IR (Ground)	3500
5.	HFSWR	7500

Table 4 Reliability Figures for Sensor Systems.

Based on the limited reliability information uncovered from extensive research and engineers with hand-on experiences, the Mean Time Between Failure (MTBF) values[3] for the radar and EO/IR sensors were determined as above.

MAINTAINABILITY

Maintainability was defined as the ability of the system to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources at each prescribed level of Maintenance and repair.[2]

	Organization	Intermediate	Depot
Max Allowable MTTR (hrs)	1	4	240

Table 5 MTTR Figures for Sensor Systems.

Considering the worst case scenarios where the maintenance crews took the maximum allowable time at both the O-level and the I-level, the maximum allowable MTTR are as above.

To facilitate trouble shooting, it was assumed that Built-In Tests (BIT) were designed and implemented in each sensor system. This allowed for easy fault detection

3 Product Specification Scanter 2001 Transceiver Including Description of Scanter 2001 Radar Sensor System Configuration, TERMA.

and isolation in the system. At the O-level, it was assumed that the mean fault detection & isolation time, administration time and installation & checkout time would be negligible. Thus, the MDT would be approximately equal to the MTTR. However, at the I-level the fault isolation, transportation, and administration times took up a substantial portion of the MDT.

Sensors	Mean Fault Detection & Isolation Time	Mean Transport Time (2 ways)	Mean Admin. Time	Mean Time To Repair	Mean Installation & Checkout	Mean Down Time
EOIR/MR1	2	4.5	3	4	2	15.5
EOIR/MR2	2	1	3	4	2	12
EOIR/MR3	2	5	3	4	2	16
EOIR/MR4	2	3	3	4	2	14
EOIR/MR5	2	3.8	3	4	2	14.8
EOIR/MR6	2	1.9	3	4	2	12.9
EOIR/MR7	2	3.8	3	4	2	14.8
EOIR/MR8	2	1.2	3	4	2	12.2
EOIR/MR9	2	3.8	3	4	2	14.8
EOIR/MR10	2	3.8	3	4	2	14.8
EOIR/MR11	2	5.6	3	4	2	16.6
EOIR/MR12	2	0.8	3	4	2	11.8
EOIR/MR13	2	3.2	3	4	2	14.2
EOIR/MR14	2	2.6	3	4	2	13.6
HFSWR1	2	11.2	3	4	2	22.2
HFSWR2	2	13	3	4	2	24
HFSWR3	2	5.6	3	4	2	16.6
HFSWR4	2	5.6	3	4	2	16.6
HFSWR5	2	1.9	3	4	2	12.9
HFSWR6	2	3.8	3	4	2	14.8
HFSWR7	2	5.6	3	4	2	16.6
HFSWR8	2	11.2	3	4	2	22.2

Table 6 MDT for I-level Maintenance.

The assumed MDT at the I-level is shown as above. Note: Mean Transport Time (in hours) was computed based on an average platform traveling speed of 50 km/h either via sea or land for a round trip to and fro from station to the maintenance base. Note that the administration time encompassed the time for collection of spares from store room, equipment setup time, and crew's rest, meal time, etc.

AVAILABILITY

Availability was defined as a measure of the degree to which the system was in an operable and committable state at the start of a mission when the mission was called for at a random time. Mathematically, it is expressed as:

$$Availability, A = \frac{Up\,Time}{Up\,Time + Down\,Time} = \frac{MTBF}{MTBF + MTTR}$$

RAM ANALYSIS

The reliability analysis was performance for each sensor types using the K of N system modeling approach for each maintenance level. The results were summarized and included in Annex A.

Microwave Radar. At O-level maintenance, each individual ground and coastal / airborne microwave radars had a very high operational availability close to unity i.e. 99.9%. This was evidence that if a failure occurred, it could be remedied on site by operators. The deployment of a fleet of coastal (14 out of 14 Fixed Installation), air deployed (3 out of 3), and land deployed (14 out of 14) radars had an operational availability of 99.86%, 99.97% and 99.93% respectively. For one year of operation (8760 hours), the expected down time of the radars for O-level maintenance is between 2.6 to 12.3 hours.

The operational availability of individual microwave radars was different at the I-level due to the difference in the transportation time to the respective I-level maintenance bases i.e. 99.26% – 99.89%. For analysis, the lowest availability value was used to compute the system operational availability for each specific sensor types. For all the microwave radars to be operating, the predicted availability was 97.7%, 99.67%, and 99.04% for the coastal, air, and land deployed radars respectively. Thus, the expected down time for I-level maintenance is between 29 to 201 hours for one year of operation.

If one or two of the coastal or fixed installation radars fail, the team assessed that it would not have a significant impact on the overall detection capability. As the contacts sailed along the Malacca Straits, their presence can still be detected by the next adjacent operational radar. Since the primary detection of the contacts in the AOR was performed by the coastal or fixed installation radars, concerns arose when three or more adjacent radars failed. In this situation, the coverage had to be provided by either the air or land deployed radar until the failed coastal radar was made serviceable at the I-level maintenance base.

In the case where a major failure occurred and forced the microwave radars to be sent to OEM, there was a significant impact on the operational availability due to the long turn around time i.e. 87% - 93% availability for each individual radar system. At the aggregate level, 99% operational availability can only be achieved when operating at least 9 out of 14 coastal radars, 1 out of 3 air deployed radars, and 10 out of 14 land deployed radars. In such a situation, complete sensor coverage of the AOR can not be achieved.

HFSWR: Like the microwave radars, each stand alone HFSWR systems had very high operational availability i.e. 99%. Based on the analysis results, an operational availability of 99% can be achieved when operating all of the 8 systems with failures occurring that only require operator's maintenance.

At the I-level, each HFSWR had a different availability figure due to the difference in traveling distance to the nearest respective maintenance bases. Considering the lowest availability value of the individual systems, an operational availability of 97.5% was achieved when operating all of the 8 HFSWR systems. Failure of a single system was acceptable due to the short turn and around time for repairing and reinstating a system.

However, the availability of each HFSWR system would drop to 83.89% if the system needed to be sent to OEM for repair as is the case for D-level maintenance. The overall system operational availability of 99% could only then be achieved if half the fleet of 8 HFSWR were in operation. In the worst situation, detection of contacts would not be possible in either the eastern approach from South China Sea or the Northwestern approach from George Town. Since HFSWR played a crucial role in "seeing" all contacts entering and exiting the AOR, the occurrence of such a situation is disastrous, and is unacceptable due to the long period of downtime.

EO/IR Sensors. All of the mounted and coastal EO/IR sensors achieved an operational availability of more than 99% for all O-level maintenance.

Similar to Microwave Radars and HFSWR, each EO/IR sensors had different operational availability ranging from 95.89% to 99.66% for I-level maintenance. The operational availability of 13 out of 14 coastal EO/IR sensors, 3 out of 3 air deployed EO/IR sensors and 11 out of 14 land deployed EO/IR sensors met the required 99% operational availability. The team opined that 1 failed coastal system and 3 failed land deployed sensors would not have a great impact on the entire system in view that the EO/IR sensors are used only to enhance the main system i.e. identification.

Sending any of the coastal, air, or land deployed EO/IR systems to OEM for depot maintenance would not meet the availability requirement. From the analysis results, operating 6 out of 14 coastal and land deployed EO/IR sensors would obtain 99% operational availability; however, this configuration would not be able to provide a complete picture of maritime activities in the AOR. In addition, the 99% availability requirement for air deployed EO/IR would not be met even if the fleet of 3 out of 3 systems were serviceable based on the current operating and maintenance policies.

CONCLUSIONS

The system still obtained an operational availability approaching 99% even with failures that required O-level maintenance by operating all coastal, air, or land sensors.

For failures that required I-level maintenance support, the required operational availability of 99% for each specific sensors type could not be achieved due to the long transport time between the sensor location and the nearest I-level maintenance base. However, the failure of one to two systems for each specific sensor type can be deemed acceptable since the turn around time would not be long with regard to the average MDT of 13 hours.

When necessary components were sent to OEM, the operational available was drastically affected due to the long turn around time.

RECOMMENDATIONS

As the primary means of surface contact tracking in the AOR, extended degraded performance of any of the coastal microwave radars or HFSWR required immediate augmentation by air and/or land deployed sensors to provide the required coverage in the affected zone.

To ensure faster turn around time of the failed systems for I-level maintenance, the sensor systems re-designed or new sensor components with modular replacement of reparable or repair parts for ease of maintenance are recommended. Additionally, sufficient spares including reparable and repair parts are required.

In order to reduce the MDT for overseas depot maintenance, local depot capability could be setup in both Singapore and Malaysia to facilitate D-level maintenance.

APPENDIX J: SENSOR GROUP EO/IR MODELING REPORT

EO/IR MODELING REPORT

Introduction

1. The Electro-Optic/Infra-Red (EO/IR) team under the Sensor Group was tasked to investigate the EO/IR sensing performance against specified targets, operating under local weather conditions, in the Area of Regard (AOR). The purpose of the tasking was to determine/assess command and control decision cycle required to deal with the specified threats of "Small Boat Attack" (SBA) and "Ship As a Weapon" (SAW) by terrorists against shipping in the Malacca Straits.

2. The modeling tool used by the team for the task was the Target Acquisition Weapons Software (TAWS) (Version 3.2). Outputs from the modeling were in the form of Probability and Ranges of Detection and Identification for the specified targets.

Model

3. The TAWS is a weather impact tactical decision aid for warfighters. The software predicts performance of electro-optical (EO) weapons and navigation systems against atmospheric/environmental, temporal and target inputs. These performance predictions are used by mission planners to make "go/no-go" decisions, modify mission execution tactics or weapon loads, or evaluate the general situational awareness of environmental conditions for Forward Looking Infra-red (FLIR), IR and TV trackers, Night Vision Goggles (NVG), and other EO systems.

4. The major input parameters to TAWS are:

   a. Weather. Information includes humidity, temperature, wind and aerosol analysis. The weather parameters can either be user-specified or "pulled" from known database.

   b. Sensors. TAWS supports EO systems in 3 regions of the EM spectrum: IR (3-5 and 8-12 μm), Visible (0.4-0.9 μm for both TV and NVG systems), and Laser (1.06 μm). The sensors in TAWS Version 3.2 (unclassified) are coded in numerics: 1000s series for 8-12 μm IR sensors; 3000s series for TV; and 8000s series for 3-5 μm IR. The main specifications of the sensors are listed in the software to enable user to choose the sensor of choice.

   c. Missions. Various types of missions are supported by TAWS, including target acquisition/detection, target designation and tracking, close air support, etc.

5 Three types of analysis can be performed by TAWS:

   a. Illumination analysis, which involves the computation of solar and lunar ephemeris information for a specified location and a series of dates or times.

b. Point-based analysis, which calculates detailed performance predictions for a single location in a selected mission. Target acquisition analysis in TAWS involves the computation of detection range, detection probability, or lock-on range for a particular target at a particular location under specified weather conditions. Point-based analysis is used for the modeling task.

c. Map-based analysis, which calculates detailed performance predictions for several locations in a given area or locations along a mission route.

Inputs of Modeling

6. The inputs for the EO/IR modeling were consciously selected to match the specified scenarios for the project as much as possible. However, certain changes (e.g. type of target for small boat attack) were needed due to restrictions in the TAWS software. The critical inputs used for this modeling were:

a. Target Geographical Position. The representative target position used in this modeling was 2°00N, 102°00E. This is a true position in the Strait of Malacca. It was also assessed that the location of the target was not as critical as the orientation that the target was detected with respect to its background. As it was not possible to simulate all orientations, it was decided that this representative position was adequate to provide the assessment of the sensors' performances unless a more specified scenario was required.

b. Sensor Height. Sensor heights of 90 ft and 1000 ft were used for this modeling. 90 ft represented sensors mounted ashore or on a ship while 1000 ft represented sensors mounted on an aircraft.

c. Orientation. The TAWS software would differentiate the sensor performances according to their orientations, whether it was facing the sun/moon or against the sun/moon etc. However, as it was not possible to model all orientations and as sensor orientations could not be controlled during operations, the implication of sensor orientation was not considered in the modeling.

d. Weather. As expected, weather was probably the most critical input for this modeling. Being so close to the equator, the weather in the Strait of Malacca was known to be quite similar throughout the year, with temperatures not varying a great deal for the various months as it was without any season. The main effects in weather with respect to the sensors were the different temperatures of the day as well as the occurrence of rain that occured at any part of the day (or night). As it was not possible to model all permutations of the weather, a good and foul weather scenario were defined to produce the best and worst sensor performances to be expected. Further elaborations of the good and foul weather[1] were:

[1] The specifications for both good and foul weather used in this modeling are attached at Annex A.

(1) Good Weather. Good weather in this modeling was defined as that when there was no rain for the entire duration concerned.

(2) Foul Weather. Foul weather in this modeling was defined as that when there was rain for the entire duration concerned.

e. Time and Date. The UTC time indicated in the model results was equivalent to the ZULU time and the local time was calculated by adding 8 hours (HOTEL time-zone). The time was critical as TAWS automatically calculated the sunrise, sunset, moonrise and moonset times for the designated date(s). An arbitrary date was used for this modeling as the timings for the moon and sun were fairly consistent throughout the year. Operations would also take place regardless of timings or moon phases.

f. Choice of Target. The choice of target selected for this modeling was a 24 ft (or 7.2 m) gray Power Boat made of Fiberglass. This was a departure from the 5 m small boat defined for the Small Boat Attack (SBA) scenario. However, this was the closest that TAWS offered. It was assessed that the difference between the 2 types of targets was negligible. Large ships were also represented in the model by a 90 ft gray Fishing Boat made of steel, which was the biggest vessel available in TAWS.

Modeling Outputs

7. Summary of Results. The results[2], 80% probability of detection, at from modeling based on the above-mentioned inputs are summarized in the following table:

Sensors	90 ft, Good Wx		90 ft, Foul Wx		1000 ft, Good Wx		1000 ft, Foul Wx	
	24 ft	90 ft	24 ft	90 ft	24 ft	90 ft	24 ft	90 ft
Id: 8500 (MWIR)	Max 2.6 nm	Max 4.0 nm	Max 0.1 nm	Max 0.2 nm	Max 2.6 nm	Max 4.0 nm	Max 0 nm	Max 0 nm
	Min 0 nm	Min 0 nm	Min 0 nm	Min 0 nm	Min 0.6 nm	Min 2.6 nm	Min 0 nm	Min 0 nm
Id: 1504 (LWIR)	Max 2.6 nm	Max 4.6 nm	Max 0.1 nm	Max 0.3 nm	Max 2.6 nm	Max 5.0 nm	Max 0.6 nm	Max 0.3 nm
	Min 0 nm	Min 2.6 nm	Min 0 nm	Min 0 nm	Min 1.6 nm	Min 2.6 nm	Min 0 nm	Min 0 nm

[2] The modeling results for the sensors and their specifications are attached at Annex B, C and D for MWIR (8500), LWIR (1504) and TV (3502) sensors respectively.

Id: 3502 (TV)	Max 8.6 nm	Max 8.6 nm	Max 8.6 nm	Max 8.6 nm	Max 9.0 nm	Max 16.6 nm	Max 9.0 nm	Max 16.6 nm
	Min 0 nm	Min 0 nm	Min 0 nm	Min 0 nm	Min 0 nm	Min 0 nm	Min 0 nm	Min 0 nm

8. Probability of Identification. Although experienced users of TAWS (including the software creator) had indicated that 60% of the detection range was a good rule-of-thumb for identification ranges, these ranges could not be used directly for SBA-type scenarios as identification of such crafts required more sophisticated definitions unlike the basic definition set for identification. Nonetheless, the 60% figure could be used as reference when short of more accurate figures.

Output Analysis

9. Explanations of the Modeling Results.

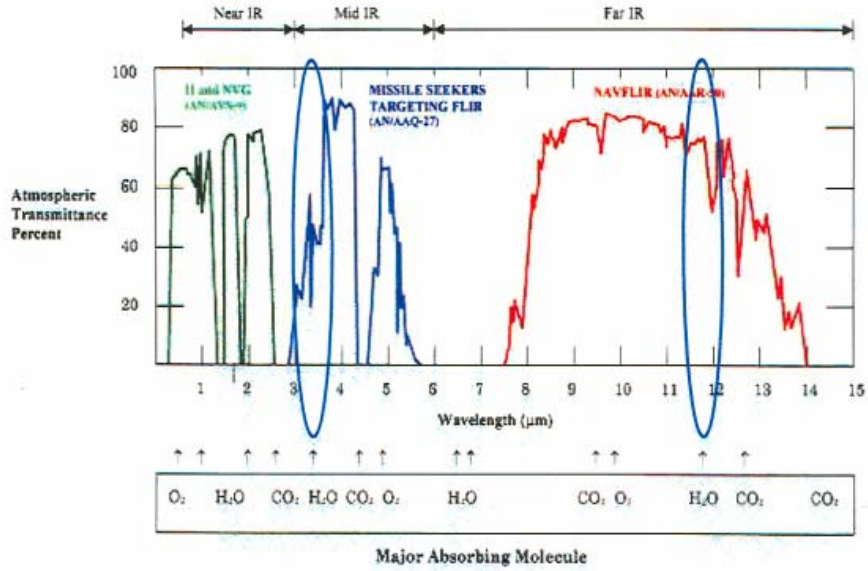
a. The MWIR sensor performances were observed to fluctuate moderately during the night, peaking at the period between 0600 and 0800 hours. A minimum in performance was observed at 1000 hours and the performances during the night were observed to be generally better than that during the day.

Explanation. The 0600-0800 hours period seemed to coincide with the period of the day when the surface temperature increases at the fastest rate due to the rising of the sun. The peak of the performance could be due to the fastest rate in the rise of the relative humidity. The generally better performance in the day compared to the night could be explained by the relative humidity which was expected to be lower during the day (less water vapor content) and higher during the night, being cooler at night and closer to the dew point.

b. The LWIR sensor performances were observed to be consistent compared to the MWIR sensor. The performances were observed to peak during the day at 0900 hours, staying at a consistently high level before dropping progressively and significantly after sunset.

Explanation. The consistency in performance of the LWIR sensors compared to the MWIR could be contributed to the percentage of IR energy absorbed by H^2O within their respective bands. As seen from the chart below, H^2O absorption within the 3 to 5 micron band (MWIR) was approximately 30 to 40 % of the total emittance, compared to only 15 to 20% in the 8 to 12 micron band (LWIR). Thus as the humidity of the environment increased, the MWIR sensors would expect to degrade more compared to the LWIR sensors.

Fig 5 - Atmospheric Transmittance



c. For TV sensor, the performance tended to be consistent during the day but drops very acutely when night falls.

Explanation. This could be explained by the lack of lamination for the TV sensor operation.

10. Insights from Modeling Results. Some of the insights provided by the modeling results are:

a. LWIR sensors performed generally better than MWIR sensors in the given operating conditions.

b. Both MWIR and LWIR sensory capabilities were greatly degraded by the presence of rain.

c. TV sensor was unable to detect at night without the presence of light.

d. TV sensor was not adversely affected by rain.

e. There was no substantial difference in performance for MWIR and LWIR at 90 or 1000 ft though there was a difference for TV sensor. However, the ranges were slant ranges[3], and it could be assumed that higher height sensor would provide a better coverage.

[3] Affecting sensors at higher heights more based on the Pythagoras Theorem.

11. Implications of Modeling Results. Some implications from modeling results are:

a. There was no EO/IR sensor that could see (or identify) through rain at night.

b. Good TV detection ranges could be achieved through air platforms during the day.

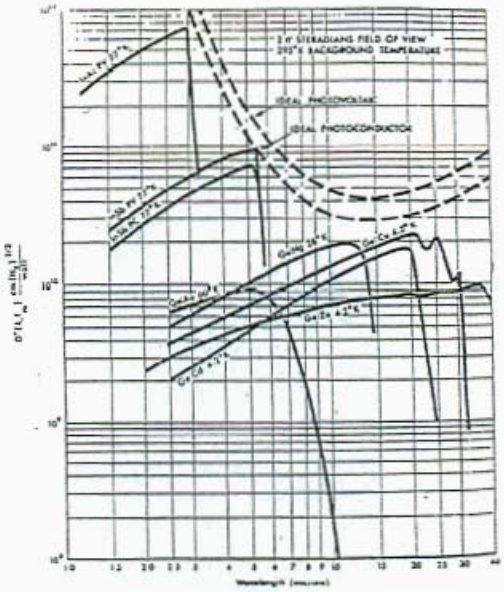
c. EO/IR detection ranges were very limited; implying that the deployment platform needs to be mobile and the suite of sensor needed to be complementary in performance for different weather conditions.

Key Performance Parameter & Measures of a IR Sensor

12. The two key performance parameters of an IR sensor are namely: the Resolution and Sensitivity of the sensor. The Resolution defines how detailed the received IR image is while the Sensitivity defines the systems ability to differentiate small changes in temperature.

13. The Resolution of the IR system is ultimately limited either by the diffraction and aberration effects of the optical system within the IR Sensor, commonly known as the Optical Modular Transfer Function, or the detector array configuration.

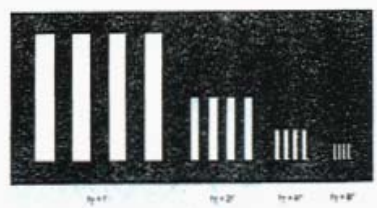
14. The Sensitivity of the IR System is dependent on a parameter D*, Specific Detectivity, which is dependent on the detector material used in the detector array. The chart on the right shows the D* of various materials mapped along with the ideal response curve.



15. Depending on the operating IR range of the detector, it is favorable to chose a material that gives the highest D* value. The numerical measure of the sensitivity of a detector is the NETD, Noise Equivalent Temperature Difference, which defines the required temperature difference between the target and noise to achieve a SNR of 1, is directly related to the D* value in the formula below.

$$NETD = \frac{\pi\sqrt{ab\Delta f}}{\alpha\beta A_o \tau_{optics} D^*(\lambda_p)\frac{\Delta M}{\Delta T}}$$

a, b	Dimension of individual detector
α	Horizontal detector subtense angle
β	Vertical detector subtense angle
A_0	Area of optics entrance pupil
τ_{optics}	Transmission of the optics
ΔM	Emittance difference between target and background
ΔT	Temperature difference between target and background in °K



16. However, as the image from the IR sensor is perceived by the human operator, there is a need for a total performance measure that takes into consideration both the Resolution & Sensitivity of the IR system and the human operator's ability to perceive targets. The Mean Resolvable Temperature (MRT), which is a measure of performance for the entire system, including the observer, measures the amount of temperature difference (ΔT) required for an observer to just resolve a standard 4 bar (7:1 aspect ratio) chart. It must be noted that the MRT is an empirical measure, and is therefore dependent on the proficiency of the human observer to resolve the 4 bars.

Types of Detectors in IR Systems

17. There are namely two board categories of IR detectors in the market, namely: photon and thermal detectors. Only the former will be discussed as the latter has slow detection response and is hardly used.

18. Photon detectors are, by virtue of their name, detectors that basically measure the amount of photons. There are 3 different types of photon detectors, the Photoconductive, Photovoltaic and Photoemissive.

19. Photoconductive detectors sense optical power with a change in conductance. Therefore the current running in a photoconductive detector circuit is proportional to the incident irradiance within the detection band.

20. Photovoltaic detectors are similar to P-N junctions, where there is an inherent generated voltage. When photons fall onto the depletion region, electrons are excited to higher energy levels, which creates excess electron-hole pairs. This will change the junction voltage which can be used to measure the incident irradiance.

21. Lastly, Photoemissive detectors are photosensitive materials that release electrons when an incident photon has enough energy to release an electron from the surface. These free electrons are collected at the Anode that creates a current, which is a measure of the incident irradiance.

22. Now understanding that the detector material, e.g., PbSe, HgCdTe, etc, can be formed into any of the above mentioned forms of IR detectors. We shall now determine what material suits best for each IR band.

Detector Material in Cooled & Uncooled IR Systems

23. It is known that one of the key parameters to an IR sensors' performance is its Sensitivity, and this is directly affected by D*(λ). Where the selection of the material with highest value of D*(λ) for the detection band is desired.

24. However, each material has its own operating temperature, which thus leads to Cooled and Uncooled IR systems. The table below highlights the best materials that can be used for both Cooled and Uncooled system in the 3 to 5 micron and 8 to 12 micron band.

Detection Band	Cooled System		Uncooled System	
	Material	D*(λ) $^{cm(Hz)^{1/2}}/_{Watt}$	Material	D*(λ) $^{cm(Hz)^{1/2}}/_{Watt}$
MWIR	InSb(PV*) 77°K InSb(PC*) 77°K PbSe 77°K	$8x10^{10}$ $6x10^{10}$ $3x10^{10}$	PbSe 295°K	$8x10^{9}$
LWIR	HdCdTe 77°K GeHg 28°K GeCu 4.2°K	$1.2x10^{10}$ $1.8x10^{10}$ $1x10^{10}$	N.A	N.A

Note: PV and PC stands for Photovoltaic and Photoconductive respectively. And D(λ) value is measured with a background temperature of 295°K

25. From the table, it can be observed that cooled systems tend to have better D*(λ) but with the trade off of needing refrigeration equipment. However cooled systems have an additional benefit of reducing the amount of dark current noise present in the system.

Present Technology – COTS EO/IR Systems

26. EO/IR systems in the commercial markets can be classified by technology and applications, such as thermal imaging, image intensifier, optronic systems and laser systems for surveillance, reconnaissance, weapon sights and fire control. These systems are also not exclusive in packaging, in that two or more systems are often incorporated into an integrated sensor suite to provide user with a complementary sensing capability. For example, a FLIR-sensor, TV-sensor and Laser range finder are integrated into one complete system for naval surveillance application. Such an approach is necessary to complement the inherent limitations of each sensor, and takes advantage of the small size

of each sub-system. The man-machine interface (MMI) is configured for the operator based on the number of sub-systems and their outputs.

27. The following examples give a sense of the of EO/IR systems available in the commercial markets:

Manufacturer	Product / Application	Key features and Specifications
Raytheon	**AN/AAS-52 Multispectral Targeting System** Application: Long-range surveillance, target acquisition, tracking, range-finding & laser designation. Platform: Rotary- and fixed wing, UAV	• FLIR, Image-intensifier TV, Fused output (Options: EO-TV, image intensified TV, illuminator, laser range finder, spot tracker, image fusion, others) • FOV: Wide: 34-45 Medium: 5.7 x 7.6 Narrow: 1.2 x 1.6 (IR&TV) Ultra-narrow: 0.21 x 0.27 (TV) • Angular coverage: 360° azimuth continuous 60° up; 120° down elevat • Slew rate: 3 rad/sec • Multi-mode automatic video tracking (centroid, area and feature) • Cooling: Self contained
Kollsman	**CoMPASS IV (Compact Multi-Purpose Advanced Stabilized System)** Application: Configurable payloads for intelligence, surveillance, targeting, and reconnaissance. Platform: Rotary- or fixed-wing, UAV	• Optional sensors: Laser range finder, daylight TV, Spotter scope, Laser area illuminator, Laser pointer, and Laser designator • FLIR Sensor – Gen II+/III MWIR Staring FPA o Resolution: 640 x 480 o FOV: Wide: 13.7° x 10.2° Medium: 2° x 1.5° Narrow: 0.61° x 0.46° • TV Sensor – Colour CCD / B&W TV o Pixels: 752 x 582 o FOV: 13.7° x 10.2° (Wide) 0.7° x 0.52° (Narrow) • Laser rangefinder – Erbium; Glass 1.54μm o Range: 200m – 20km o Range resolution: ± 5m o Target discrimination: 40m • Laser target illuminator – NVG-compatible diode o Spectral bandwidth: 830nm o Output power: 50mW o Range capability: 10km

		• Laser designator – Diode pump advance technology o Wavelength: 1.064μm o Pulse energy: 80mJ o PRF: up to 20 pps
Radamac	**1000N Naval EO Surveillance System** Application: Covert detection and observation; Laser range finding Platform: Shipborne. **1000L Land-based EO Surveillance System**	• Above-deck EO director & Below-deck control console. • TV camera and Thermal Imager (TI) • High slew speed and acceleration • Azimuth and elevation stabilized • Sensor focus and zoom function • Automatic scanning between pre-set limits • Remote indication from external source 1000L has similar capability to 1000N but configured for land/portable application
SAGEM	**VIGY10** Application: Day/Night naval surveillance. **MATIS Thermal Imager** Application: Surveillance and Observation. Platform: Handheld or Modular versions.	• Sensor head and Control console. • Sensor head comprises TI (MWIR/LWIR) abd II or TV camera. • Gen II+/III focal plane array IR detector

Advanced Concepts for Future EO/IR systems

28. Listed are some of the more prospective concepts of improving EO/IR systems that may occur during the next 5 to 10 years. These concepts aim to reduce or eliminate the limitations of present days EOIR systems.

a. Adaptive Optics. As electronic fabrication technology increases, and nanotechnology matures, it is likely that the dimensions of the detector array may surpass the diffraction limit of the optical system. The next step to improving the resolution of the EO/IR system is to improve the optical system itself. However, to achieve a diffraction limited system, one must design the optics such that there

are no aberration effects or other forms of distortion in the optical system. Adaptive Optics is this next step in achieving diffraction limited optical system.

b. Data Alignment/Fusion. Data Alignment is the ability to synchronize sensory information from different sensor platforms for further computation or use. This capability is already present through the implementation of time stamping. However, Data Fusion is the ability to extract information on an entity from different types of sensors and fuse all these information to achieve an overall better perception of the entity compared to using a single type sensor.

c. Hologram. Lastly, with the ability to fuse data on a target, the next best thing would be the ability to create a 3D, 3 dimensional, representation of the target through the use of hologram technology.

Conclusion

29. As we look into the protection of the maritime region of the Malacca Straits against possible hostile threats, the task of functioning as the eyes of the Command HQ - monitoring and feeding back sensory information within the Area of Regard - lies on upon the shoulders of the sensors employed. It is therefore impervious that the appropriate sensors are employed which will enhance the Command HQ's ability to shorten its OODA loop and react to a threat effectively and in a timely manner.

30. The use of TAWS allowed the Sensors group to analyze the performance characteristics of different EO/IR sensors operating within the environmental conditions experienced in the Malacca Straits. From these findings, the most appropriate suite of sensors and its employment vulnerabilities could be derived.

31. In addition, the physics relating to the different type of detectors and the respective sensors performance was explored in this report. This had helped the team to relate the simulations results from TAWS and derivation of explanations to its simulated performance.

32. Ultimately, it is the team's goal to understand the performance of current EO/IR sensors and its characteristics, in order to support and validate the overall CONOPS towards the protection of the maritime region of the Malacca Straits.

Written by:

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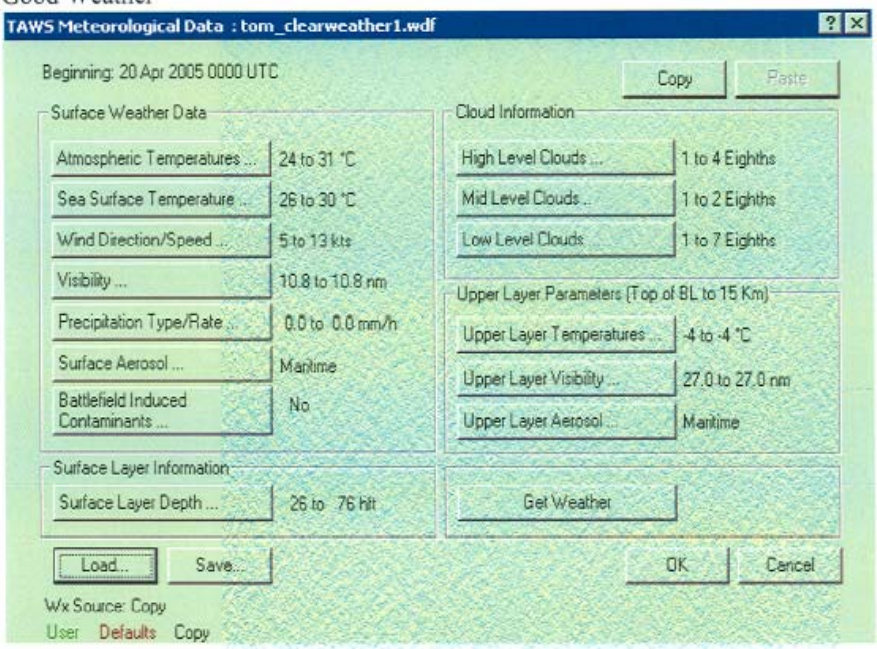
MAJ Tommy Hsu Yu-Chih, Republic of Singapore Navy
LTC Yong Yoke Chuang, Republic of Singapore Air Force

Annexes:

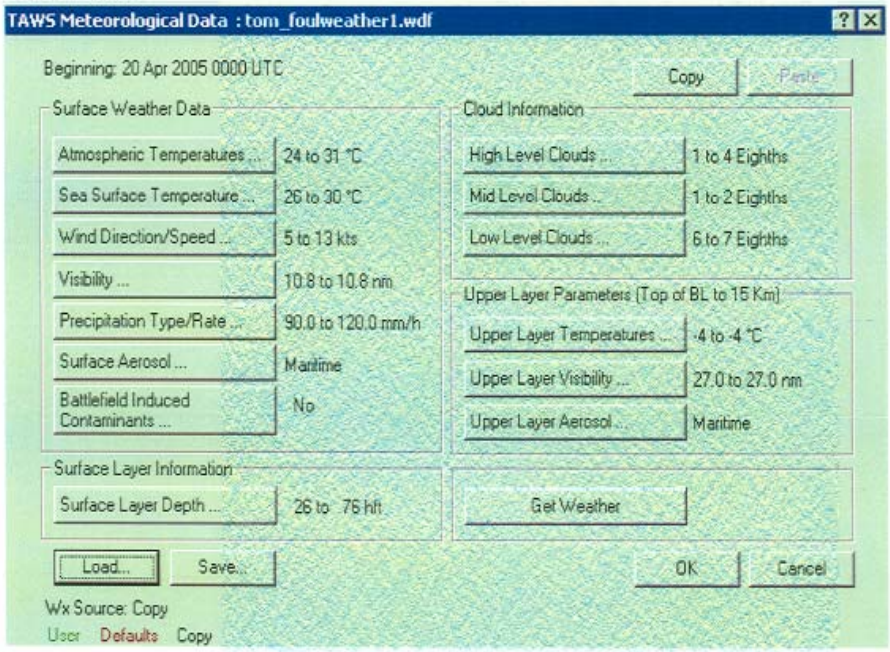
A. Weather Specifications
B. Modeling Results and Specifications of MWIR Sensor
C. Modeling Results and Specifications of LWIR Sensor
D. Modeling Results and Specifications of TV Sensor

WEATHER SPECIFICATIONS

Good Weather



Foul Weather

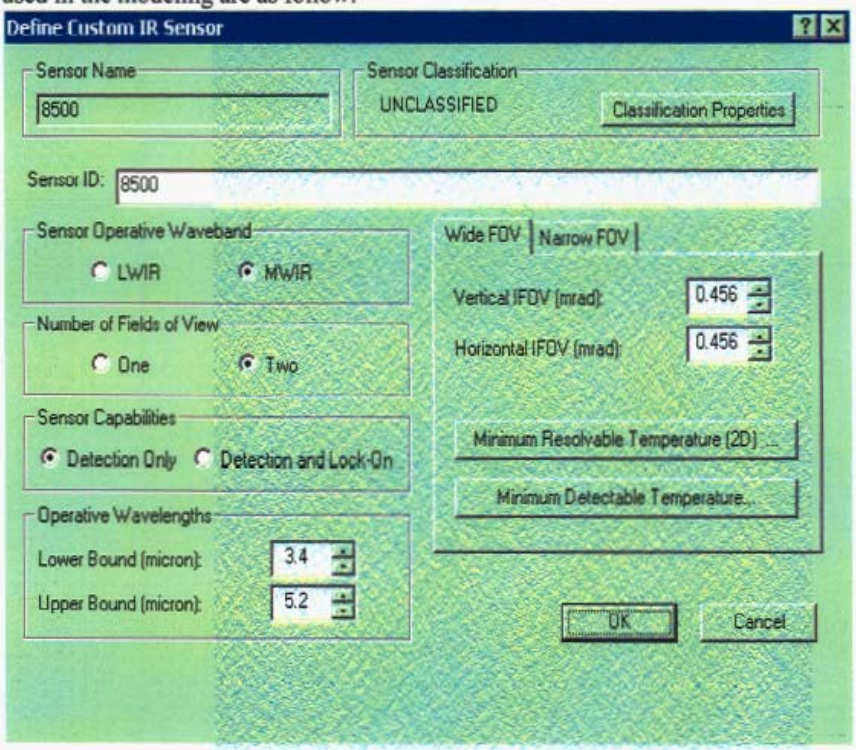


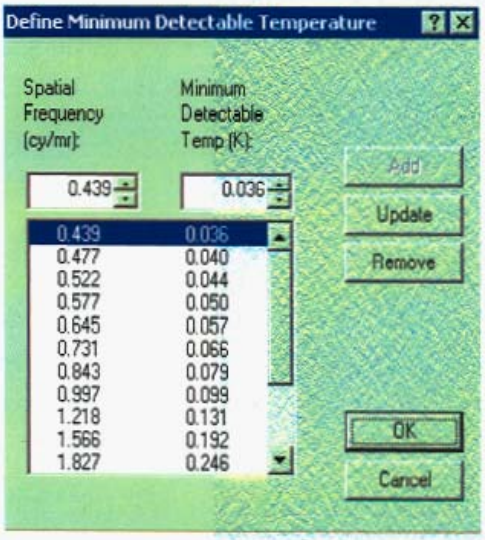
Annex B

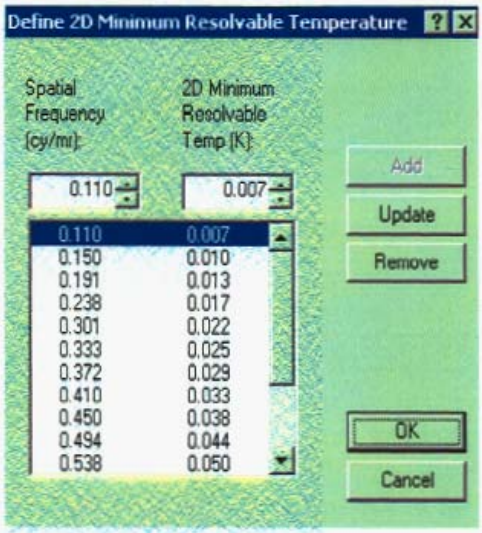
MODELING RESULTS AND SPECIFICATIONS OF MWIR SENSOR

Specifications

The specifications for the assessed best performing MWIR sensor (IR Sensor 8500) as used in the modeling are as follow:

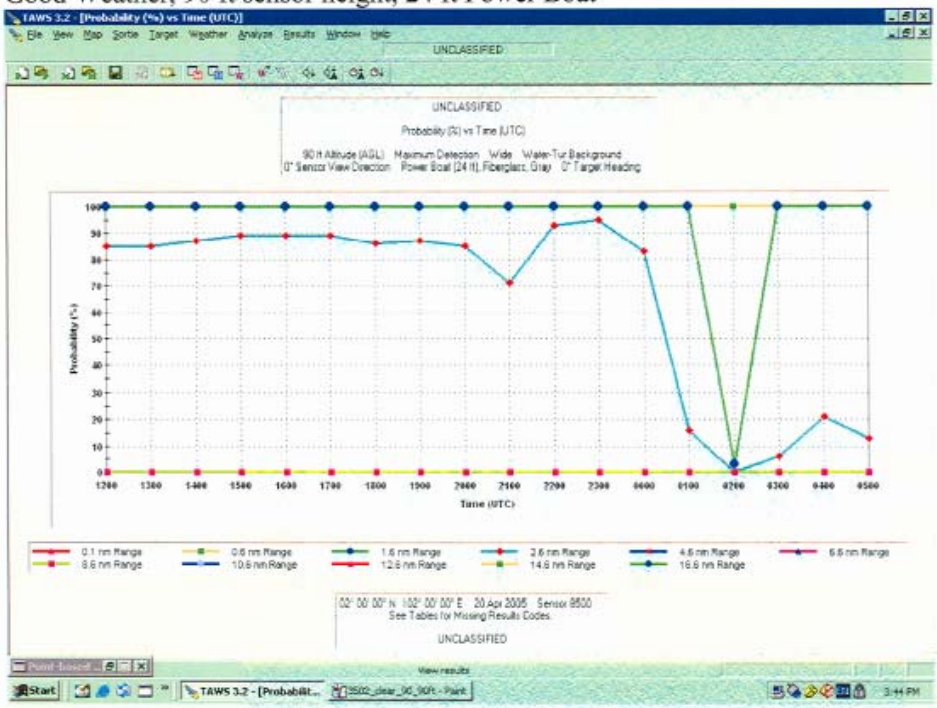




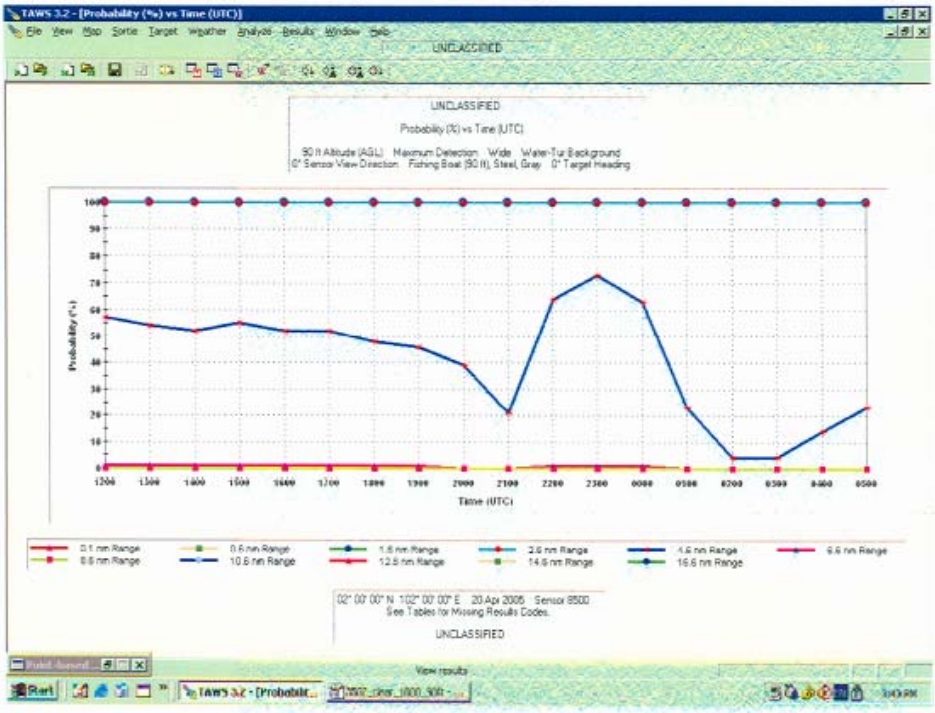


Modeling Results (MWIR Sensor 8500)

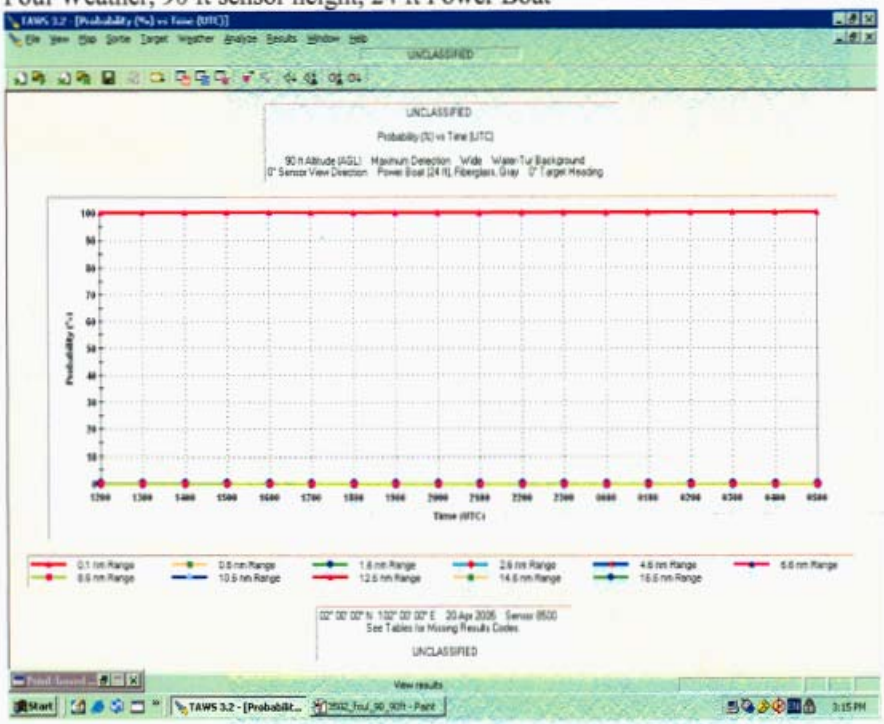
Good Weather, 90 ft sensor height, 24 ft Power Boat



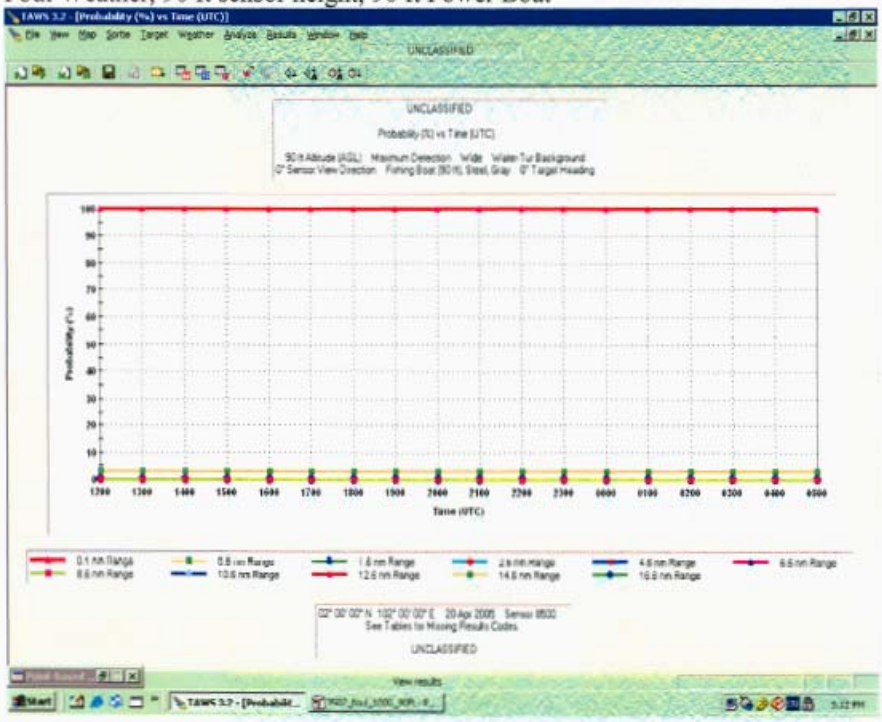
Good Weather, 90 ft sensor height, 90 ft Fishing Boat



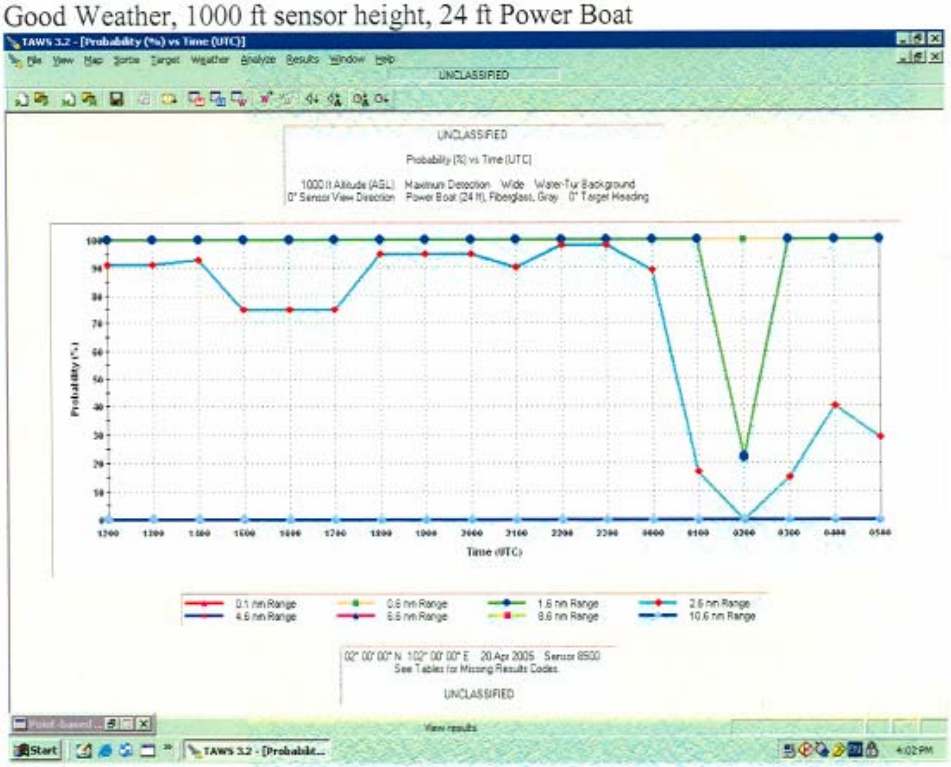
Foul Weather, 90 ft sensor height, 24 ft Power Boat



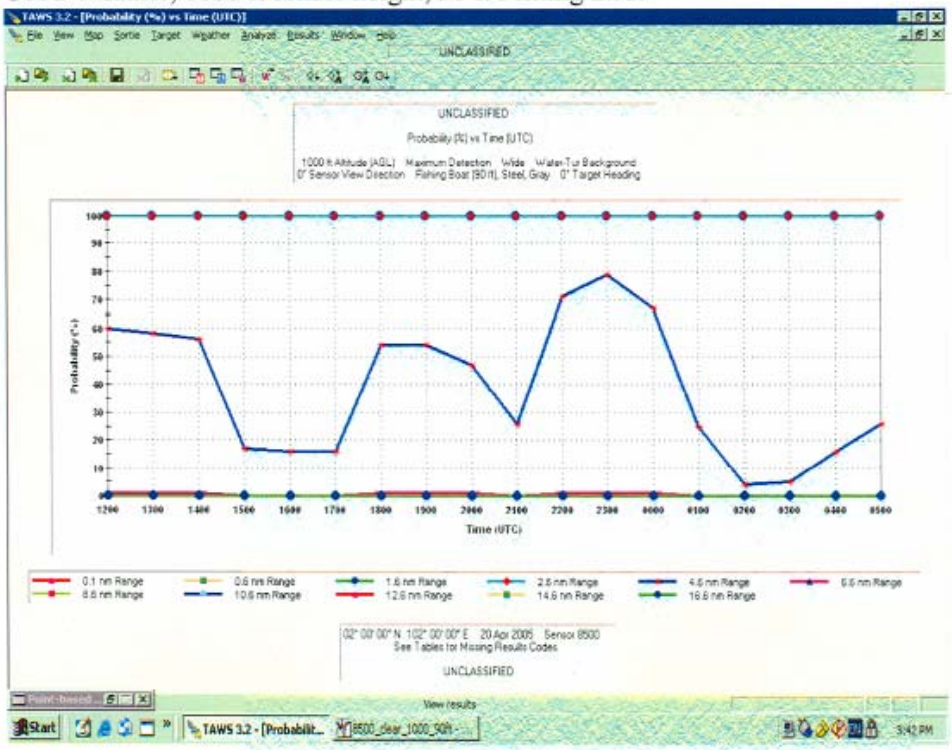
Foul Weather, 90 ft sensor height, 90 ft Power Boat



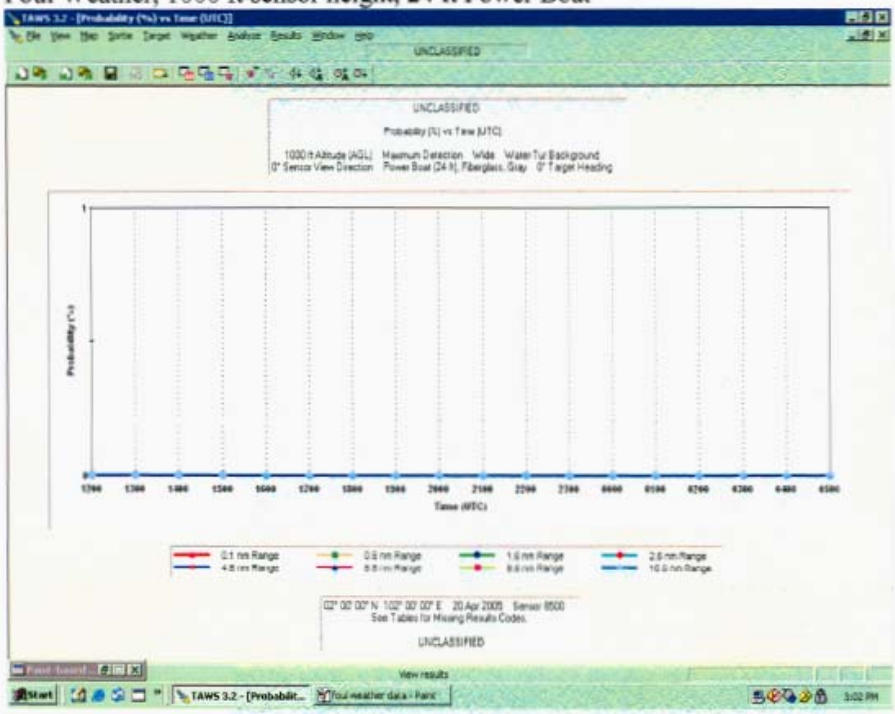
Good Weather, 1000 ft sensor height, 24 ft Power Boat



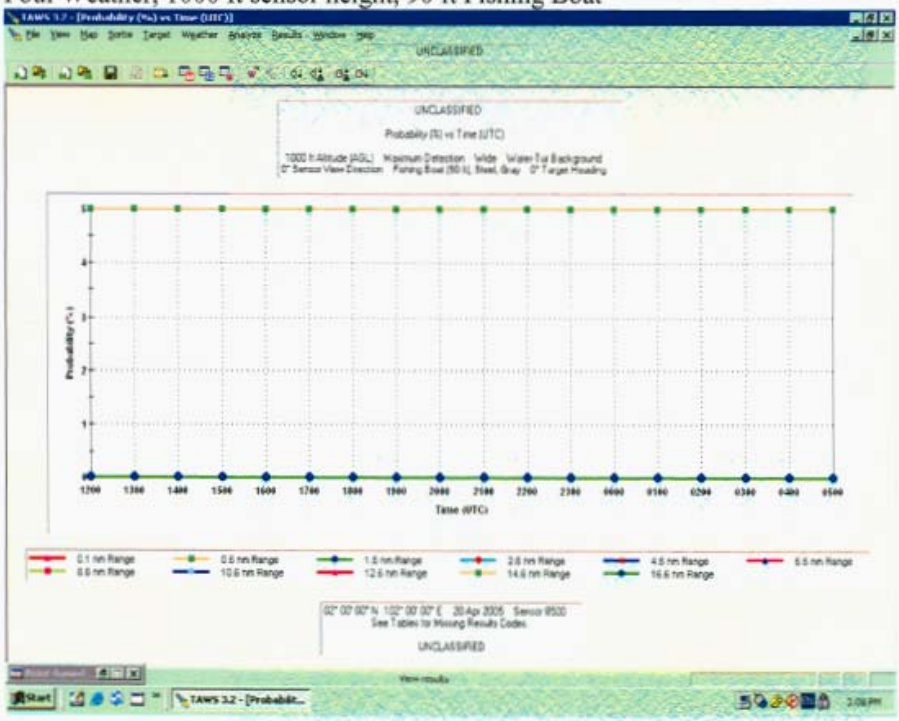
Good Weather, 1000 ft sensor height, 90 ft Fishing Boat



Foul Weather, 1000 ft sensor height, 24 ft Power Boat



Foul Weather, 1000 ft sensor height, 90 ft Fishing Boat



MODELING RESULTS AND SPECIFICATIONS OF LWIR SENSOR

Specifications

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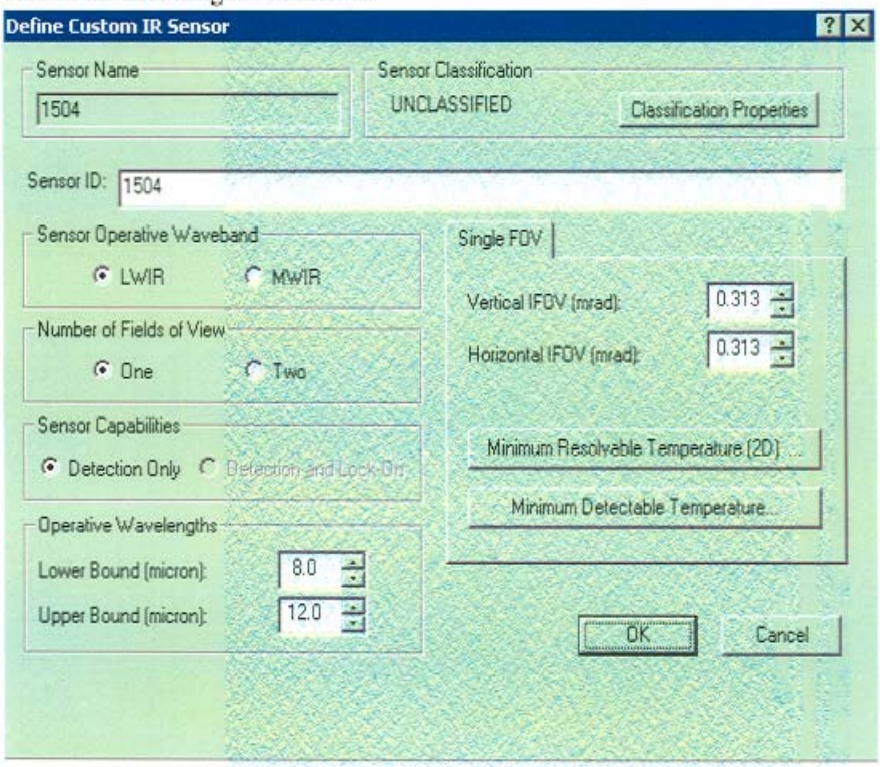
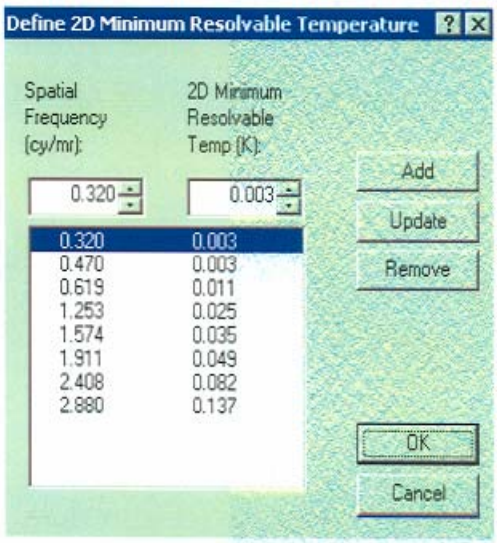
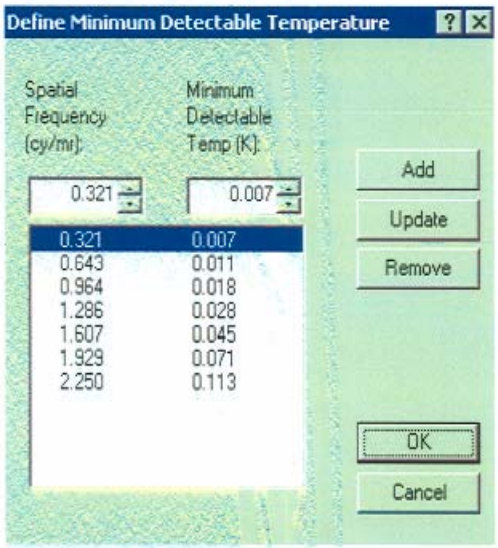
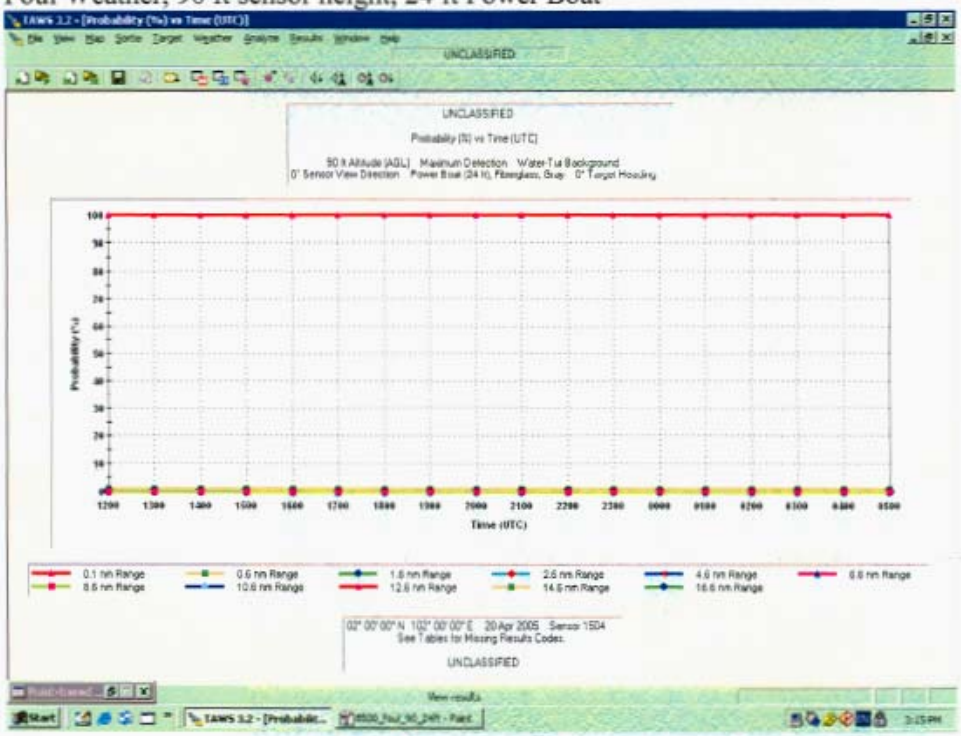


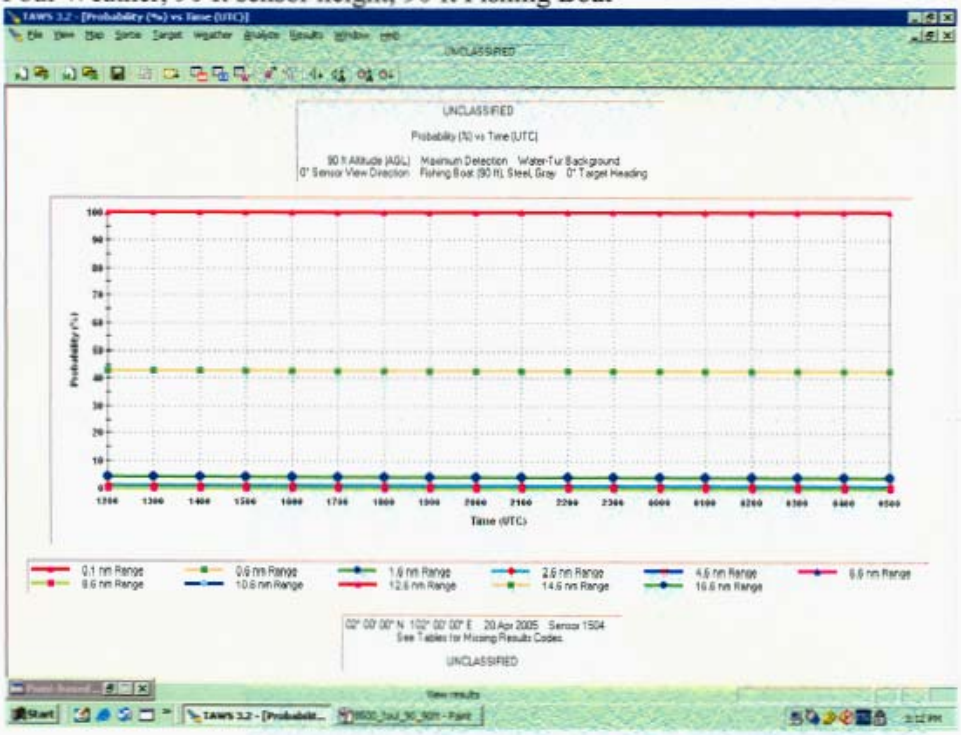




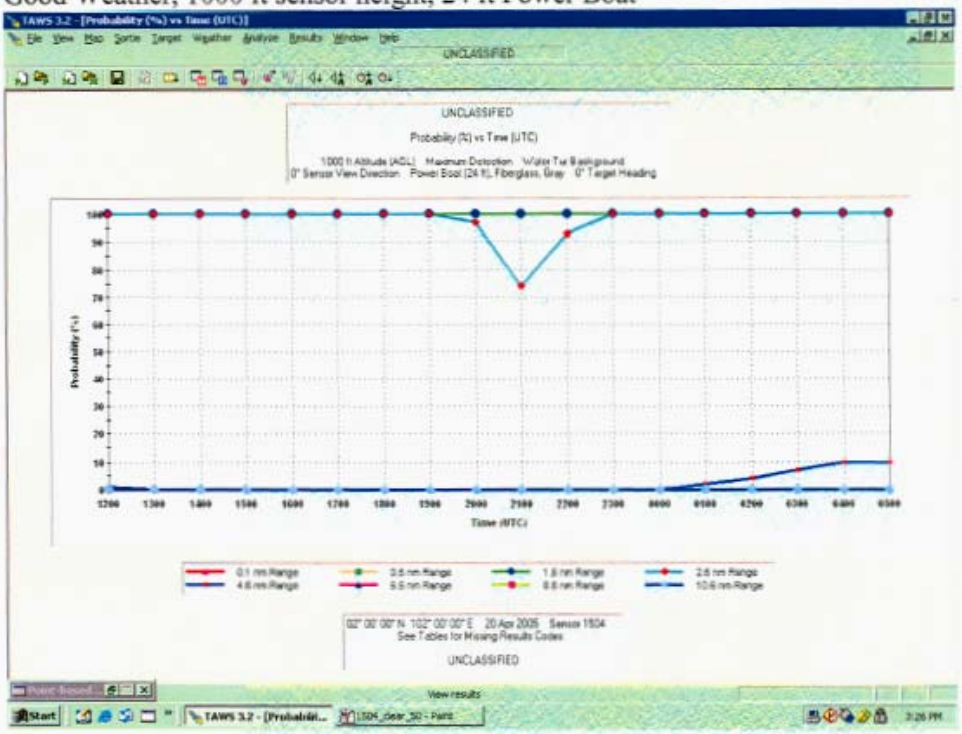
Foul Weather, 90 ft sensor height, 24 ft Power Boat



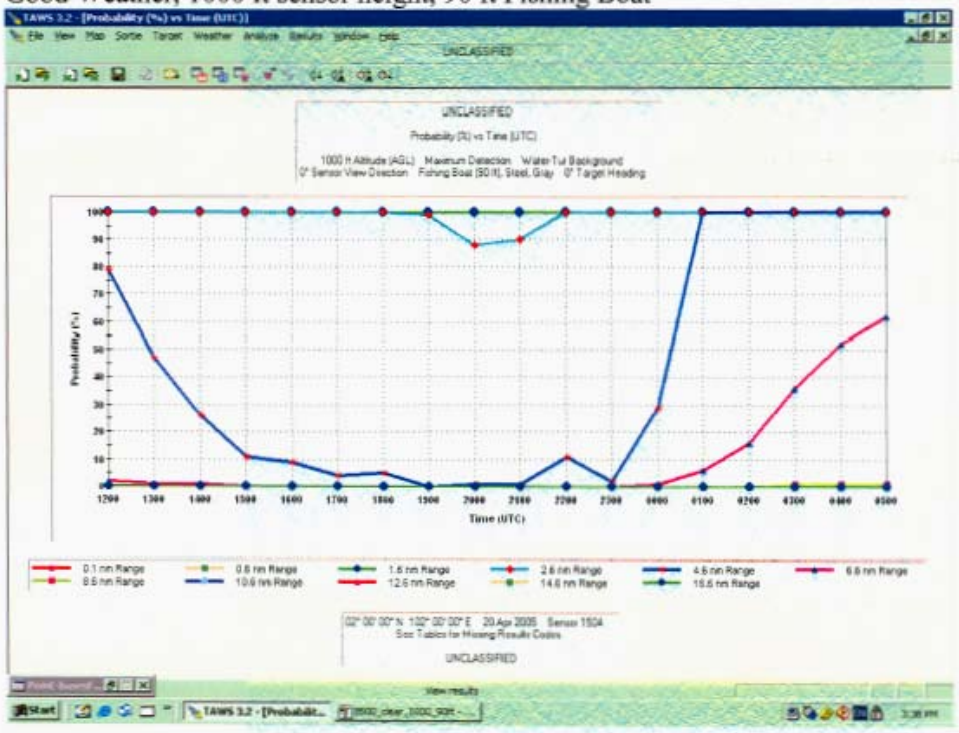
Foul Weather, 90 ft sensor height, 90 ft Fishing Boat



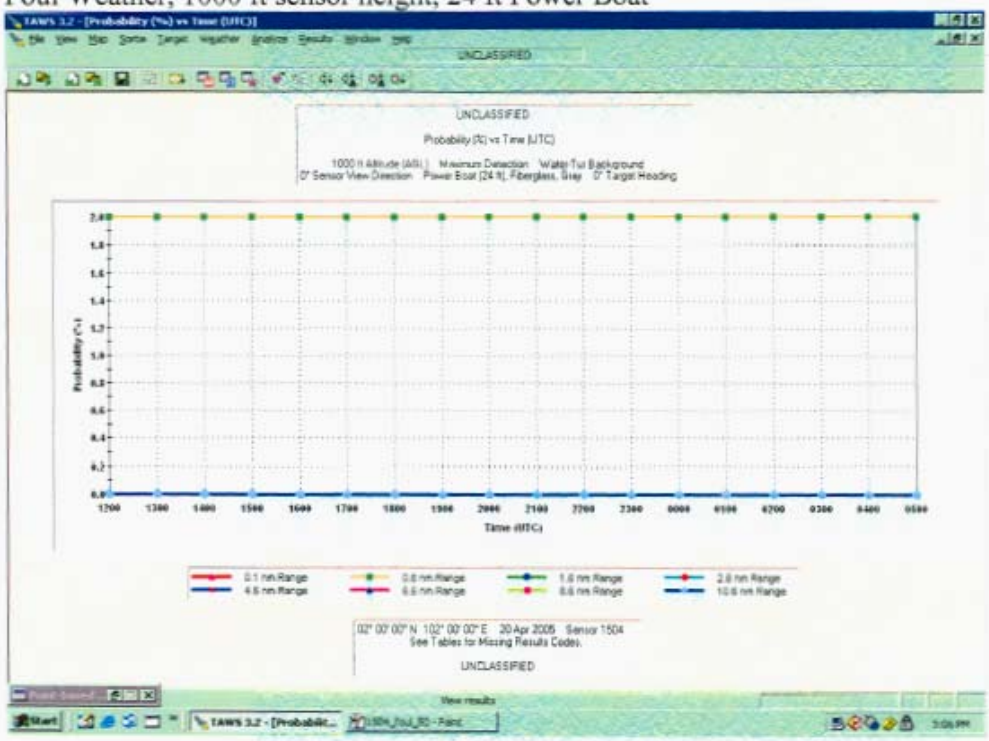
Good Weather, 1000 ft sensor height, 24 ft Power Boat



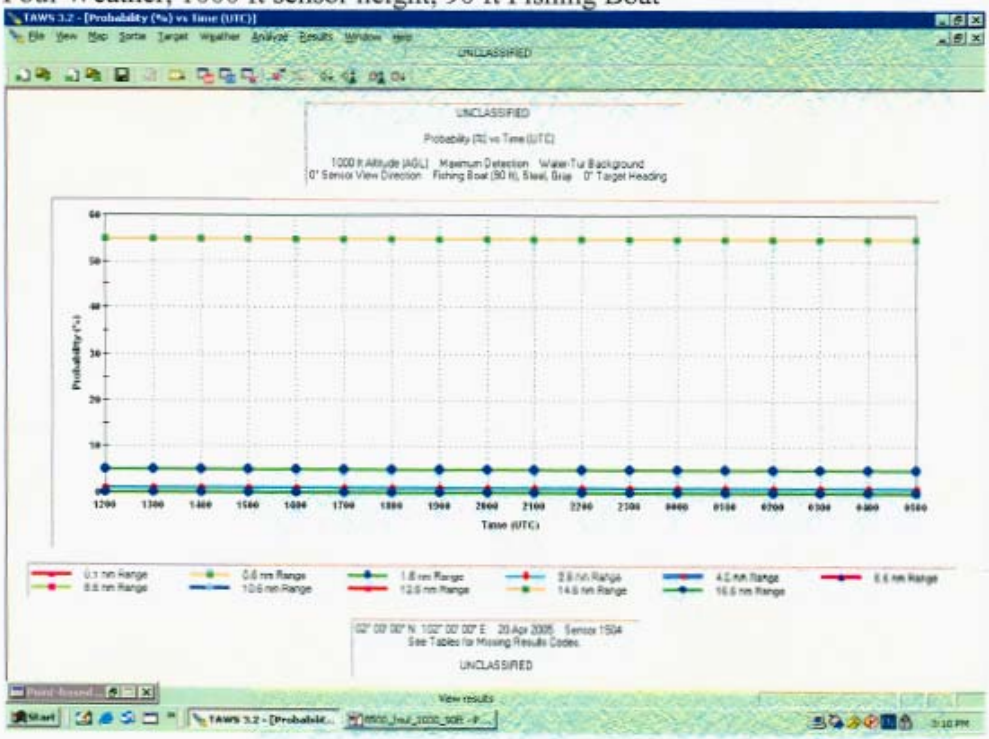
Good Weather, 1000 ft sensor height, 90 ft Fishing Boat



Foul Weather, 1000 ft sensor height, 24 ft Power Boat



Foul Weather, 1000 ft sensor height, 90 ft Fishing Boat



MODELING RESULTS AND SPECIFICATIONS OF TV SENSOR

Specifications

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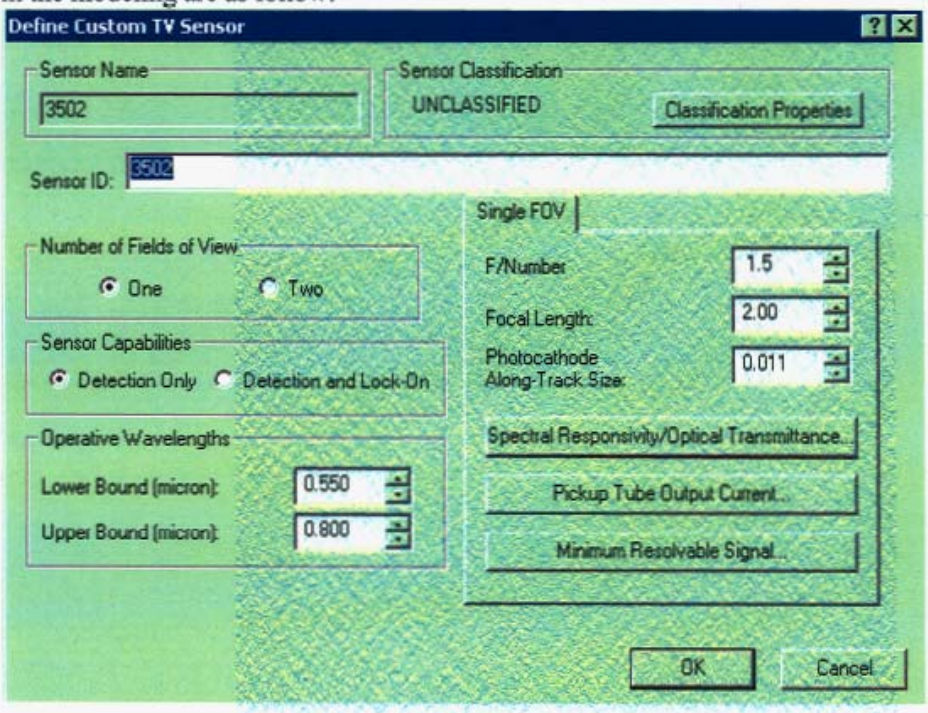
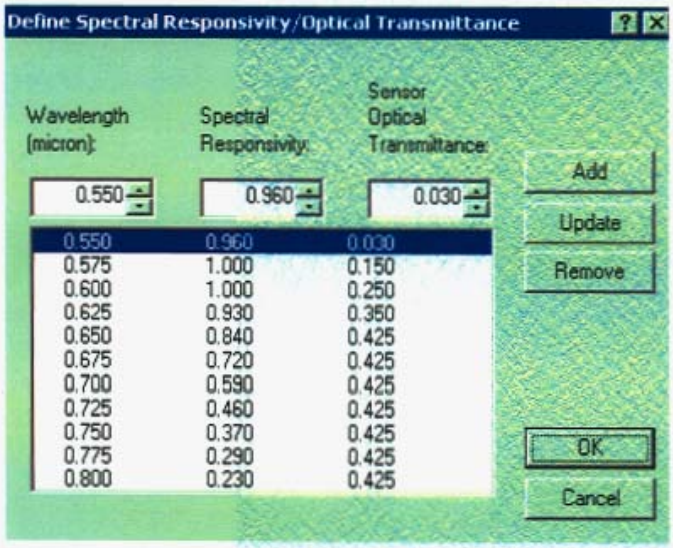
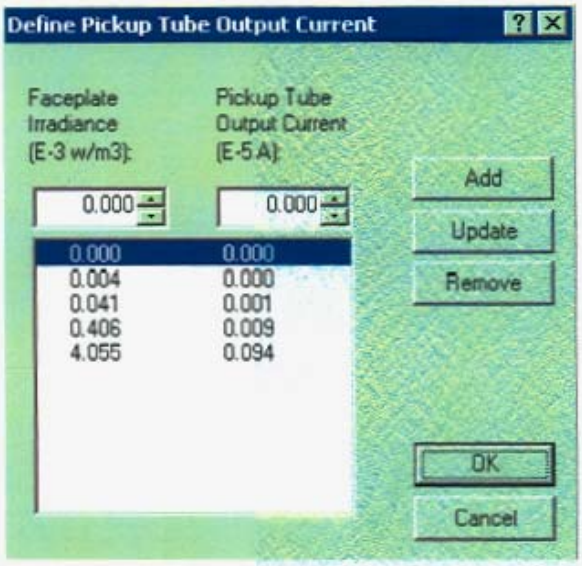
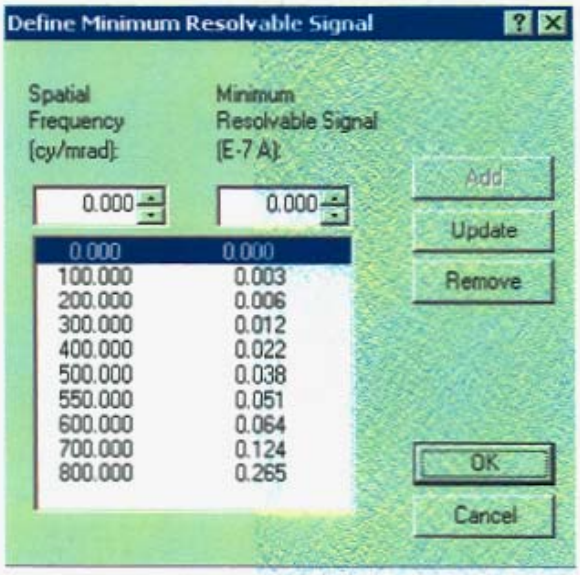


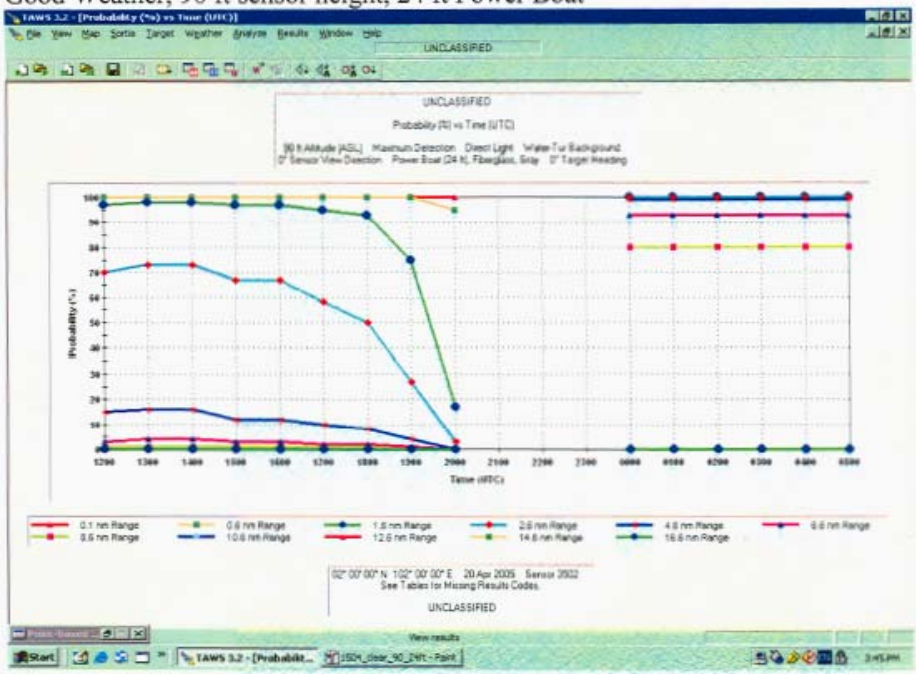



Define Pickup Tube Output Current
Faceplate Irradiance (E-3 w/m3):
Pickup Tube Output Current (E-5 A):
0.000
0.000
Add
Update
Remove
0.000 0.000
0.004 0.000
0.041 0.001
0.406 0.009
4.055 0.094
OK
Cancel

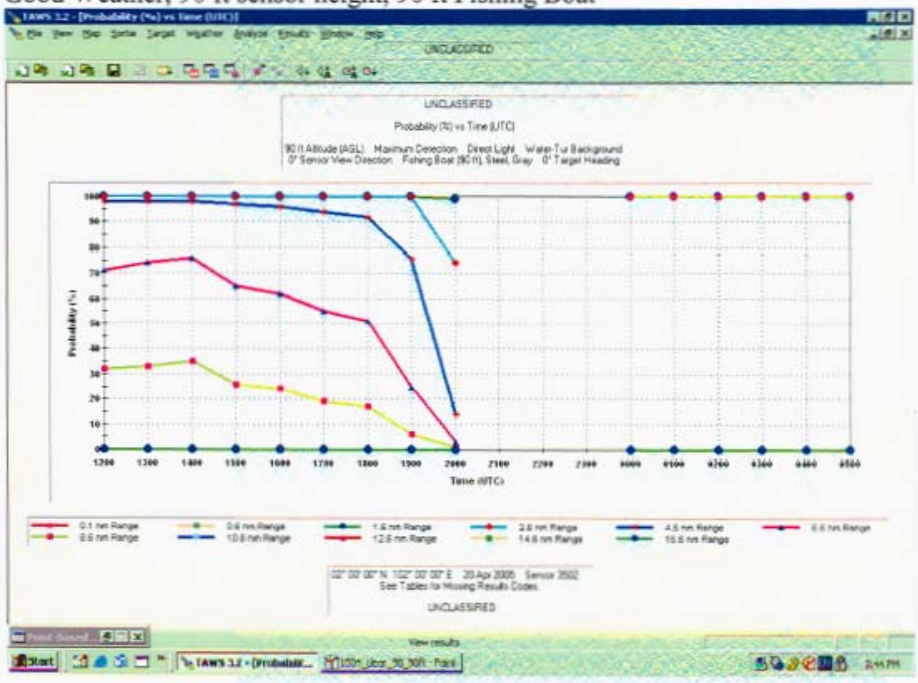

Define Minimum Resolvable Signal
Spatial Frequency (cy/mrad):
Minimum Resolvable Signal (E-7 A):
0.000
0.000
Add
Update
Remove
0.000 0.000
100.000 0.003
200.000 0.006
300.000 0.012
400.000 0.022
500.000 0.038
550.000 0.051
600.000 0.064
700.000 0.124
800.000 0.265
OK
Cancel

Modeling Results (TV Sensor 3502)

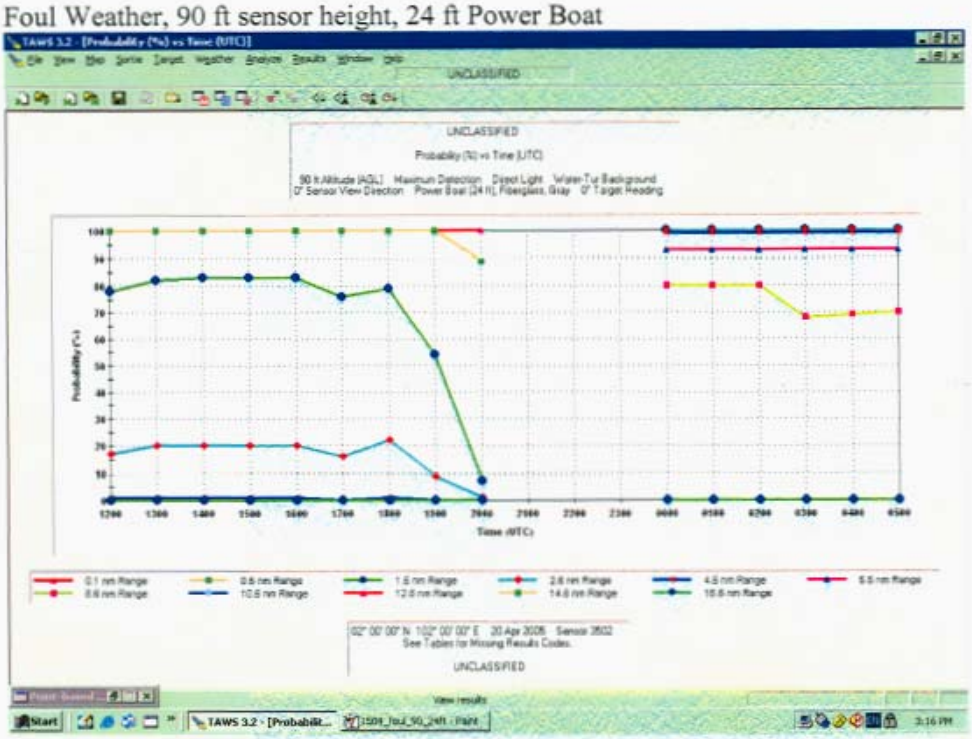
Good Weather, 90 ft sensor height, 24 ft Power Boat



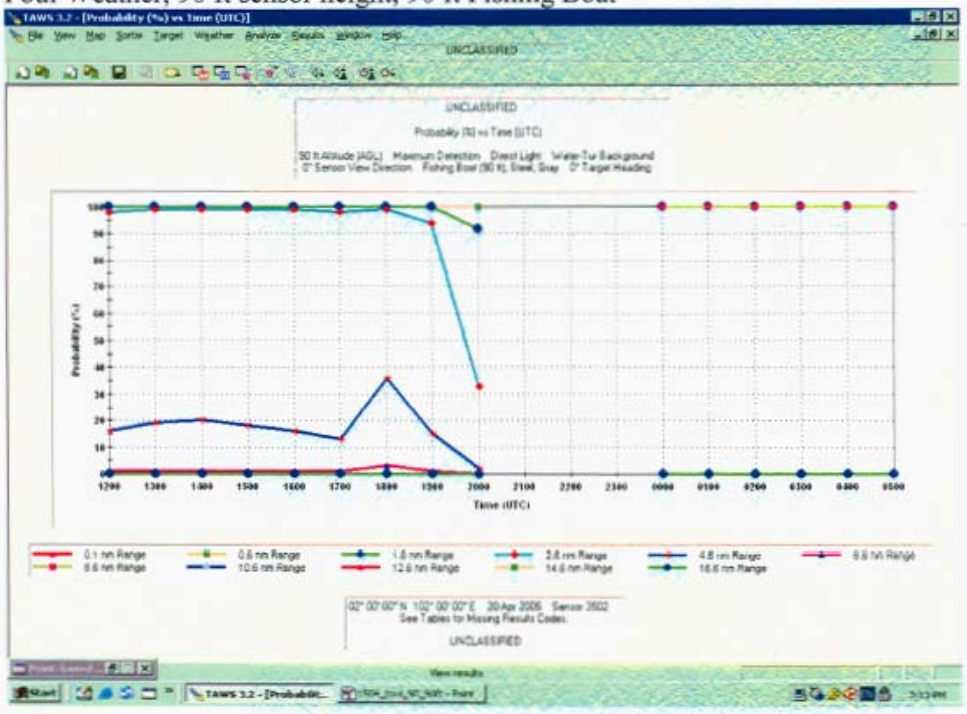
Good Weather, 90 ft sensor height, 90 ft Fishing Boat



Foul Weather, 90 ft sensor height, 24 ft Power Boat

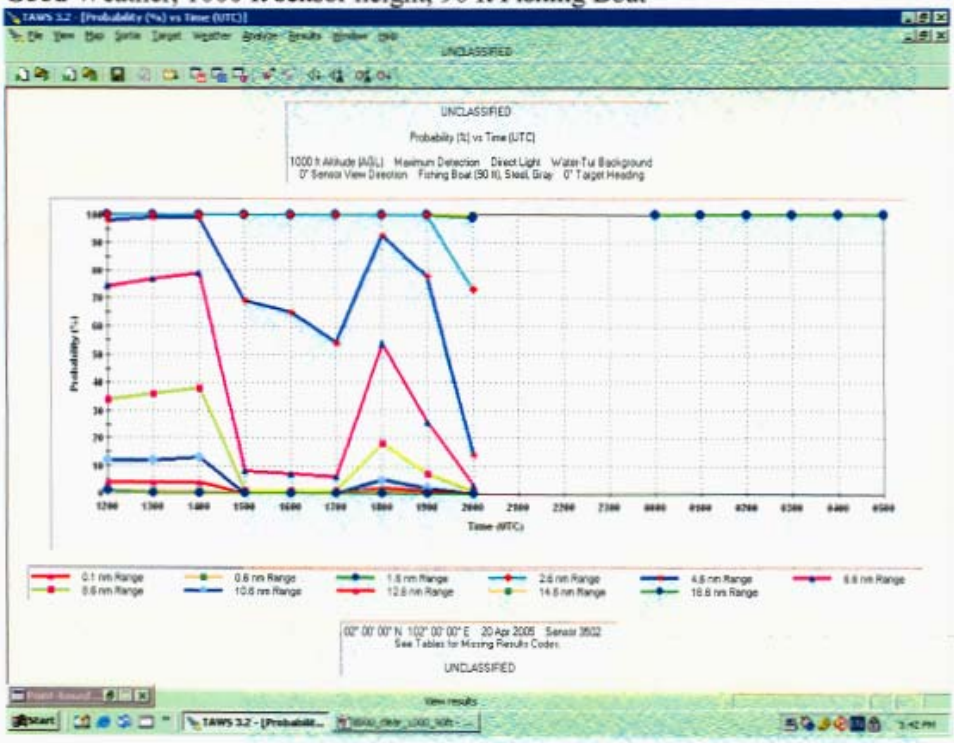


Foul Weather, 90 ft sensor height, 90 ft Fishing Boat

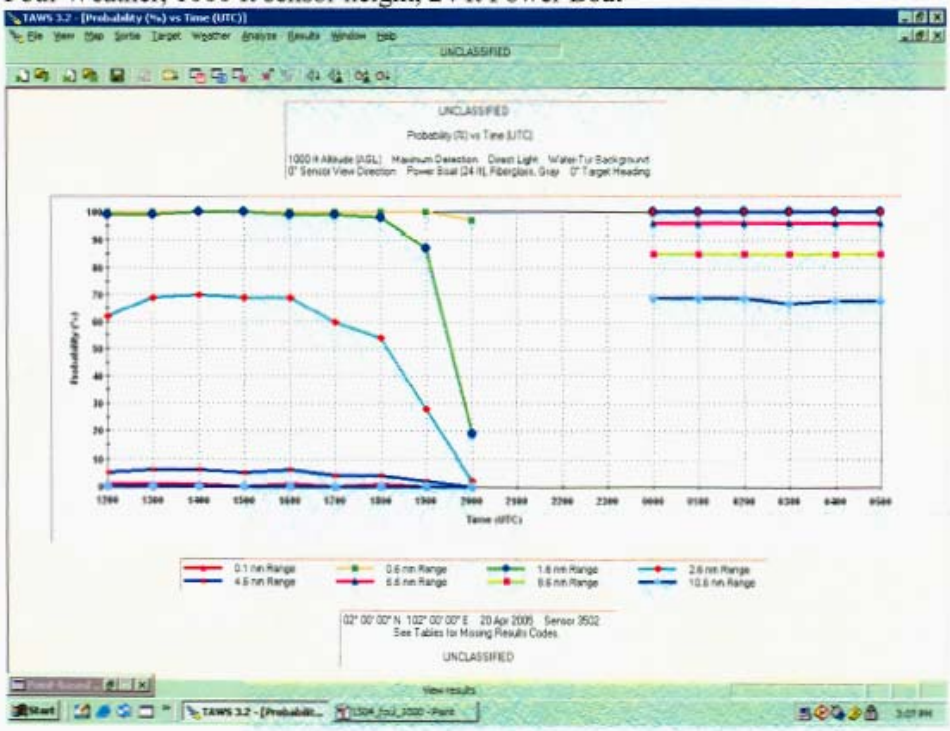


Good Weather, 1000 ft sensor height, 24 ft Power Boat

Good Weather, 1000 ft sensor height, 90 ft Fishing Boat



Foul Weather, 1000 ft sensor height, 24 ft Power Boat



Foul Weather, 1000 ft sensor height, 90 ft Fishing Boat

APPENDIX K: SENSOR GROUP MICROWAVE RADAR MODELING REPORT

Written by Tong, Chin Hong Matthew
20th May 2005

EXPLOITING MICROWAVE RADAR TECHNOLOGY FOR MARITIME DOMAIN PROTECTION IN THE STRAITS OF MALACCA

INTRODUCTION

Microwave radars have traditionally been the only remote sensor capable of providing continuous long range surveillance under all weather conditions. Microwave radar technology is well-researched and widely used globally, making it easily implemented, affordable and hence a "ready" solution for maritime domain protection in the Straits of Malacca. Microwave radars, however, have several inherent limitations. The detection range is limited by the line-of-sight, diurnal changes in weather alter the propagation path dynamically and sea clutter increases the difficulty of detecting small surface targets.

This section investigates the challenges of employing microwave radars for coastal surveillance along the Straits of Malacca. A combination of theory, modeling and experience was used to understand and predict the detection performance of four different microwave radars mounted on four distinct platforms.

The first step in the performance prediction was to study the atmospheric environment along the Straits of Malacca, in particular, the effects of ducting on the propagation of microwaves. Next, several critical parameters in the radar equation were examined before selecting the specific radar systems. Thereafter, the Advanced Refractive Effects Prediction System (AREPS) was used to model the performance of the radar systems within the Straits of Malacca. Finally, the findings were augmented with internet research material.

ATMOSPHERIC DUCTS IN THE STRAITS OF MALACCA

Classical radar theory works on the assumption that electromagnetic waves propagate in a straight line. Spatial variations in temperature, humidity and pressure within the atmosphere, however, can cause the propagation path to bend from a straight line – refraction. Ducts are formed when atmospheric layers refract the propagation path so much that the electromagnetic waves are "trapped" within a narrow region of the troposphere.

Ducts are thus channels in which electromagnetic energy can propagate over extended ranges. A surface duct is formed when meteorological conditions cause a trapping layer to occur such that the base of the resultant duct is at the earth's surface. Two types of surface ducts are discussed below - surface-based ducts and evaporation ducts.

Surface-Based Ducts

Surface-based ducts exist in the lower 1km or so of the atmosphere. They occur when the air aloft is exceptionally warm and dry, compared with the air at the earth's surface. Various meteorological processes can result in surface-based ducts, such as the advection

of warm, continental air over the cooler water surface, the divergence of cool air under a thunderstorm, among many others.

Along the Straits of Malacca, surface-based ducts occur approximately 15% of the time or less, depending on the location and time of the year. Figures 1 and 2 show the percentage occurrence of surface-based ducts and the trapping frequency as observed by a meteorological station in Kuala Lumpur/Subang, Malaysia.

Figure 1: Percentage Occurrence of Surface-Based Ducts as observed in Kuala Lumpur/Subang, Malaysia.

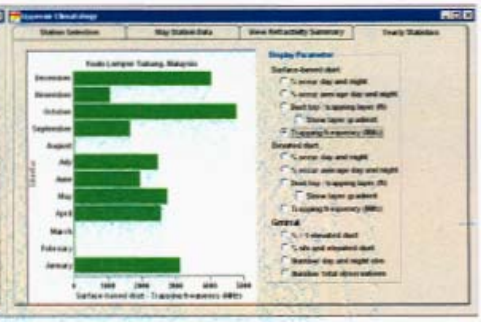


Figure 2: Trapping Frequency of Surface-Based Ducts as observed in Kuala Lumpur/Subang, Malaysia.

Evaporation Ducts

Evaporation Ducts are caused by a rapid decrease in humidity just above the sea surface. Along the Straits of Malacca, evaporation duct heights typically vary from 1 to 35 meters. Evaporation ducts can extend the detection range of radar systems, depending on the antenna location relative to the duct (above, within). Evaporation ducts affect the higher frequencies (above and about 3 GHz), the exact frequency depending on the height of the duct.

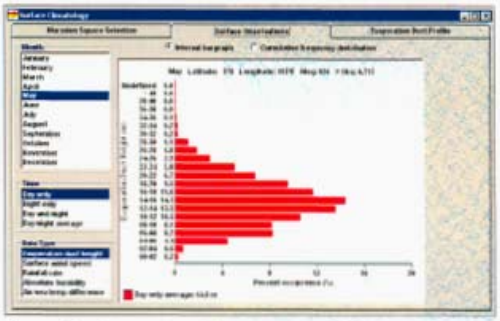


Figure 3: Percentage Occurrence of Evaporation Ducts vs Height as observed in Kuala Lumpur/Subang, Malaysia.

Evaporation ducts almost always exist over the ocean (including the Straits of Malacca). Figure 3 shows the percentage occurrence of evaporation ducts against height as observed by a meteorological station in Kuala Lumpur/Subang, Malaysia.

Written by Tong, Chin Hong Matthew
20th May 2005

MICROWAVE RADAR PARAMETER SELECTION

An important part of radar system design is the specification of the parameters such as frequency, antenna dimensions and transmitter power. A good basis for determining such parameters is the radar range equation.

$$R_{max}^4 = \frac{P_t G A_e \sigma}{(4\pi) k T_0 B_n F_n (S/N)}$$

In practice, however, the radar equation can yield results which are far from accurate, with a tendency to overestimate the maximum range of the radar. This failure of the basic radar equation is because many of the parameters in the equation (receiver noise, target radar cross-section, propagation loss, etc) are statistical in nature and cannot adequately be described by a single number. As a result, this sub-section will not attempt to discuss the complexities of parameter selection in detail but rather outline a few principles that guided the sensor team in radar and platform selection.

Frequency/Wavelength – Combining Experience and "Common Sense"

Selecting the frequency of the radar is one of the most critical and difficult issues. The frequency does not appear explicitly in the fundamental form of the radar equation – but it is implicit in almost every radar parameter. Some radar parameters are more favorable at the lower frequencies (e.g. weather effects, ability to achieve high power, atmospheric attenuation) while others are more readily obtained at the higher frequencies (e.g. narrow antenna bandwidths, freedom from cosmic noise).

A search through the multitude of modern radar systems employed globally indicated that most coastal surveillance radar systems (particularly those in the Straits of Malacca) operate in the S-band (2 to 4 GHz) or X-band (8 to 12 GHz). Of these two options, the S-band appeared to achieve slightly greater ranges (attributed to its lower frequency) while the X-band appeared to achieve better resolution (attributed to its higher frequency). Radar systems, such as the FURUNO system, that allow switching between the two frequency-bands are commercially available and commonly used.

Antenna Height – The Major Factor Limiting Radar Range

Microwaves in the 1 to 10 GHz frequency bands propagate in a line-of-sight (in the absence of ducting) from the transmitting antenna. As a result, the effective range of shore-based microwave radars is limited by the inability of microwave radars to see beyond the horizon. Range is therefore determined by the height above sea-level of the shore based radar antenna. With an antenna elevation of 400ft, the predicted maximum range is around 30 nautical miles. To extend the range to 50 nautical miles, the antenna elevation has to increase to over 1500ft.

	Radar Horizon [nm]	Target Horizon [nm]
Radar Height = 60 m		
Target Height = 1 m	17.2	19.5
Target Height = 3 m	17.2	21.1

Figure 4: Antenna Height Dependence of Radar Range [7].

In the modeling process, the "height-of-the-eye" proved to be the major factor in limiting the range of the radars. Subsequently, much effort was invested into studying the feasibility of raising the antenna height, such as through the use of tethered aerostats.

Target Characteristics – Discriminating Between Small Targets and Sea Clutter

A target is characterized by its Radar Cross Section (RCS) and the fluctuations in RCS. Formally, the RCS is defined as the ratio between the power scattered by the target back towards the receiving antenna and the power density hitting the target.

There is, however, no simple relation between the physical area of the target and the RCS, as the reflected power depends on the angle of incidence as well as target properties such as material (conducting/non-conducting), coating, physical shape (smooth/sharp corners), etc. The total reflection from a target is made up from the "elementary" reflections from different parts of the targets. These elementary reflections will interfere constructively or destructively to form the total reflection. Therefore, small changes in attitude of the target may change the amount of reflected power dramatically.

In particular, fluctuations in target RCS can make small surface targets difficult to detect in sea clutter. On the other hand, although these uncertain fluctuations in RCS appear to be a disadvantage, techniques to overcome and even exploit them are presented later in the section. In essence, different types of wanted targets (e.g. ships, fast surface craft, etc) and unwanted targets (e.g. sea clutter, rain, birds, etc) have different statistical distributions. These differences can be exploited in the radar signal processing to enhance target visibility.

For the purposes of modeling, three simplified RCS values were used:

Representative Vessel	RCS [m^2]
Inflatable	**4**
Ship	**800**
Super Tanker	**10,000**

Resolution – Critical in Congested Waterways

The Straits of Malacca is known to be one of the most congested waterways in the world. Subsequently, having a high resolution is critical, especially to detect hostile small craft amongst many legitimate fishing boats.

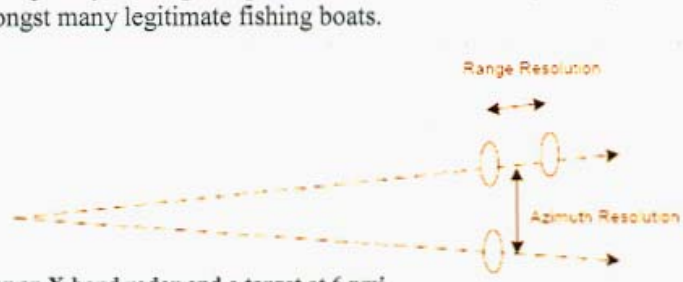


Figure 5: Depiction of Angular and Range Resolution [7].

For an X-band radar and a target at 6 nmi,

Beamwidth[°]	Antenna Dim[ft]	Angular Resolution [m]
0.41	18	80
0.37	21	61

Angular Resolution

Angular resolution can broadly be defined as the 3dB azimuth beamwidth of the radar antenna. Good angular resolution is not as easy to achieve as good range resolution, requiring a trade-off in the size of the antenna[1]. Rough trigonometric calculations indicate that given a beamwidth of 0.41° for a 18ft (fan beam) antenna, the angular resolution is approximately 80 meters at a range of 6 nautical miles. Similarly, a 0.37° beamwidth for a 21ft (fan beam) antenna gives an angular resolution of 61 meters at a range of 6 nautical miles.

Range Resolution

The range resolution is determined by the transmitted pulse width, rise/fall time, dispersion along the signal path, multiple path reflections, digitalization by sampling and even the display pixel resolution.

The theoretical range resolution for small point targets is 7.5 m for a 50 ns ideal pulse width and 150 m for 1000 ns pulses. Rise/fall time and dispersion will typically add 3 to 5 meters. 40 MHz sampling may further add 4 meters. Multipath effects may add another 5 meters. This gives the following discrimination (estimated) for small point targets. Numbers are rounded up to the nearest 5 meters. The display pixel resolution is not yet included.

Transmitter Pulse Width [ns]	Approximate Range Resolution [m]
330	65
120	30
50	18

[1] Beamwidth, $\theta[°] \approx 65\lambda / L$, where L is the antenna dimension [m], λ is the wavelength [m].

RADAR SYSTEMS SELECTED

The parameters examined above, though not exhaustive, were used as guidelines in selecting the specific radar systems for modeling. The following four radars and platforms were decided upon.

Possible New Generation Low-Altitude Coastal Surveillance System

Radar : SCANTER2001 (X-/S-Band)
Platform : Coastal Tower (400ft)

Possible New Generation High-Altitude Coastal Surveillance System

Radar : APS-143 (X-Band)
Platform : Aerostat (5000ft)

Existing Mobile Coastal Surveillance System (also proposed for use in future)

Radar : APS-137 (X-Band)
Platform : Maritime Patrol Aircraft (3000ft)

Existing Low-Altitude Coastal Surveillance System ("as-is" system)

Radar : FURUNO (S-/X-Band)
Platform : Coastal Tower (400ft)

RESULTS AND ANALYSIS OF MODELING USING THE ADVANCED REFRACTIVE EFFECTS PREDICTION SYSTEM (AREPS)

The specific parameters of the individual radar systems were gleaned from their respective datasheets and entered into AREPS. The following data was used for all the modeling runs:

Terrain : Digital Terrain Elevation Data (DTED) Level 0.
Environment : Meteorological data from the Department of Meteorology of the Naval Postgraduate School.

In addition, a probability of false alarm ($P_{FALSE\ ALARM}$) of 1×10^{-8} was used.

Exploiting Surface-Based Ducts and Evaporation Ducts to Extend Radar Detection?

Figures 6 and 7 depict the effects of surface-based ducts and evaporation ducts on radar detection ranges. The specifics of the radar system are shown on the right of the graphs. Observe that both surface-based ducts and evaporation ducts appear to extend the detection ranges of the X-band radar (mounted on a 90ft tall coastal tower) for surface targets.

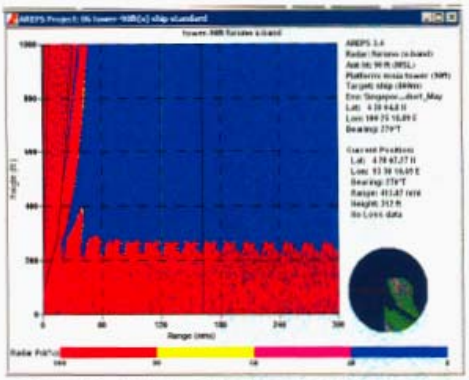


Figure 6: Effects of Surface-Based Ducts on Radar Performance. Observe that the detection range is extended beyond 300nmi for altitudes below 200ft.

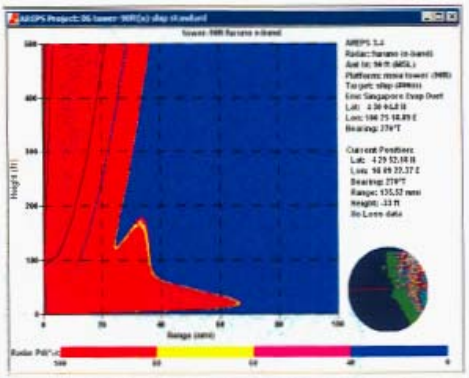


Figure 7: Effects of Evaporation Ducts on Radar Performance. Observe that the detection range is significantly extended, especially for altitudes below 50ft.

Surface-Based Ducts – Infrequent and Unpredictable

Despite the apparent attractiveness of exploiting surface-based ducts to enhance radar detection performance, in reality, the effects of surface-based ducts are difficult to predict. Although the duct acts like a waveguide for the electromagnetic energy, this "waveguide" does not have rigid or impermeable boundaries. Therefore, energy is continually "leaking" from the duct.

As a result, it is exceedingly difficult to exploit surface-based ducts for radar detection. In addition, surface-based ducts occur less than 15% of the time along the Straits of Malacca, making it infeasible to rely on them for continuous extended coverage. On the other hand, if and when surface-based ducts do occur, their presence is expected to enhance radar operations aimed at detecting targets on the sea surface.

Evaporation Ducts – Lower Radar, Longer Range?

Evaporation ducts, on the other hand, are almost always present over the Straits of Malacca. Conceptually, a radar with a high enough frequency could have a longer range in the evaporation duct than if it was positioned above the duct – contrary to conventional wisdom (i.e. higher radar, longer range)!

There are, naturally, other factors that make it difficult to exploit evaporation ducts for continuous extended detection ranges. These include:

> Sea Clutter. A radar system that operates within the height of the evaporation duct will invariably experience strong signal returns from sea clutter. Conventional wisdom will require the radar operator to decrease the sensitivity to achieve a higher signal-to-noise ratio – effectively and inadvertently decreasing the detection range.

"Leaking" of Signals. Similar to the surface-based duct, evaporation ducts do not have rigid or impermeable boundaries. Therefore, energy is continually "leaking" from the duct. In addition, although less energy may be lost in the vertical dimension, there will still be horizontal spreading of energy and hence a substantial loss nonetheless.

Which is Better: Higher or Lower? Conceivably, there will be a point where the advantage of being higher outweighs the advantage of being within the duct. While it is not clear where this point is, what this study shows is that the least detection range is expected to occur just above the region affected by evaporation – and that is NOT where the radar system should be located.

Predicted Ranges for Selected Radar Systems and the Associated Platforms

Figure 8 presents the probability of detection against predicted ranges for the selected radar systems mounted on the associated platforms. These results reflect the expected ranges when there is no temperature inversion above the surface of the Straits of Malacca, i.e. no surface-based ducts or evaporation ducts. Since surface-based ducts and evaporation ducts extend the detection ranges of targets on the sea surface, the *"worse-case"* scenario is actually modeled by excluding them.

From Figure 8, we observe that the major factor limiting the detection ranges of the radar systems appear to be the "height-of-the-eye".

Figures 9 to 16 show the propagation pattern and probability of detection vs predicted range for each of the individual radar systems. This information was used to estimate the number of radar systems and associated platforms that were needed for the overall sensor architecture.

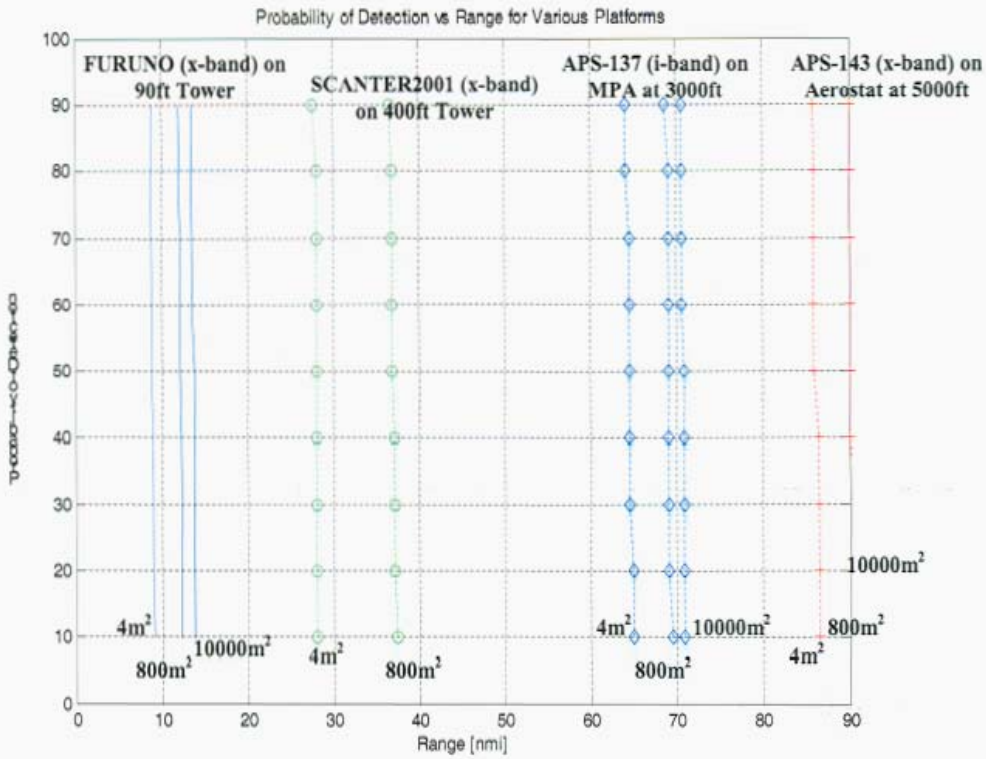


Figure 8: Probability of Detection vs Predicted Ranges for Selected Radar Systems and the Associated Platforms for Varying Target RCS.

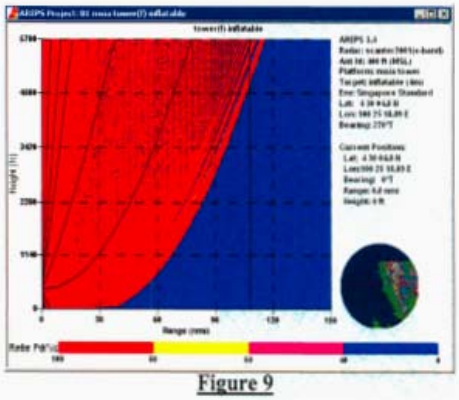


Figure 9

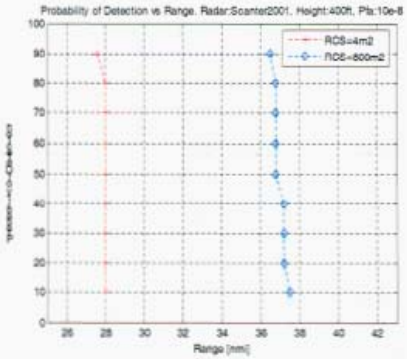


Figure 10

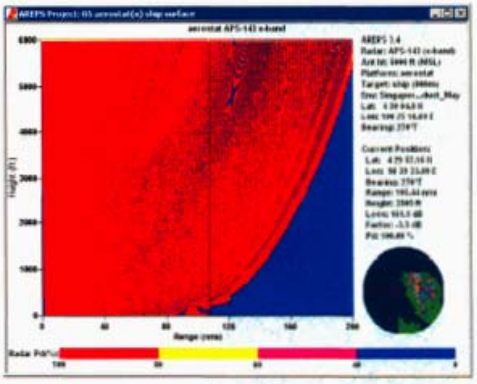


Figure 11

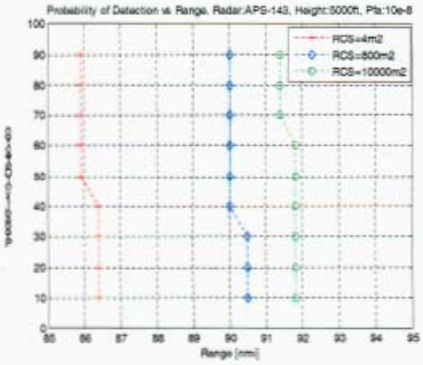


Figure 12

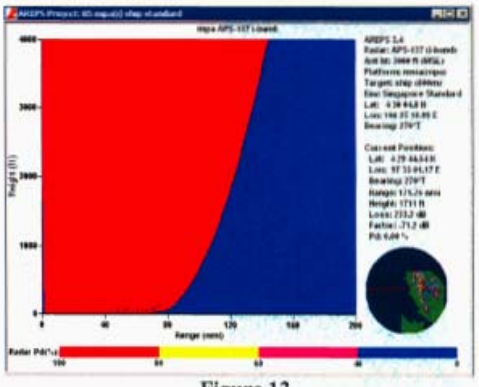


Figure 13

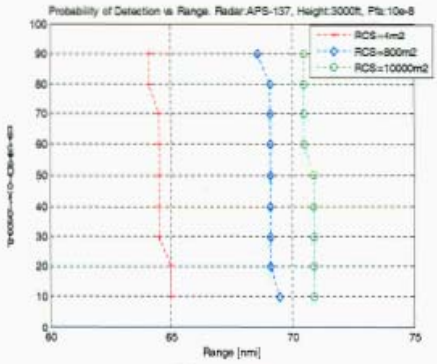


Figure 14

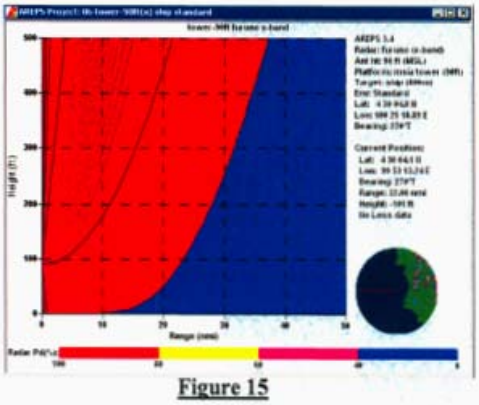


Figure 15

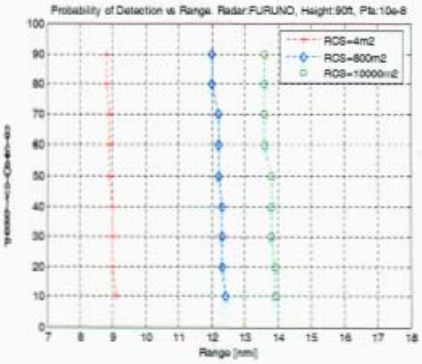


Figure 16

Written by Tong, Chin Hong Matthew
20th May 2005

TECHNIQUES TO ENHANCE DETECTION OF SMALL TARGETS IN SEA CLUTTER

Sea clutter is a subject that has already been widely researched amongst radar academics and engineers alike. One of the key tasks of the sensor architecture, however, is to detect small, fast moving surface targets. As such, the radar group believes that sea clutter is an important enough topic to discuss explicitly.

Small target detection in sea clutter is a highly demanding task and requires the use of various radar techniques to successfully discriminate between target and sea returns. The radar must continuously adapt to the changing environment to maximize the probability of detection of targets whilst controlling false alarms. Sea clutter is difficult to suppress, since it has high correlation between two successive sweeps of the radar. There are, however, three possible techniques to de-correlate sea clutter, all of which require the use of two beams:

Frequency Diversity

Frequency Diversity refers to the sequential transmission on two different frequencies. The idea is that the property of the sea clutter from the same place is dependent upon frequency. Theoretical analysis indicates that when the clutter echo consists of large amounts of scatterers, such as rain or the sea surface, the correlation between the returned signals will be very small. In addition, target fluctuations are reduced after integration of signals from independent pulses and the total transmitted power will be the total combined power of the two pulses. The combined effect of frequency diversity processing is reduced fluctuation of desirable targets and enhancements of targets relative to the clutter. Figure 17 shows the possible improvement in small target detection using frequency diversity.

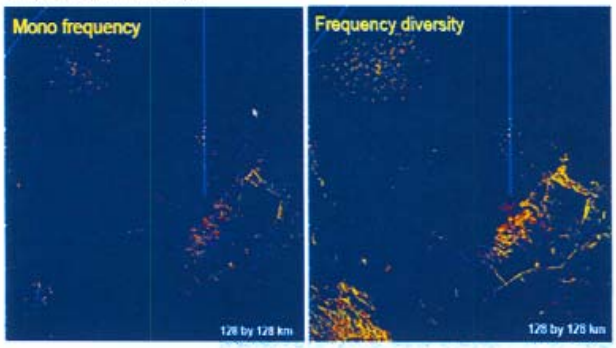


Figure 17: Improvement in Small Target Detection using Frequency Diversity.

Polarization Diversity

If the two beams are also in a quadrature polarization state, the clutter echoes from the same place on the sea will theoretically also have quadrature polarizations that are independent – hence more easily de-correlated.

Time Diversity

Sea clutter is most strongly correlated in the time domain. It is possible to de-correlate the sea clutter by irradiating the same spot with two sequential beams. Experiments by the Nanjing Research Institute of Electronics Technology, China, shows that when the frequency difference is 400MHz and the antenna scans in clockwise at a speed of 13.5 rpm, the time difference generated by beam 1 and 2 irradiating the same place successively is 36.8ms. According to statistical data, the correlation time of sea clutter is approximately 4 to 10 ms (at sea state 3). Therefore, when the time difference is larger than 10ms, the sea clutter may be de-correlated.

All radar de-correlation signal processing have inherent limitations. For example, frequency diversity is effective in de-correlating clutter from rain and the sea surface, but only in more favorable sea states. Polarization diversity is effective in worse sea states. Time diversity can effectively de-correlate both sea clutter and noise. As a result, synthetic utilization of three kinds of diversity processing could conceivably achieve considerable improvement in detecting small targets in sea clutter.

CONCLUSION

Microwave radars are a "ready" solution to provide all-weather, continuous coastal surveillance in the Straits of Malacca. Microwave radar technology is well-established and the relevant expertise is easily available, making it easy and affordable to quickly implement a network of coastal surveillance radars along the Straits of Malacca. Modeling results indicate that the height of the antenna is one of the primary factors that limit the performance of the radar systems. As a result, efforts should be invested in solutions that can increase the "height-of-the-eye" significantly.

Deploying microwave radar installations along the Straits of Malacca will face other challenges that have not been discussed in this section, such as (1) the electromagnetic interference from the high density shipping in the straits will significantly impact the operation of a large network of radar installations, and (2) the vulnerability of static microwave radar installations to attacks, particularly attacks coordinated with maritime terrorism.

RECOMMENDATIONS

The following studies have been identified as possible approaches to enhance the performance of microwave coastal surveillance radars along the Straits of Malacca:

(1) Exploitation of evaporation ducts using low or variable height antennas to extend the detection range of high frequency radars.

(2) Feasibility of high altitude platforms, such as aerostats, within the Straits of Malacca to achieve higher antenna heights and hence greater detection ranges.

(3) Impact of electromagnetic interference from high density shipping on the operations of a large network of microwave coastal surveillance radars.

(4) Feasibility of combining three different types of diversity processing (frequency, polarization and time) to enhance the detection of small surface targets in sea clutter.

ACKNOWLEDGEMENTS

The radar group wishes to thank Professor Kenneth Davidson and Professor Peter Guest for their invaluable guidance and helpful suggestions.

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APPENDIX L: SENSOR GROUP HFSWR MODELING REPORT

High Frequency Surface Wave Radar (HFSWR)

and

Advanced Refractive Effects Prediction System (AREPS)

By Winston Ong

INTRODUCTION

High frequency surface wave radar (HFSWR), known for its capability of detecting surface targets over an ocean surface at distances beyond the horizon of a co-located microwave radar system is a key candidate for providing the long range surveillance on the Strait of Malacca maritime domain. The referenced system is the prototype Raytheon's SWR305 system installed on Canada's east coast, where it is being used to demonstrate continuous, all weather surveillance to beyond 200nm.

This section investigates the suitability of employing high-frequency surface wave radar (HFSWR) for monitoring sea surface activity out to 200nm range along the Strait of Malacca. The investigation will focus on studying the propagation pattern and losses in the lower end of the high frequency (HF) band along the Strait of Malacca.

For this purpose, the sensor-radar group is using the Advanced Refractive Effects Prediction System (AREPS) to model and predict the HF propagation losses in the area of Strait of Malacca.

CHARACTERISTICS OF RADIO WAVE PROPAGATION

Radio signals in the lower wave bands travel by two basic means. The first is known as a ground wave, and the second a sky wave.

GROUND WAVE AKA SURFACE WAVE

Ground wave radio propagation is used mainly on the MF to lower end of HF band. It might be expected that the signal would travel out in a straight line. However it is affected by the proximity of the earth, it is found that the signal tends to follow the earth's curvature. This occurs because currents are induced in the surface of the earth and this slows down the wave front close to the ground. This results in the wave front tilting downward, enabling it to follow the curvature of the earth and travel beyond the horizon.

Ground wave propagation becomes less effective as the frequency rises. The actual coverage is affected by a variety of factors including the transmitter power, the type of antenna, and the terrain over which the signal is travelling. Signals also leave the earth's surface and travel towards the ionosphere, some of these are returned to earth. These signals are termed sky waves for obvious reason.

SKY WAVE

When a sky wave leaves the earth's surface and travels upwards, the first layer of interest that it reaches in the ionosphere is called the D layer. This layer attenuates the signals as they pass through. The level of attenuation depends on the frequency. Low frequencies are attenuated more than higher ones. This means that low frequency

signals are often prevented from reaching the higher layers, except at night when the layer disappears.

(Further information on this section can be found in Appendix 1 - Characteristics of Radio Wave Propagation.)

AREPS

THE TOOL

In response to a request from Commander, Sixth Fleet during the Bosnian campaign, a new assessment system, the Advanced Refractive Effects Prediction System (AREPS) was developed and fielded to aid in the computation and prediction of the performance of EM radars and transmitters.

AREPS computes and displays radar probability of detection, propagation loss and signal-to-noise ratios, electronic-support-measures (ESM) vulnerability, UHF/VHF/HF communications, and surface-borne surface search radar capability vs. range, height, and bearing from the transmitter. At the core of AREPS is the Advanced Propagation Model (APM), a hybrid ray-optic and parabolic equation (PE) model that uses the complementary strengths of both methods to construct a fast yet very accurate composite model. APM considers absorption of electromagnetic energy by oxygen and water vapor. APM accounts for all normal propagation mechanisms, including troposcatter and the anomalous propagation mechanisms of sub-refraction, super-refraction, and ducting.

AREPS is an unclassified program and, hence the possibility for it to be used in commercial application such as this study. Also since AREPS do not have pre-defined classified databases, it allows users to create or amend system parameter database appropriate to their situation. AREPS capabilities include antenna radiation patterns of specific system height-finder antennas and a user-defined antenna pattern. Detection threshold calculations include radars using incoherent and coherent integration techniques. In addition to pulsed radar systems, users may enter continuous wave and other non-pulsed systems, UHF and VHF communications systems, ESM receivers, and radar target descriptions.

TERRAIN DATA

AREPS derives its terrain height data primarily from the Digital Terrain Elevation Data (DTED) provided by the National Imagery and Mapping Agency (NIMA), available either on CD-ROM or from the NIMA Internet homepage. DTED data are provided in level 0, level 1, and level 2 formats. Level 0 data spacing is 30 arc seconds in horizontal resolution (approximately 1 km). DTED level 0 data are unlimited distribution and has been used in this study.

ENVIRONMENTAL INPUT

Atmospheric data may be derived from World Meteorological Organization (WMO) upper air observations and the entry of environmental data into AREPS is completely automated. For those without access to observational data in the WMO format, AREPS contains options to import observational data in a generic column format. Should real-time data be unavailable, AREPS contains a climatology of ducting conditions taken from 921 observing stations worldwide. With the release of AREPS version 3.0, environmental data may now be obtained from mesoscale numerical meteorological models such as the Coupled Ocean and Atmosphere Mesoscale

Prediction System (COAMPS). Thus, for the first time, predictions of systems' performance based on future atmospheric conditions are possible, giving the operator

FINDINGS AND RESULTS FROM AREPS

PROPAGATION LOSSES IN STRAIT OF MALACCA

The propagation of the electromagnetic waves on the surface of the sea depends on its frequency in great measure. The results from AREPS are compiled and shown in the chart below giving an idea of the predicted propagation losses suffered by different HF frequencies along the Strait of Malacca. It can be seen that it is possible to obtain an efficient propagation using low values of high frequency with vertical polarization, in the range of 3-5 MHz and this makes possible the propagation of the electromagnetic wave over the surface of the ocean well beyond the horizon, which assists in obtaining the desired long range coverage. For 10-18MHz band, the attenuation is high hence operation in this band would be expected to be of shorter range.

HF Surface Wave propagation loss

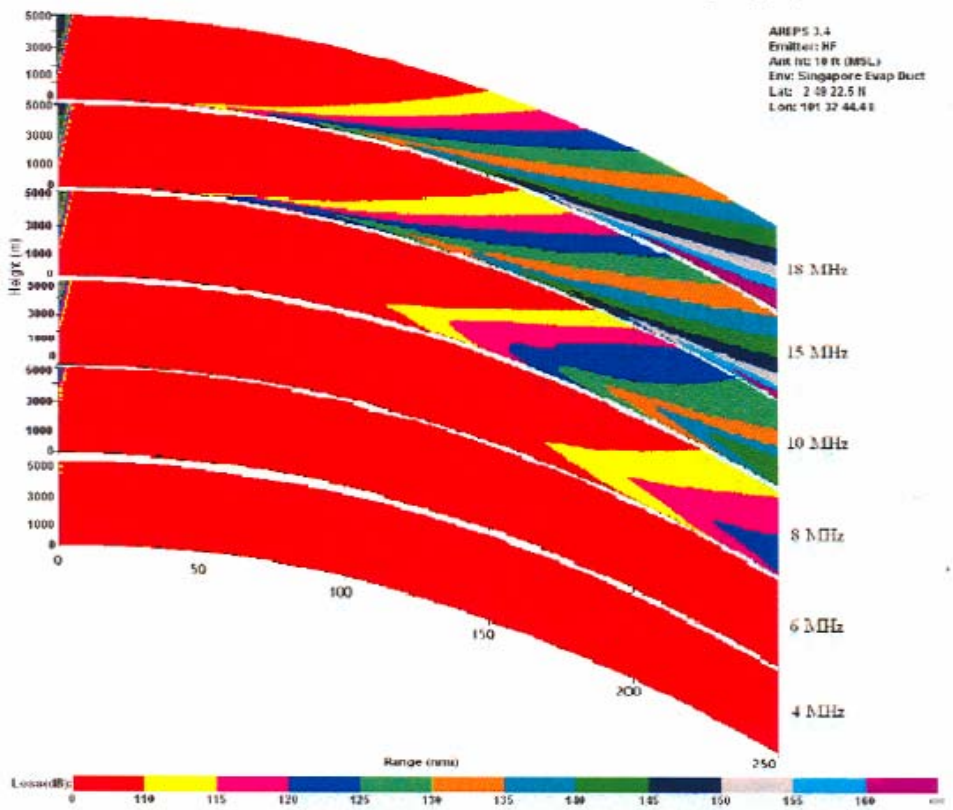

Figure 1: AREPS ground wave prediction for the Strait of Malacca region

Note: The above is not a direct modeling of the propagation loss for a typical HF surface wave radar. The results obtain from AREPS are one way propagation losses for vertically polarized HF waves meant for communication. For a complete and definitive study, it would be necessary to take into consideration two way path-loss as well as target RCS and its aspect angle. Nonetheless the current result would be indicative enough for assessing the most efficient propagation frequency and its potential losses.

SKY WAVE INTERFERENCE

The Ionosphere changes during nighttime decreasing its absorptive capacity, and for that reason, the HF signals from other distant sources along with the echo reach the antenna, causing interference. Hence it is important to take into consideration the geographic location of HFSWR site, related with the propagation characteristics of the ionosphere.

The optimum value of an HF frequency that will be reflected by the ionosphere over Strait of Malacca maybe significantly different of those values for the location of the radar stations in Canada. And AREPS was able to predict optimum HF frequencies with regard to the ionosphere over Strait of Malacca. This is essential in understanding the potential sky wave interference in the Strait of Malacca.

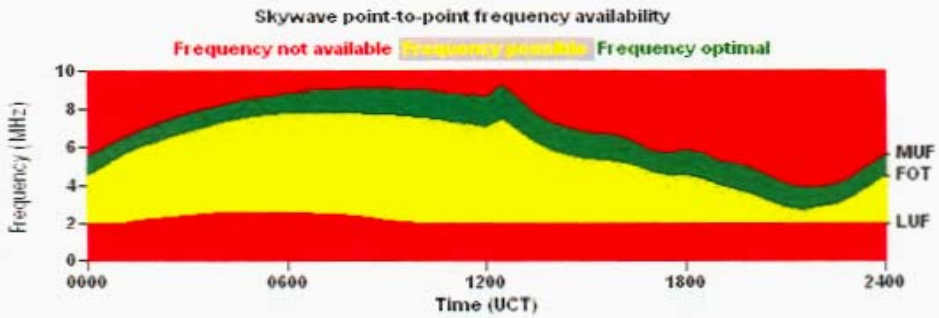

Figure 2: AREPS sky wave prediction in the month of April for the Strait of Malacca region.

For interpretation of the chart above – The green band represent region where HF frequency would be optimally reflected by the ionosphere. This chart is produced by AREPS to indicate the optimum HF frequency to use for point to point sky wave communication. Using this chart one can have a feel which are the frequencies that will be reflected by the ionosphere and cause sky wave interference for the HFSWR operating in that frequency band.

From the above AREPS predictions, it is apparent that at night after 1830hrs, the 3-5 MHz frequency band would be within the optimum reflection frequency band and hence would be greatly affected the sky wave interference.

OTHER INTERFERENCE CONSIDERATION

In addition, the High Frequency spectrum is crowded by civilian and military users, which is a very important reason to carefully select the radar's working frequency, in order to avoid interferences and the consequent degradation in the system performance.

CONCLUSION AND RECOMMENDATION

From the investigation, it is found that although the Ionosphere affects the 3-5MHz band propagation degrading its performance during nighttime, but the benefit of long range detection far out weighs its current limitation and advanced signal processing techniques will continuously bring about better tolerance against interference and noise and provide improvement in its overall detection capability. For long range detection above 150nm radius, it is more desirable to use the 3-5MHz band.

However for mid range surveillance, where range radius does not exceed 150nm, 10-18MHz should be considered. This is because at that frequency, it is less dependent on ionospheric condition and provides better detection capability against smaller targets.

The capability of the HFSWR to detect surface targets at ranges beyond 200 nautical miles, working continuously 365 days of the year with low operating cost is encouraging. However, it is necessary to take into account the decrease of performance that affects the radar to detect targets of less than 1,000 tons when the conditions of the sea are not optimal. In addition, High Frequency spectrum is crowded by civilian and military users, which is very important in order to avoid cross party interference.

Taking these parameters under consideration, it will be necessary to test its operational capabilities at the designated sites, due to the different propagation conditions of the ground and of the Ionosphere as well as other man-made interference over Strait of Malacca. Such tests could be performed in similar ways as the tests that are being performed in the United States (using a mobile station at different locations during six months to detect small targets.)

With the above pre-cautionary step, it can then be determined if HFSWR is suitable for operation in the Strait of Malacca.

APPENDIXES

1) Characteristic of radio wave propagation
2) Additional information on Raytheon's SWR-503.

REFERENCES

Product Brochures;

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CHARACTERISTIC OF RADIO WAVE PROPAGATION

Radio signals in the lower wave bands travel by two basic means. The first is known as a ground wave, and the second a sky wave.

GROUND WAVE AKA SURFACE WAVE

Ground wave radio propagation is used mainly on the MF to lower end HF band. It might be expected that the signal would travel out in a straight line. However it is affected by the proximity of the earth it is found that the signal tends to follow the earth's curvature. This occurs because currents are induced in the surface of the earth and this slows down the wave front close to the ground. This results in the wave front tilting downward, enabling it to follow the curvature of the earth and travel beyond the horizon.

Ground wave propagation becomes less effective as the frequency rises. The actual coverage is affected by a variety of factors including the transmitter power, the type of antenna, and the terrain over which the signal is travelling. Signals also leave the earth's surface and travel towards the ionosphere, some of these are returned to earth. These signals are termed sky waves for obvious reason.

SKY WAVE

When a sky wave leaves the earth's surface and travels upwards, the first layer of interest that it reaches in the ionosphere is called the D layer. This layer attenuates the signals as they pass through. The level of attenuation depends on the frequency. Low frequencies are attenuated more than higher ones. In fact it is found that the attenuation varies as the inverse square of the frequency, i.e. doubling the frequency reduces the level of attenuation by a factor of four. This means that low frequency signals are often prevented from reaching the higher layers, except at night when the layer disappears.

D Layer

The D layer attenuates signals because the radio signals cause the free electrons in the layer to vibrate. As they vibrate the electrons collide with molecules, and at each collision there is a small loss of energy. With countless millions of electrons vibrating, the amount of energy loss becomes noticeable and manifests itself as a reduction in the overall signal level. The amount of signal loss is dependent upon a number of factors: One is the number of gas molecules that are present. The greater the number of gas molecules, the higher the number of collisions and hence the higher the attenuation. The level of ionisation is also very important. The higher the level of ionisation, the greater the number of electrons that vibrate and collide with molecules. The third main factor is the frequency of the signal. As the frequency increases, the wavelength of the vibration shortens, and the number of collisions between the free electrons and gas molecules decreases. As a result signals lower in the frequency spectrum are attenuated far more than those which are higher in frequency. Even so high frequency signals still suffer some reduction in signal strength.

E and F Layers

Once a signal passes through the D layer, it travels on and reaches first the E, and next the F layers. At the altitude where these layers are found the air density is very much less, and this means that when the free electrons are excited by radio signals and vibrate, far fewer collisions occur. As a result the way in which these layers act is somewhat different. The electrons are again set in motion by the radio signal, but they tend to re-radiate it. As the signal is travelling in an area where the density of electrons is increasing, the further it progresses into the layer, the signal is refracted away from the area of higher electron density. In the case of HF signals, this refraction is often sufficient to bend them back to earth. In effect it appears that the layer has "reflected" the signal. The tendency for this reflection is dependent upon the frequency and the angle of incidence. As the frequency increases, it is found that the amount of refraction decreases until a frequency is reached where the signals pass through the layer and on to the next. Eventually a point is reached where the signal passes through all the layers and on into outer space.

Different frequencies

To gain a better idea of how the ionosphere acts on radio signals it is worth viewing what happens to a signal if the frequency is increased across the frequency spectrum. First it starts with a signal in the medium wave broadcast band. During the day signals on these frequencies only propagate using the

ground wave. Any signals that reach the D layer are absorbed. However at night as the D layer disappears signals reach the other layers and may be heard over much greater distances.

If the frequency of the signal is increased, a point is reached where the signal starts to penetrate the D layer and signals reach the E layer. Here it is reflected and will pass back through the D layer and return to earth a considerable distance away from the transmitter.

As the frequency is increased further the signal is refracted less and less by the E layer and eventually it passes right through. It then reaches the F1 layer and here it may be reflected passing back through the D and E layers to reach the earth again. As the F1 layer is higher than the E layer the distance reached will be greater than that for an E layer reflection.

Finally as the frequency rises still further the signal will eventually pass through the F1 layer and onto the F2 layer. This is the highest of the layers reflecting layers in the ionosphere and the distances reached using this are the greatest. As a rough guide the maximum skip distance for the E layer is around 2500 km and 5000 km for the F2 layer.

ADDITIONAL INFORMATION ON RAYTHEON'S SWR-503.

From the performance testing conducted by Raytheon, it is possible to obtain the following information about the SWR-503 operating capability:

Range;

Big ships (3000 tons or more), have been detected at a range beyond 200 nautical miles during daytime.

Smaller ships (1000 tons) can be detected without problems when the sea state is low, but it is not possible to establish a range prediction for this type of target, due to variations that they show in their construction, especially in regards to the height of the superstructure.

Nominal resolution; is the capabilities of a radar system to distinguish between two targets close one to another. The radar detects the targets providing three parameters, namely: range, bearing and speed.

1. The range resolution depends directly on the bandwidth of the beam transmitted. Since the HFSWR works with a bandwidth less than 20 Hz, this resolution is estimated in 4 nautical miles.
2. The bearing resolution is directly proportional to the aperture size of the receiving antenna. For an array of 16 receiving elements, a resolution of 9° is estimated.
3. The speed resolution is estimated in 0.5 knots for moving targets and 0.05 knots for stationary targets.

The probability to detect 2 distinct targets matching the three parameters is not very high, however, in case of this occurs the radar will follow up the target with the bigger echo until, they get separated.

Probability of detection; It is very high, utilizing the advanced signal processing techniques of this radar system.

Precision; The position of the target can be estimated with a very high grade of precision (potentially up to one tenth of the nominal resolution values), due also to the signal processing techniques of the radar system.

APPENDIX M: TDSI OR MODELING REPORT

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

OR MODELING OF MARITIME DOMAIN PROTECTION IN THE STRAITS OF MALACCA

by

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June 2005

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Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE Jun 05	3. REPORT TYPE AND DATES COVERED Technical Report

4. TITLE AND SUBTITLE: Title (Mix case letters)	5. FUNDING NUMBERS
6. AUTHOR(S)	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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OR MODELING OF MARITIME DOMAIN PROTECTION REACTIONARY FORCE

by

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ABSTRACT

This study focuses on Operations Research (OR) modeling and analysis conducted in support of a campus-wide integrated project for developing a conceptual system of systems to provide maritime domain protection in the Strait of Malacca in the year 2020. The study features models supporting unmanned aerial vehicles, force disposition and search techniques to support this mission. The paper discusses problem definition, solution methodologies—including optimization, simulation, and analytical modeling—and insights.

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ABSTRACT

This study focuses on Operations Research (OR) modeling and analysis conducted in support of a campus-wide integrated project for developing a conceptual system of systems to conduct Maritime Domain Protection in the Strait of Malacca and Singapore Strait. The study features models supporting sea cargo inspection, unmanned aerial vehicles, and reactionary force for small boat attack. The paper discusses problem definition, solution methodologies—including optimization, simulation, and analytical modeling—and insights.

I. INTRODUCTION

Maritime Domain Protection (MDP) in the Straits of Malacca and Singapore covers various areas of maritime operations, including defense against Small Boat Attack (SBA), a Ship as a Weapon (SAW), and Weapons of Mass Destruction (WMD). The Operations Research (OR) Group used operational analysis and modeling and simulation to generate insights and facilitate resource allocation decisions for the sensors, force, and ship inspection areas of the System of Systems (SoS). The specific focus of the OR group was:

1. Sea Cargo Inspection. The problem is how to inspect shipping in a methodical manner that will pose the minimum delay on vessels' arrival at the Port of Singapore, while being reasonably confident that there are no nuclear weapons traversing the Straits. Discrete event simulation was used to determine the average time delay incurred by a vessel to its destination port when penalized by an off-shore checkpoint platform that conducts external monitoring of shipping as vessels travel past the platform. Additionally, the study addresses the operational effectiveness of a "last-ditch" ship-threat detection scheme in a final layer of threat detection and provides a notional sensor deployment scheme to obtain a probability of timely detection and optimal sensor coverage.

2. Protection from SBA in the Approach Area Employing Unmanned Aerial Vehicles (UAVs). The problem is to provide effective coverage of the approach area to the Strait of Malacca where conventional sensing alternatives are limited for detecting small boats. The OR Group explored the possibility of using UAVs to provide sensor coverage of vessels approaching the shipping lanes. The group conducted a study to propose sensor coverage areas, coverage method alternatives, and numbers of UAVs needed through analytical analysis and discrete event simulation.

3. Reactionary Force for SBA. This study explored force configurations and alternatives to ensure a certain level of success to neutralize a hostile small boat before successfully reaching its target. The OR Group used Map-Aware Non-uniform Automata (MANA), agent based modeling, to build scenarios representing different MDP force alternatives.

The OR Group's analysis yielded insights into these specific issues applicable to the overall goal of designing a conceptual SoS architecture to conduct Maritime Domain Protection in the Straits of Malacca and Singapore. These models and analyses proved useful to the entire project.

II. SEA CARGO INSPECTION EFFORTS

1. BACKGROUND

The detonation of a nuclear weapon on U.S. soil is the most feared type of terrorist attack that we face and will continue to face as long as terrorist networks are in existence. As technology becomes more advanced, terrorist organizations will use this to their advantage to successfully smuggle Nuclear, Biological, and Chemical (NBC) devices or conventional explosives, and explode them causing catastrophic damage to their intended targets. To prevent this, we need to take advantage of technological developments to successfully detect these nuclear devices before they arrive at the debarkation ports.

The ideal plan would be for every container ship to be monitored twenty-four hours a day, seven days a week, but as we know, this is not practical. Hence, we must deploy technological developments in a way that will increase our probability of detection with a low false alarm rate that does not significantly slow down world trade.

There are already in place many layers of protection. For example, container mechanical seals, which allow remote verification of serial numbers but require manual validation that the seal is intact. However, this type of protection can easily be defeated. With that on mind, General Electrics and SAVI Technology are now testing "Smart Container Technology", which incorporates anti-tampering, intrusion, tracking, communications, and reporting elements that give stakeholders the location and status of the cargo in real time.

In this technological age, the goal is to maintain tactical advantage over the adversary using a robust layered security system to effectively prevent or deter terrorist organizations from the importation of illicit nuclear materials in shipping containers.[1]

2. PROBLEM STATEMENT

The Department of Homeland Security cannot be too modest in implementing a series of security system strategies away from home and in the vicinity of debarkation ports for the detection of nuclear devices being smuggled into our homeland undetected.

This Operations Research (OR) Group's study is two-fold as per the System Engineering Analysis (SEA) Project scenario.

3. OFF-SHORE PLATFORM IN THE STRAIT OF MALACCA

The first study investigates the impact on the flow of shipping by strategically positioning an off-shore platform in the Strait of Malacca which is considered to be a "chokepoint", that is, a location that limits the flow of shipping and cannot be easily bypassed. This implies that any alternative to the chokepoint involves a level of detour or the use of a different route that amounts to substantial financial cost and time delays. Chokepoints are defined by several characteristics that impact voyage time, cost, and risk. The chokepoint is used as a "checkpoint" allowing for the external monitoring of shipping as it moves past the platform.

3.1 Assumptions

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[1] L. M. Wein, A. H. Wilkins, M. Baveja, and S. E. Flynn, "Preventing the Importation of Illicit Nuclear Materials in Shipping Containers".

This platform incorporates several sensors in a drive-by sensing scheme. Sensors included on the platform are: density screening devices, gamma imaging devices, neutron detection devices, platform mounted hull imaging devices (SONAR), and Sodium Iodide (NaI) detectors in channel buoys. The platform is placed 300 nautical miles (nm) from the Port of Singapore to allow active Inspection Teams to be placed onboard vessels that fail the checkpoint inspection, i.e., the sensor(s) detect the presence of some type of NBC material or conventional explosive residue.

When the vessels approach the platform, they are to call and check in with the checkpoint. Vessels approaching the checkpoint are expected to maintain 1 nm distance between each other and slow down to five knots in preparation for passing past the inspection point. If there are no ships currently in the queue, the ship can slow down to 5 knots when it is 1 nm from the checkpoint. The checkpoint designated distance is 1.6 nm. Vessels triggering a detection alarm will be directed to join a queue where an active Inspection Team will board the ship to do a complete container inspection using handheld equipment. The Group assumes that an average of one hour delay will be assessed from the time the ship was flagged to the time the Inspection Team boards the vessel provided Inspection Team availability. If no Inspection Team is available, the ship will need to wait until an Inspection Team is available. Once the team is onboard, the vessel can proceed as scheduled on course and speed to its destination port. If nothing is found, the Inspection Team will disembark on arrival in Singapore. Again an hour is estimated to unload the Inspection Team and their equipment and return to the off-shore platform at 30 knots. On the other hand, if weapon signatures persist, then the vessel will be directed to an anchorage area for a more detailed inspection.

It is estimated that approximately 25,000 commercial shipping vessels per year transit the Strait of Malacca en route to Singapore at speeds between 15 and 25 knots. This is approximately three vessels per hour transiting the strait transporting oil and container/bulk cargo.

The purpose of this study is to illustrate the average time delay of a vessel to its destination port arrival, Port of Singapore, penalized by the checkpoint system. The probability that the ship is selected for inspection is the system probability of false alarm because the objective of the study is to capture both the traffic and effects of delay caused by the off-shore platform system. Figure 1 depicts the off-shore platform model.

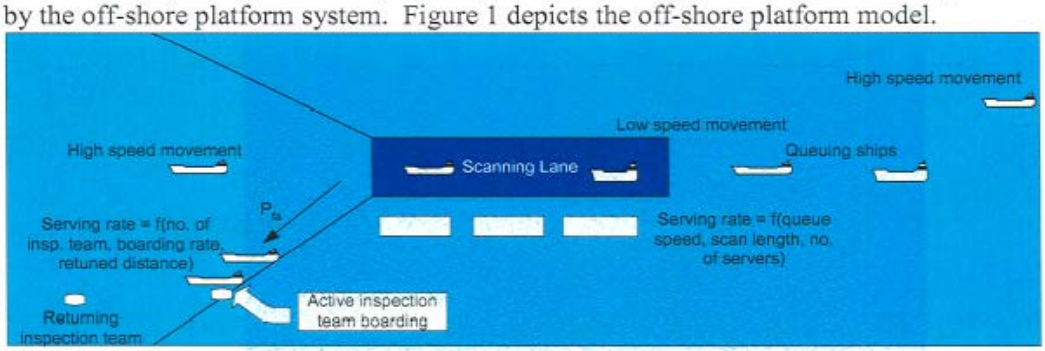

Figure 1. Off-shore platform model.

3.2 Methodology

In the first study, a simulation model was implemented using Simkit (a discrete event simulation package) to measure the traffic and delays caused by the off-shore checkpoint. A simulation model was chosen over an analytical model due to its ease of implementation and realistic representation in the model.

3.3 Model Formulation

In this model, the delay caused by the off-shore checkpoint is the difference in the time between the time the ship will take to arrive the Port of Singapore at its original speed, and the time the ship takes to arrive the Port of Singapore with the off-shore checkpoint, starting from the time the ship decreases its speed to 5 knots. The delay due to the deceleration of the ship to 5 knots is not considered in the model.

The model is essentially a two-cascading queuing model with the first queue being a "moving queue" of container ships into the checkpoint system and the second queue being the active boarding inspection queue, with the serving rate determined by the number of active Inspection Teams available, boarding time, and returning speed of the active Inspection Team to the off-shore platform. The ship arrival rate is modeled using an exponential distribution based on the yearly traffic through the strait. The speed of the container ship has a uniform distribution with transit speeds between 15 and 25 knots. The checkpoint scanning length, queuing speed, distance to port, inspection team boarding and unloading time, and returning are constants, and the base case parameters are given in Table 1.

Description	Value
Checkpoint Scanning Length	1.6 nm
Queuing Speed	5 knots
Distance to Port	300 nm
Buffered Distance Between ships	1 nm
Probability of False Alarm	0.025
Ships/Hour	2.85 ships/hr (Exponential Distribution)
Speed of Ships	15 - 25 knots (Uniform Distribution)
Number of Scanning Lane	1
Inspection Boarding/Unloading Time	1 hr
Inspection Team Return Speed	30 knots
Number of Active Inspection Teams	10

Table 1. Base case parameter values.

Each scenario was run for 8760 hours, that is, one year, and with ten replications. The average response of the replications were calculated and evaluated. A total of 40 scenarios with the parameters given in Table 2 were run. The response variables are essentially the traffic and delay parameters which are:

a. average time delay caused by the checkpoint system
b. average maximum time delay caused by the checkpoint system
c. average time in the first queue (queue to the checkpoint)
d. average time in the second queue (queue for inspection team boarding),
e. average utilization of the active team (for example, 0.6 means on average 6 teams are in action at any one time).

Scenario	Traffic/year	Pfa	Number of teams	Number of Scanning

				lanes
1.	25000	0.025	10	1
2.	25000	0.05	10	1
3.	25000	0.075	10	1
4.	25000	0.1	10	1
5.	25000	0.025	15	1
6.	25000	0.05	15	1
7.	25000	0.075	15	1
8.	25000	0.1	15	1
9.	30000	0.025	10	1
10.	30000	0.05	10	1
11.	30000	0.075	10	1
12.	30000	0.1	10	1
13.	30000	0.025	15	1
14.	30000	0.05	15	1
15.	30000	0.075	15	1
16.	30000	0.1	15	1
17.	35000	0.025	10	1
18.	35000	0.05	10	1
19.	35000	0.075	10	1
20.	35000	0.1	10	1
21.	35000	0.025	15	1
22.	35000	0.05	15	1
23.	35000	0.075	15	1
24.	35000	0.1	15	1
25.	50000	0.025	15	1
26.	50000	0.05	15	1
27.	50000	0.075	15	1
28.	50000	0.1	15	1
29.	50000	0.025	20	1
30.	50000	0.05	20	1
31.	50000	0.075	20	1
32.	50000	0.1	20	1
33.	50000	0.025	15	2
34.	50000	0.05	15	2
35.	50000	0.075	15	2
36.	50000	0.1	15	2
37.	50000	0.025	20	2
38.	50000	0.05	20	2
39.	50000	0.075	20	2
40.	50000	0.1	20	2

Table 2. Scenario parameter values

3.4 Results and Analysis

The base case scenario (traffic 25000 ships per year, 0.025 system probability of false alarm, 10 number of active Inspection Teams, 1 scanning queue) causes only a 0.50

hours average time delay in the system, 0.32 hours in the scanning queue, and 0 hours waiting time at the inspection boarding queue. The Inspection Team utilization is 0.19. If traffic is to increased to 30000 ships per year, average time delay caused by the system increases marginally to 0.55 hours, average waiting time in the scanning queue increases to 0.39 hours, and the average waiting time in the inspection queue remains at 0 hours.

When the traffic is increased to 35000 ships per year, the group observed that the average time delay caused by the checkpoint system increased to 0.66 hours, average waiting time at the scanning queue increased to 0.53 hours, and the waiting time at the inspection queue remains at 0 hours. Here, we see that 10 inspection teams are more than sufficient to effectively manage the incoming traffic. The increase in average waiting time in the system is due mainly to the delay caused by the scanning queue (see figure 2).

When the probability of false alarm is increased to 0.75, the average delay of a ship increases, though the delay is minimal (see Fig 2). We also observed that the average delay of a ship increases (at different rate) as the traffic or/and the probability of false alarm increases.

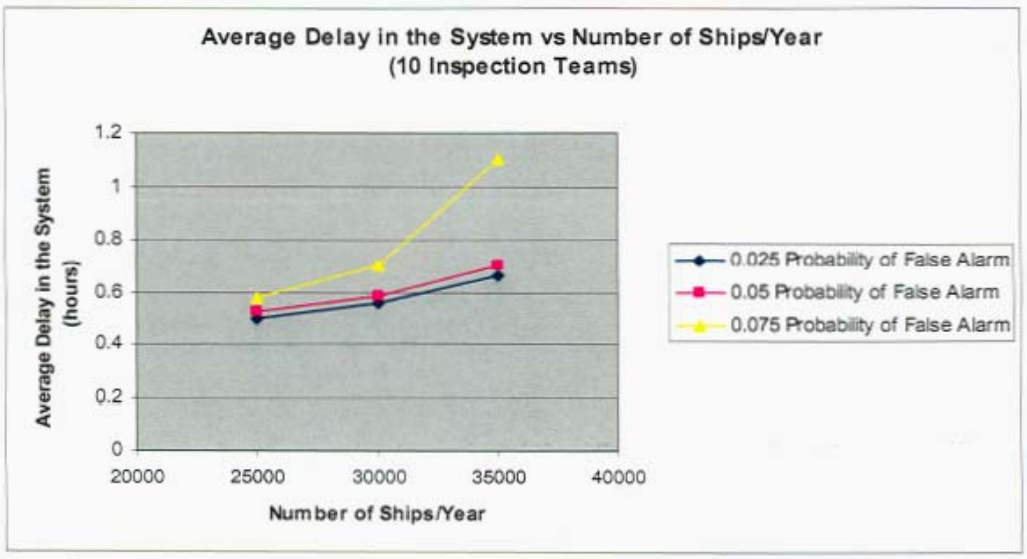

Figure 2. Average delay in the system versus number of ships per year with 10 Inspection Teams available

If the probability of false alarm is increased to 0.1, that is, to search 1 in 10 incoming ships, for a traffic of 25000, the average time delay caused by the system is increased to 0.83 hours, the average waiting time in the scanning queue remains at 0.32 hours, and the average waiting time in the inspection queue increases to 2.56 hours. If the traffic is increased to 35000 ships per year, the average time delay caused by the system is increased significantly to 42.1 hours (see fig 3).

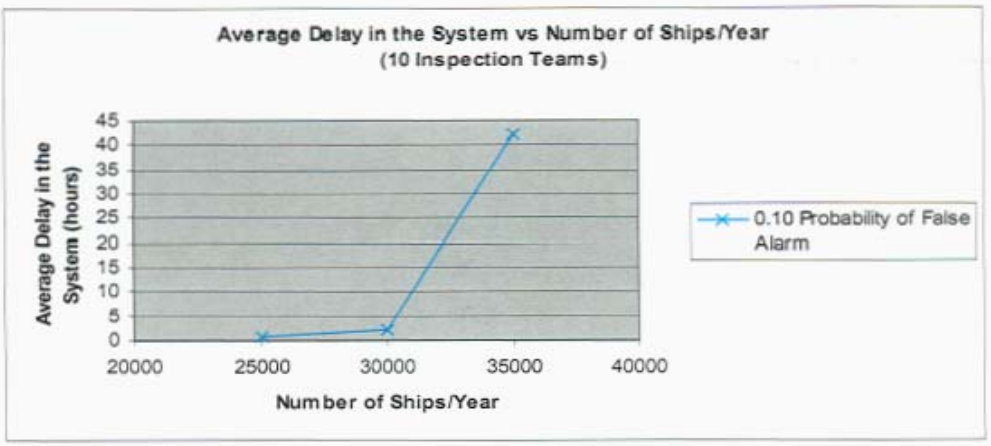

Figure 3. Average delay in the system versus number of ships per year with 10 Inspection Teams available and Probability of False Alarm of 0.1.

The average time delay caused by the system is due mainly to insufficient inspection teams. With 10 Inspection Teams and false alarm of 0.1, when the number of ships is greater than 30000 ships per year, the average delay in the system increases significantly. A check on the utilization of the team confirmed this. With high traffic and high probability of false alarm, the team utilization is significantly higher (see figure 4). For such a scenario, the inspection teams need to be increased to reduce the average delay.

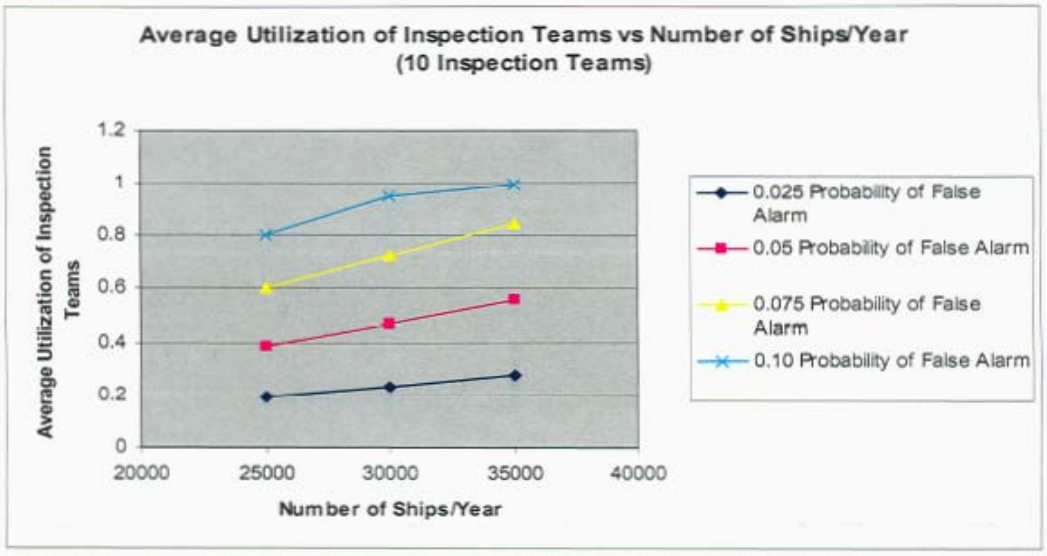

Figure 4. Average utilization of Inspection Teams versus the number of ships per year

Another important observation in the simulation is that though the average time delay is generally less than 2 hours for traffic less than 30000 ships per year, the maximum time delay caused by the checkpoint system could be significantly higher – as

high as 44.3 hours in the scenario of 35000 ships per year and 0.075 system probability of false alarm (see fig 5). In the scenario with probability of false alarm of 0.1, the average maximum delay could reach as high as 953.5hr. For our base case scenario, the average maximum time delay encountered by a ship in the simulation is only about 2.26 hours. A plot of the average maximum time delay encountered by a ship in the simulation is depicted in figures 5 and 6.

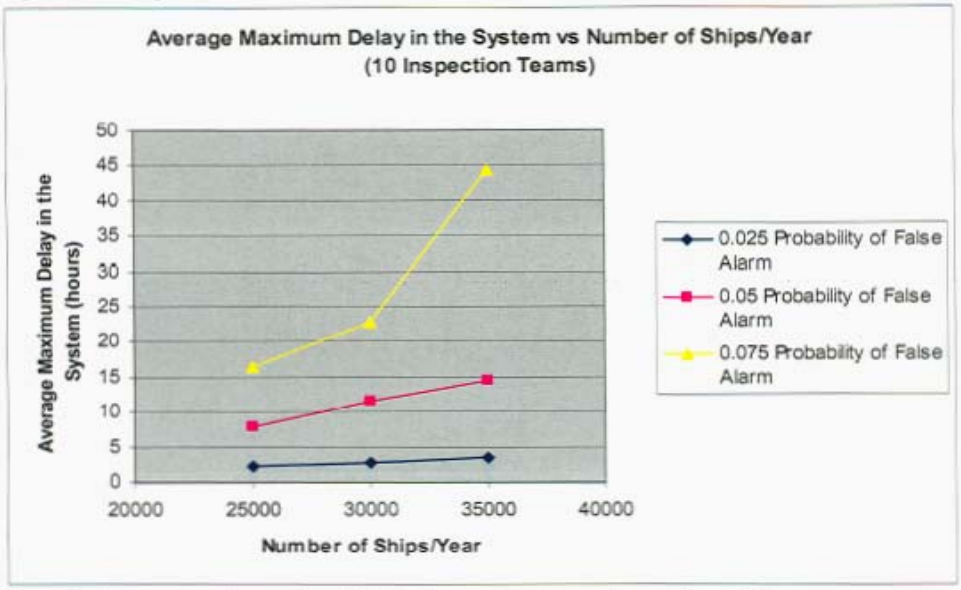

Figure 5. Average maximum time delay in the system versus the number of ships per year.

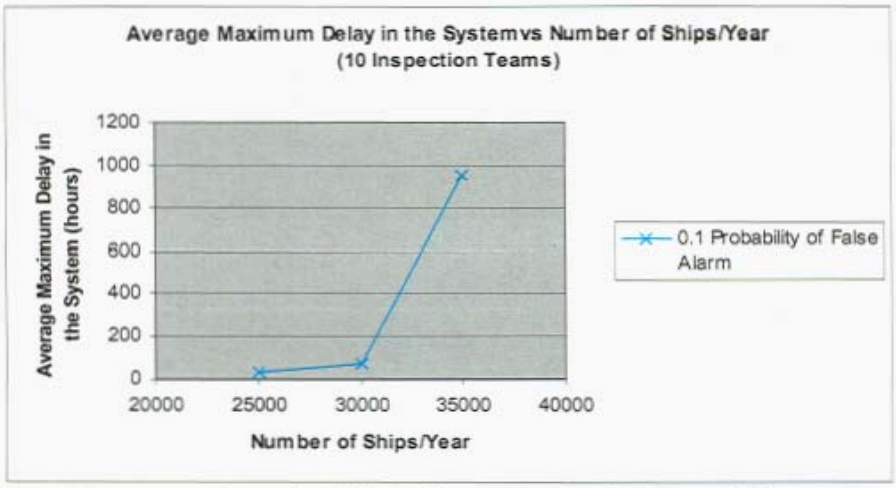

Figure 6. Average maximum time delay in the system versus the number of ships per year, with probability of false alarm of 0.1

Next, if the number of inspection teams is increased to 15, the average time delay caused by the system is reduced, as the inspection queue has a higher serving rate. The average delay caused by the system still increases with increase in traffic, which is mainly due to the queue delay caused by the scanning lane. The average time delay for the 35000 ships and false alarm of 0.1, is less than 0.81 hours (see fig 7).

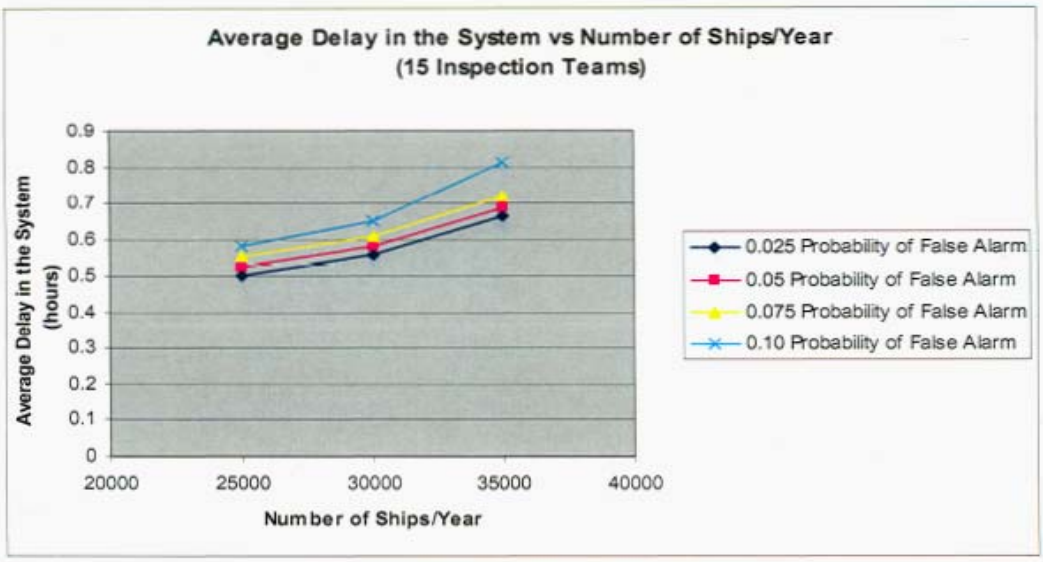

Figure 7. Average time delay in the system versus the number of ships per year.

The inspection utilization rate is also significantly lower, when compared to the 10-Inspection Team scenario (see figure 8).

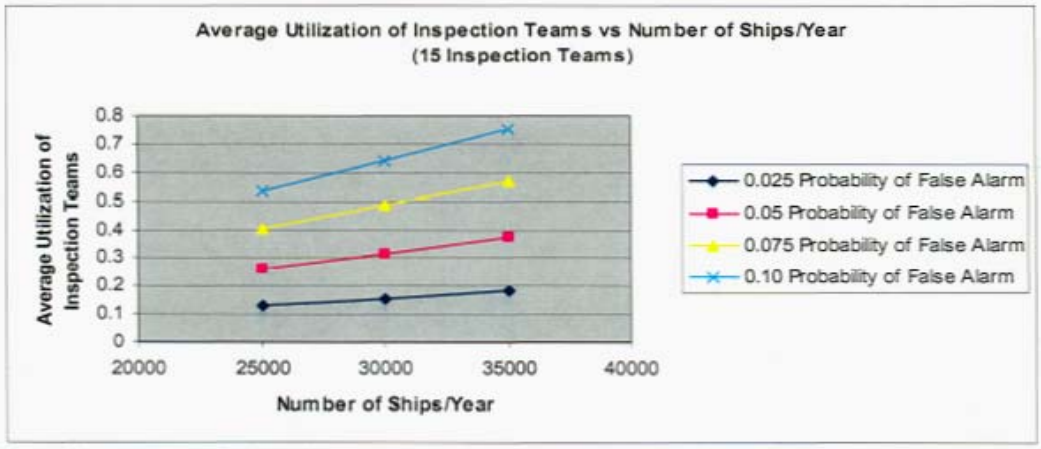

Figure 8. Average utilization of Inspection Teams versus the number of ships per year.

It is also observed that the average maximum time delay observed in the simulation is significantly lower (see figure 9). The highest maximum time delay is

about 17.8 hours. Therefore, for such high traffic and high probability of false alarm scenario, a 15 inspection team will be required.

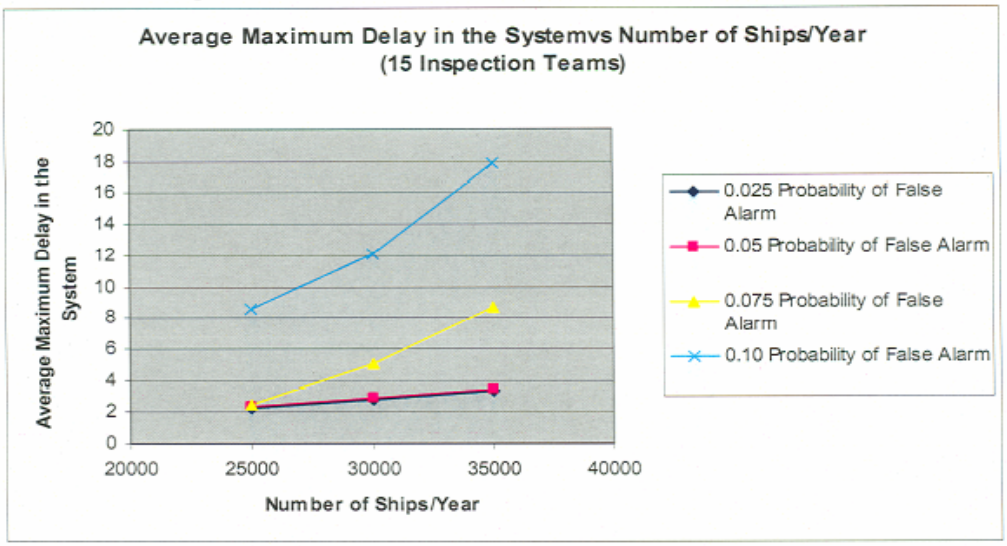

Figure 9. Maximum time delay in the system versus the number of ships per year.

If it was decided to scan all traffic passing through the Strait of Malacca or if the shipping volume was to increase at say six percent a year, traffic will easily doubled to 50000 ships per year in less than 12 years. Figure 10 indicates that the off-shore platform will cause a bottleneck even with 15 or 20 active Inspection Teams available. The average time delay of a ship with 15 Inspection Teams and 0.025 probability of false alarm is about 320 hours because the scanning lane is unable to serve the ships fast enough. If a second queue was opened, both 15 and 20 active Inspection Teams would reduce the average time delay in the system tremendously to less than an hour (see figure 11). However, if one in ten ships was to be inspected, a 20 Inspection Team scheme is preferred. As figure 10 illustrates, a 15 Inspection Team scheme is insufficient as the average time delay of a ship is about 28 hours. On the other hand, a 20 Inspection Team scheme decreases the average time delay to less than hour.

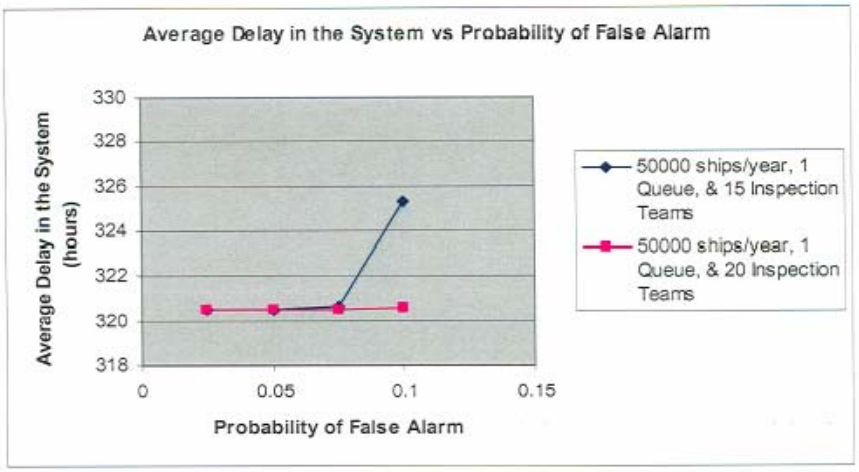

Figure 10. Average delay in the system with 50000 ships per year and 1 scanning queue.

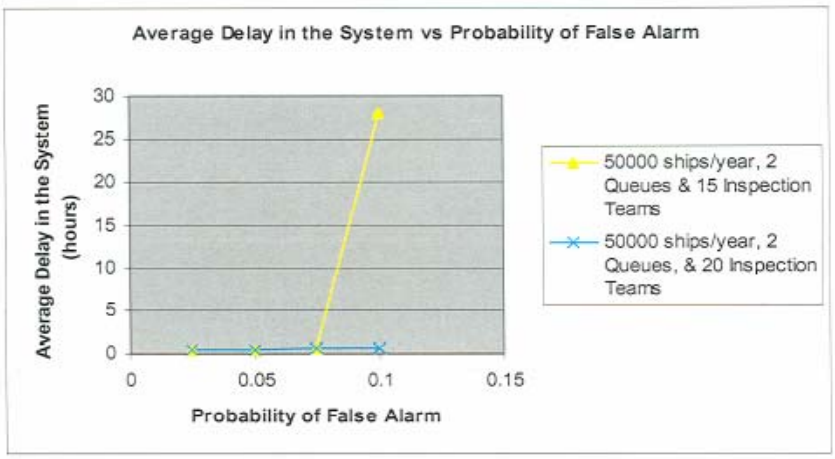

Figure 11. Average delay in the system with 50000 ships per year and 2 scanning queues.

3.5 Conclusions

The off-shore platform model indicates that at the current number of 25000 ships per year transiting the Strait of Malacca, the base case scenario is effective. But as the number of ships and the probability of the false alarm increases, there is the possibility of significantly affecting world trade.

As the shipping volume increases, increasing the number of active Inspection Teams may not be the solution. Opening a second queue and increasing the number of active Inspection Teams will significantly reduce the bottleneck problem caused by the shipping volume.

As probability of false alarm increases, we will need more inspection teams to ensure that the delay at the active inspection queue is reduced to an acceptable level.

This study provides quantitative results for analysts to determine the operational effectiveness and relative effectiveness of investment in weapon detection. Clearly, the

number of active Inspection Teams and the number of queues directly influences the operational effectiveness of the off-shore platform.

4. PORT OF SINGAPORE DETECTION SCHEME MODEL

The second study investigates the operational effectiveness of a "last-ditch" ship-threat detection scheme in a final layer of threat detection, where specific covert sensors are randomly distributed[2] in the port surveillance area as depicted in figure 12.

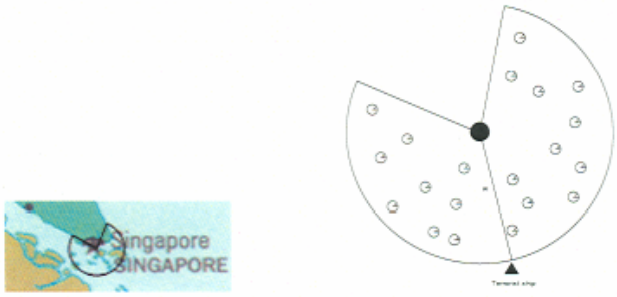

Figure 12. Port of Singapore sector vulnerable to terrorist attacks.

In theory, an optimal sensor deployment scheme would place the limited sensors at the boundary of the coverage area to optimize the probability of detection. In practice, terrorist ships knowing the deployed sensor scheme (via intelligence) will avoid the boundary deployed sensors using appropriate shielding. Terrorists will only reveal their intentions (for example, remove shielding or break shipping rules) when they think it is safe to do so or at the last minute close to the port. This makes the boundary sensor scheme easily defeated. Furthermore, terrorist ships will also not move in a specific path to the target, hence, putting sensors at specific locations is ineffective. The scheme in this report looks at random deployment of sensors to detect terrorist ships possibly moving from all directions, though the base case scenario describes the terrorist ship moving in a straight path. In the case when the terrorist ship reveals its intention at the last second, i.e. weapon signature is never detectable (our sensor is not perfect) or is not detectable until just prior to activation, this scheme will fail as the probability of timely detection will near zero.

4.1 Assumptions

The randomly distributed sensors can be sensorized buoys, Unmanned Aerial Vehicles (AUVs) or helicopters with NBC/conventional explosive sensors scanning at random. In an ideal scenario, these covert sensors have perfect sensor specificity (no costly false alarm), perfect sensitivity within the detection radius r, perfect covert sensor deployment, and perfect non-overlapping deployment to maximize detection. But this is neither possible nor practical from an operational perspective. Conversely, relaxing any of these assumptions can only lower the operational effectiveness of the ship-threat detection scheme for timely detection. This is because operational effectiveness is measured by the probability of timely detection where the reactionary force is able to intercept the terrorist ship on time. This is crucial in reducing the devastation effect of

2 E. H. Kaplan and M. Kress, "Operational Effectiveness of Suicide Bomber Detector Schemes: A Best Case Analysis", January 2005.

the NBC or conventional explosives detonations at the port (though it may still be too late if the weapon employed is a nuclear device).

An alternative approach is for the covert sensors to be randomly distributed in the Area of Interest (AOI) within detection range constraints. Since each covert sensor has limited detection range, the problem is to maximize detection of a NBC/conventional explosive. In the event that the number of sensors is fixed, the problem is further defined as the optimal sensor deployment in order to minimize the amount of uncovered area.

4.2 Methodology

The second study, as depicted in figure 12, portrays the area of the Port of Singapore most likely vulnerable to terrorist attacks. A terrorist ship has the possibility to arrive at a random location around the circumference of the area under port surveillance (radius w), and moves at a speed of v_t knots towards the port. In a realistic scenario, the terrorist ship would probably move in a non-linear motion so as not to reveal its intention and due to the possibility of other vessels in its path. This increases the expected distance, E(L), traveled by the terrorist ship to the targeted terminal. This means that the actual probability of timely detection will be higher than the straight line model.

The objectives of this study is to find an efficient sensor deployment scheme to obtain a probability of timely detection, an optimal sensor cover range, and determine how the reactionary force speed affects the sensor deployment scheme. Cost, logical support, and tactical deployment considerations also limit the number of sensors that may be fielded in a realistic scenario.

The initial analysis uses a base case scenario. Variations of this scenario include doubling the number of sensors deployed, and increasing the intercept speed of the reactionary force.

4.3 Model Formulation

Perfectly specific covert sensors capable of detecting a terrorist ship which passes within r nm, are deployed in non-overlapping fashion with $\gamma\,\mathrm{m}^{-2}$. Detection in this model does not guarantee sufficient time to intervene. Timely detection is defined as detection of a terrorist ship at a distance greater than z nm from the port, with the reactionary force traveling at v_r knots, intercepting the terrorist ship at least i nm from the port. The probability of timely detection can be computed as a function of γ, r, w, and z.
The surveillance area of the port is modeled as a pie-sector coverage with length w and angle θ. A terrorist ship arrives at a random point outside the coverage area, and proceeds directly towards the port. The terrorist ship, assuming it moves directly to the port, will need to travel a distance L to reach its intended target as depicted in figure 13. The expected distance of the terrorist ship is E(L) = w nm, since it is at the boundary of the port surveillance area.

Perfectly specific covert sensors are distributed throughout the port surveillance coverage area. Each sensor can perfectly detect any terrorist ship which passes within r = 0.054 nm (base case assumption). A terrorist ship which travels a distance L nm to the target will be detected if a sensor is located within the en route detection zone of area $2rL$ centered along the direct path from the arrival point to the center of the target area.

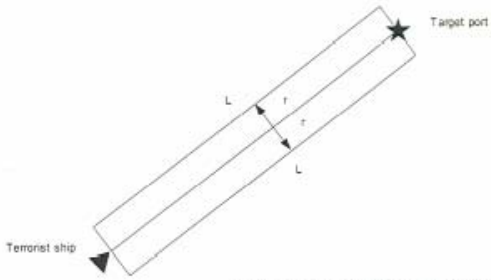

Figure 13. Path of terrorist ship to the target

If there are *m* sensors distributed over the port coverage area, this will result in a sensor density of $\gamma = \frac{m}{0.5w^2\theta}$ sensors per unit area, and the probability of the terrorist ship being detected en route is $P_{ed} = m\frac{2rE(L)}{0.5w^2\theta} = 2\gamma rE(L)$. To ensure physical plausibility, the total detection zone accounting for all sensors, *m x 2rE(L)* cannot exceed the port coverage area, that is, $\gamma < \frac{1}{2rE(L)}$. We also define $f = \gamma(2rE(L)) = 2\gamma rE(L)$ as the sensor deployment fraction, which varies from 0 to 1 and it reports the fraction of maximal coverage achieved for a given sensor deployment in the model.

As previously mentioned, detection in the model does not guarantee sufficient time for intervention. Assuming that a minimum intercept distance, *i*, that is, the minimum distance from the port where a terrorist ship is successfully intercepted, and the terrorist ship is traveling at v_t and the reactionary force is traveling at v_r, the minimum detection distance from the port is $z = (\frac{v_t}{v_r} + 1)i$. If the terrorist ship is detected en route, it could be at any random location along its travel path. This means that the terrorist ship is detected at least *z* nm from the port with probability

$$\Pr\{\text{Timely detection/en route detection}\} = P_{td/ed} = \frac{E(L)-z}{E(L)}$$

The probability of timely detection is therefore,

$$P_{td} = P_{ed}P_{td/ed} = 2\gamma rE(L)\frac{E(L)-z}{E(L)} = 2\gamma r(E(L)-z) = \frac{4mr}{w^2\theta}(E(L)-z)$$

given that E(L) = w in the model. The actual probability of timely detection will be higher if the terrorist ship moves in a non-linear path towards the port target.

4.3.1 Parameter Values

Table 3 contains base case parameter values. The port surveillance coverage radius is set at w = 8.1 nm; coverage angle is set at $\theta = 315$ degrees; the number of sensors employed is m = 50; sensor radius coverage r = 0.054 nm; speed of terrorist ship is $v_t = 8.1$ knots; speed of reactionary force is $v_r = 16.2$ knots; and minimum intercept distance is i = 16.2 nm.

Parameter	Description	Value
w	Port coverage radius	8.1 nm (15km)
θ	Port coverage angle	315 deg (5.50 rad)
m	Number of sensors employed	50
r	Sensor detection radius	0.054 nm (0.1km)
v_t	Speed of terrorist ship	8.1 knots (15km/h)

v_r	Speed of reactionary force	16.2 knots (30km/h)
E(L)	Expected distance of terrorist ship	8.1 nm (15km)
i	Minimum intercept distance	1.62 nm (3km)

Table 3. Base case parameter values.

4.4 Results and Analysis

In the base case scenario, a probability of timely detection of 0.1698 is obtained. Figure 12 reports the optimal port coverage (w) given a fixed number of sensors. The probability of timely detection of about 0.2 can be achieved with a port coverage of w = 4.86 nm (9 km) = 2z. As the port coverage is increased to approximately 15.1 nm (30 km), the probability of timely detection decreases quickly, this probability quickly asymptotically approaches zero for larger port coverage area. If the coverage is less than the optimal value, *the probability of timely detection* decreases though the probability of detection increases. Conversely, if the coverage is increased beyond the optimal value, the probability of timely detection will also decrease due to decreased sensor density though the probability of successful interception (given detection) is increased.

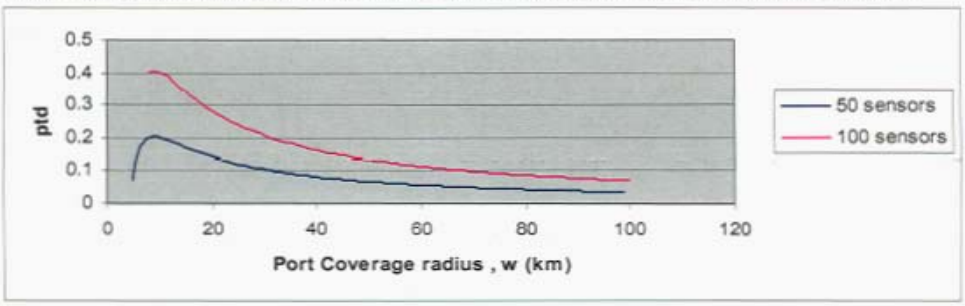

Figure 14. Probability of timely detection given a number of sensors

Figure 14 reports the probability of timely detection grows quickly as the speed of the reactionary force approaches 8.1 knots (15 km/hr) but does not increase as much for larger reactionary force speeds.

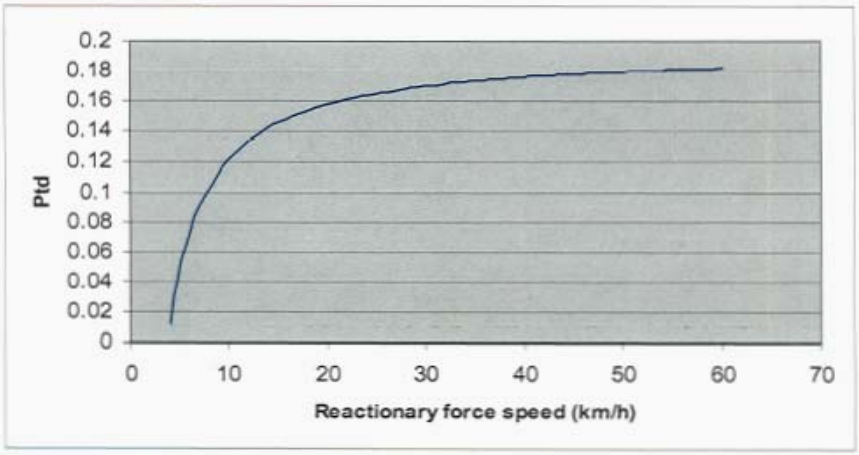

Figure 15. Probability of timely detection versus speed of reactionary force

Figure 15 reports if the number of sensors, the radius of the sensor coverage, expected distance of the terrorist ship from the port coverage (ships, obstacles or circumstances that increase the distance the terrorist ship need to travel to the port) or the speed of the reactionary force is increased, the probability of timely detection will also increase accordingly as summarized in Table 4.

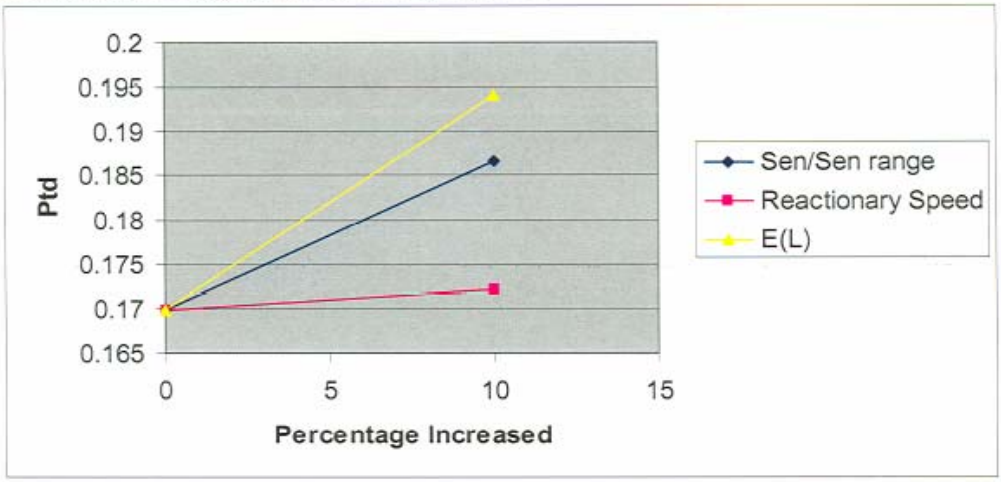

Figure 16. Probability of timely detection if the number of sensors, speed of reactionary force, and expected distance of the terrorist ship are increased.

	Probability of timely detection	Percentage increase
10% increase in the number of sensor, or sensor radius	0.1867	9.95%
10% increase in the reactionary speed	0.1720	1.28%
10% increase in the expected distance of the terrorist ship	0.1940	14.25%

Table 4. Summary when number of sensors, speed of reactionary force, and E(L) is increased by 10 percent.

4.5 Conclusions

The base case scenario achieved a probability of timely detection of 0.1698. The base case is not an optimal case of deploying the sensors. An optimal port coverage radius could be obtained by setting the port coverage radius w to about 2z, that is, two times the minimum required detection distance. This will yield the highest probability of timely detection of slightly more than 0.2.

Doubling the number of sensors employed or doubling the sensors' radii will effectively double the probability of timely detection. To achieve the greatest increase in timely detection probability, sensors and sensor radius should be doubled at the optimal sensor deployment radius. An increase in the expected distance of the terrorist ship (to reduce the number of direct line of sight paths to the port terminals), will also increase the probability of timely detection. An increase of 10% in the number of sensors or

sensor range, increases the probability of timely detection by about 9.95%; an increase of 10% in the expected distance of the terrorist ship, increases the timely detection probability by about 14.25%; an increase of 10% in the speed of reactionary force, increases the timely detection probability by 1.28%.

An increase in the speed of the reactionary forces increases the probability of detection more quickly as the speed approaches the speed of the terrorist ship, v_t, but the probability quickly flattens as the speed increases. It is crucial that the speed of reactionary force be faster than the expected speed of the terrorist ship, beyond which, an increase in the reactionary speed only marginally increases the probability of timely detection.

The timely detection probability of the "last-ditch" threat detection scheme is low, and increasing the number of sensors or sensor radius may be costly. Investing in intelligence may be the solution to approach the problem of detecting a terrorist ship transiting to its intended target. The group feels that this scheme in conjunction with intelligence or other threat detection schemes (threat behavior detection systems) can make a difference in deterring terrorist attacks, thereby, achieve a higher probability of timely detection.

III. PROTECTION FROM SMALL BOAT ATTACK (SBA) IN THE APPROACH AREA EMPLOYING UAVs

1. INTRODUCTION

Protection from small boat attack is an important function of Maritime Domain Protection (MDP). In the Straits, and to some extent the approach area, there is a high density of small vessels in close proximity to the sea lanes. This creates three major challenges for a protection system, namely the physical sensing aspect, the number of potential threats, and the short time for reaction.

The northern approach area to the Strait extends for approximately 300 nautical miles. The area of interest for this model is between Kelang, Malaysia and Labuhanbilik, Indonesia on the southern end and near Teluk Intan, Malaysia to the north. This section of the approach varies in width from 60 nm to 90 nm and is approximately 120 nm in length.

Figure 1. Strait of Malacca with specific area of interest for this study circled.

Inside the Straits, even though detecting small boats poses some technological challenges, the sensing problem can be tackled with commercial microwave radars. Thus, the major challenge becomes dealing with the large amount of contact information that does not facilitate discrimination among potentially hostile small boats. Even under the "perfect sensor" assumption, which assumes knowledge of the location of all vessels in the Straits, it is still difficult to identify and neutralize a potential terrorist before he reaches a high value unit (HVU).

In the approach area to the Straits, however, the problem assumes different characteristics. One characteristic that is in favor of the protection force is the low

density of small boats in close proximity to the shipping lanes. Another is that the wider geometry of the approach area enables the protection system earlier warning about potential hostile small boats by detecting them at a significant distance from the shipping lanes. On the other hand conventional sensing alternatives are limited for the purpose of sensing small boats (typically low radar cross sections) around the shipping lanes that are 30 to 45 nautical miles from shore. This region may be susceptible to a small boat attack due to the relative proximity to the coastline and the perception that ships not yet in the strait may be less well protected.

The usefulness of ground-based radar is limited due to the geometry of the Strait. The maximum range of microwave radar is typically around 20 miles. This makes microwave radar inappropriate as a complete sensing solution in the approach areas. Depicted in the figure 1 are typical coverage radii of microwave radars in the Straits, and HF radar coverage radii in the approach areas. The HFSWR (High Frequency Surface Wave Radar) coverage radii are sufficient for covering the approach areas but the poor resolution (due to the low frequency) limits its ability to detect small boats that typically have a low Radar Cross-Section (RCS).

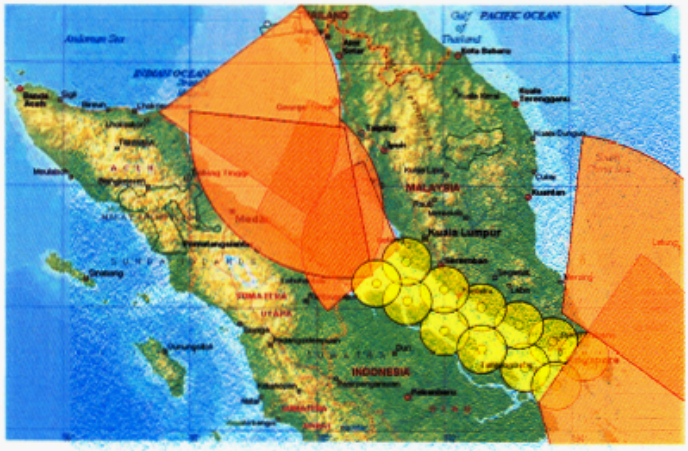

Figure 2. Nominal radar coverage of the Strait of Malacca using microwave and HFSWR.

The scope of this analysis is to evaluate the employment of mobile sensors, or more specifically UAVs, to provide the sensory input to the overall protection system in the area of the approaches. In order to evaluate this alternative it is necessary to study the objective characteristics of the protection problem, which includes the geometry, scope of areas of interest, small boat density, distribution and speeds, HVU density, sea lane width, and weather conditions. Even though the main focus of the analysis is the sensing issue, a broader approach is adopted in the preliminary phases of the problem study. Some general feasibility aspects are explored to ensure a realistic system integrating the sensors and the forces is effective in providing protection. For example, is neutralization of all potential threats possible even in the presence of perfect sensors?

The main focus of the study is to propose optimal utilization of UAVs as the sensing portion of the protection system. This proposal is to include an evaluation of the

sensing performance as a function of possible paths, number and specifications of the UAVs. The output of this analysis will be used to evaluate the feasibility of a system of UAVs. This will also be used to determine how well a sensor system of UAVs can perform given a realistic number of assets.

The analysis also takes into account the following limitations and characteristics of UAV systems.

- sensor limitations
- operability in varying weather conditions
- durability
- sustainability
- ingress and egress times
- manpower associated with operation

Additionally, the implications of these factors on the cost of the proposed approach to this solution are explored. Since the sensor portion and the force are highly interactive it is necessary to include some assumptions and characteristics of the force part of the system in our model.

2. BACKGROUND

The small boat density in close proximity to the traffic lanes in the approach area is significantly lower than inside the Straits. Most of the small boat traffic is concentrated along the coasts. However, it is possible for a hostile vessel to cross the distance from the coast to the traffic lanes. A realistic estimate for the one way range of a go-fast boat is 50 nm, which makes it logistically feasible for a vessel of this type to be a potential threat.

The Traffic Separation Scheme (TSS), or preferred shipping lane, in this area spans approximately 5 nm. Large vessels transit the Strait at a rate of approximately 150 vessels a day, which implies an average of one vessel every six miles along the Strait heading in each direction. Small boats are not usually present within the TSS and generally only enter the shipping lanes to cross to the open waters on the other side. Along the shoreline, however, there are hundreds of small vessels.

3. PROBLEM FORMULATION

3.1 Area of Interest (AOI)

To protect each HVU that transits the Strait, it is logical to first define an area around each vessel called the blast damage range, R = 70 yards, which is the maximum range at which a detonated explosive will cause damage. A further extension of this area, based on the expected time needed for a force to react to a threat, creates a zone around the HVU that becomes the area of interest for neutralizing potential threats. This distance assumes that there is a reaction force in the area available for deployment to investigate any potential threat as it emerges. Having a reaction force always in the area is not a realistic assumption, however, so it is necessary to use an alternative method to determine the appropriate early warning.

Another approach to determining the areas of interest to the sensing part of the system is based on assuming a perfect sensor system and a reaction force that uses the perfect information to protect the shipping lanes. This perfect sensing system detects and classifies with 100% certainty, no false alarms and zero delay, all boats within its area of

employment. Naturally, minimizing the area of interest is desirable. The minimum area of employment that will still allow the reacting force a reasonable performance is defined as the area of interest. Having established this area, the realistic sensor must provide effective coverage of the area of interest.

Since the density of HVUs along the lane is relatively high, the shipping lane itself can be considered the target for the terrorist small boat. While this is a worst case assumption for the protector, it makes the analysis simpler and provides an overestimate of the resources needed. As shown above, the area of interest for sensing is directly related to the availability of forces. For the purpose of this analysis, and in the absence of a known reaction force's employment tactics, a basic and realistic assumption of a patrolling surface force is used. In further detail, two specific tactics are taken into consideration when there are N boats available to protect the sea lane throughout the entire approach area. The first tactic is to divide the entire length of the lanes into N sectors each under the responsibility of one patrol boat. The second tactic is to divide the entire length of the lane into N/2 areas of responsibility, each one protected by two boats, one on either side of the lane. In the latter tactic, each protects the lane in one direction only (outward). This tactic, although more "expensive" in boats for a given sector size, spares the need for a patrol boat to cross the five mile wide lanes, possibly through traffic, to engage small boats coming from the other side. Notice that in both tactics for assigning N boats to the entire approach area, each patrol boat is in charge of the same length of boundary with the area outside the lanes , 2*L/N, where L is the length of the entire protected portion of the approach area. The determining factor for which tactic to use is dependent on the rate of small boats entering the area of interest. For higher inter-arrival rates the second tactic will be a more effective for force employment. For lower inter-arrival rates, however, the first tactic will be sufficient.

Based on these assumptions, a relationship between the number of patrol boats, N, and the distance, D, from the edge of the shipping lane that needs to be covered is established. Intuitively, the longer the sector, the larger the distance from the lane edge to effectively neutralize threats. Other assumptions to the model include that small boats appear at the edges and are uniformly distributed along the boundary with exponentially distributed inter-arrival times and the small boats continue along the shortest path toward the middle of the lane at constant speed, V_{sb}. The protecting force employs proportional navigation, with speed, V_{pv}, to intercept the small boats on a first come first serve basis. For simplicity, a rectangular geometry is assumed for the area of interest. If a small boat reaches the center of the lane, it is assumed it attacked an HVU and the system failed to neutralize that small boat. The assumptions described above do not include different behaviors for "red" boats and "white" boats, it assumes that all boats behave as "red" hostile boats. This assumption is a worst case assumption that might reflect reality given an attack of multiple hostile small boats.

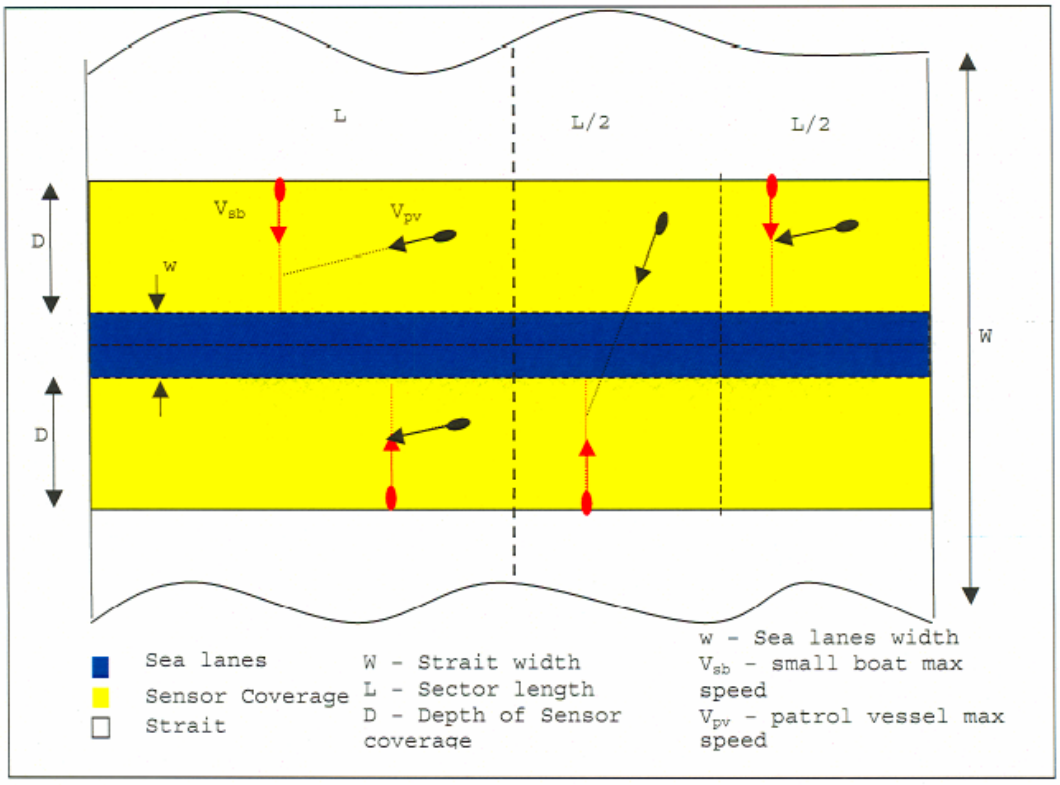

Figure 3. The two tactics to divide a sector of length L between two patrol boats. Tactic one is depicted on the right half of the diagram and tactic two is on the left.

3.1.1 Lower Bound For Sensor Coverage

The lower bound on D is derived for both tactics, based on a worst case scenario. The main assumption that simplifies the derivation of a lower bound is that there is only one small non-neutralized boat in the area of responsibility of each patrol vessel at a time. In the presence of multiple small boats the required coverage depth can only increase. Total time to neutralize a small boat is $T_n = t_r + t_t + t_e$. The time to travel for interception of the small boat is t_t. The time necessary for a reaction force to orient and decide to intercept the small boat, t_r, plus the time necessary to engage a small boat in order to neutralize the threat, t_e, will be set to a fixed time, t_d. This supposition when applied to the small boat's path means that the small boat will not have to travel the total distance, D, but instead will only need to travel a shorter distance, $D_s = D - t_d * V_{pv} = D - d$. The following equation is derived using the above assumptions to determine the lower bound for D.

$$\frac{D-d}{V_{sb}} \leq \frac{\sqrt{(D+w)^2 + L^2}}{V_{pv}}$$, which yields

$$D \geq \frac{d * V_{pv}^{\ 2} + w * V_{sb}^{\ 2} \pm \sqrt{(d * V_{pv}^{\ 2} + w * V_{sb}^{\ 2})^2 - (V_{pv}^{\ 2} - V_{sb}^{\ 2})(V_{pv}^{\ 2} * d^2 - w^2 * V_{sb}^{\ 2} - L^2 * V_{sb}^{\ 2})}}{V_{pv}^{\ 2} - V_{sb}^{\ 2}}$$

When w=0, the above equation represents the case where there is one patrol vessel on each side of the traffic lanes. Setting d=0 would infer that the orientation and neutralization are instantaneous and only the actual traveling time is of consequence. This might be a good lower bound if hostile intent has already been established and it is determined that the patrol vessel will be able to neutralize a small boat without having to complete the intercept, i.e. the patrol vessel can shoot and disable the small boat from a range approximately equal to the range of the weapon onboard. Then, the additional travel time to the exact intercept point from the maximum weapon engagement range can be translated as the time necessary to orient before action. Since hostile intent is not being addressed in this study, the distance referred to in the graph below is for actual intercept of the small boat.

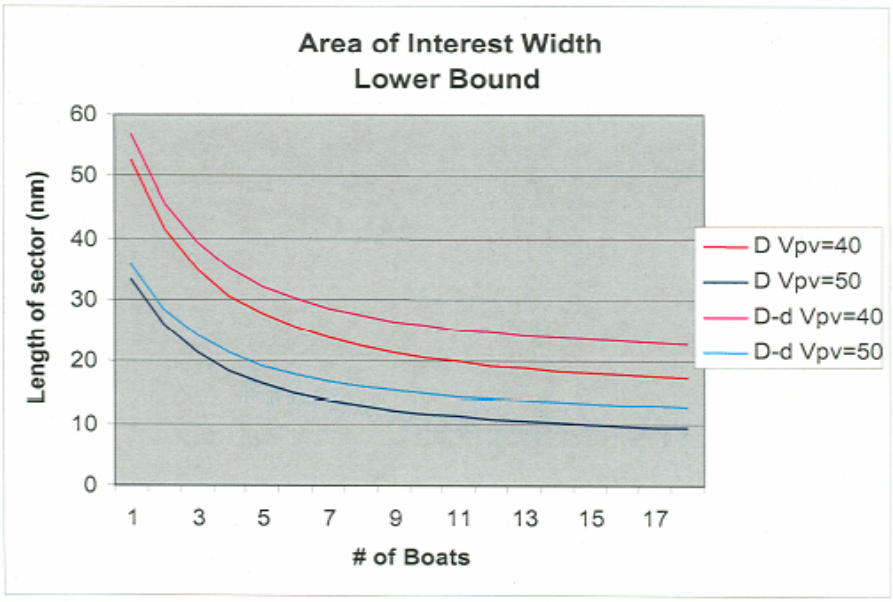

Figure 4. Required minimum area of interest width based on worst case scenario with only one target vessel in the area of interest of any one patrol vessel. (d=1.5nm => t_d=3min).

Figure 4 shows the relationship between sensing area of interest and the engaging force. If engagement resources are limited causing a larger sector, L, more early warning from the sensors will be needed so that the force can handle all the threats. A decision has to be made whether to invest in sensing assets or force numbers. The graph also shows the asymptotic decrease of the lower bound for the area of interest by increasing the speed of the engaging force patrol boats to 50 knots.

3.2 Simulation

To gain further insight of the relationship between the number of boats available to protect the lanes in the approach area, and the width of the strip that has to be covered by the sensor system a simulation of the two aforementioned basic tactics was run.

3.2.1 Models

For the purpose of the simulation, assumptions similar to the ones described in the previous section were adopted. Two different models were run, corresponding to the same two basic tactics described in figure 3. The area under surveillance (to the depth of D, beyond the traffic lanes) was assumed to have a perfect sensor system and a reaction force that uses the perfect information to protect the shipping lanes.

Other assumptions to the model are that small boats appear at the edges and are uniformly distributed along the boundary with exponentially distributed inter-arrival times and they continue along the shortest path toward the middle of the lane at constant speed, V_{sb}. Since a basic assumption in the SBA (small boat attack) scenario is the inability to establish the boat's intent the patrol vessel intercepts all incoming small boats. In reality this interception does not necessarily involve destroying the small boat. It may simply be instructing it to turn around and leave the area. Under these assumptions there is no difference in behavior between hostile (red) small boats and neutral (white) small boats, and all small boats are engaged in the same way. Since in reality, the sensor system will not be able to establish the intent of the small boat, similar action will be taken in engaging all small boats. All small boats in the protected area will be approached by a patrol boat, and be warned off or verified as hostile or neutral. The assumption made in the simulation that all small boats will assume maximum speed towards the lanes is a "worst case" assumption in terms of the load on the patrol boat. In reality only hostile small boats are expected to assume maximum speed toward the victim HVU. The weapon range of the patrol boats does not effect the results of this analysis. Under the model assumptions a patrol boat will have to reach zero range with small boat (hostile or not) in order to verify its intentions or warn it off and direct it to exit the protected zone.

The patrol vessel in the simulation has a maximum speed of V_{pv} and uses a proportional navigation route to intercept a small boat. If the small boat is intercepted before reaching the lanes the interception is considered to be successful. If the small boat reaches the traffic lanes before the patrol boat catches up with it, it is a failure. Every "failure", "successful interception" or an "arrival" of a new small boat causes the patrol vessel to make an updated decision about the optimal order of engaging the small boats. The patrol vessel considers all possible routes (n! possibilities, if there are n small boats in the area of responsibility) and chooses the path with the least failures and shortest duration, in that order of priority.

The discrete event graph model is depicted in figure 5.

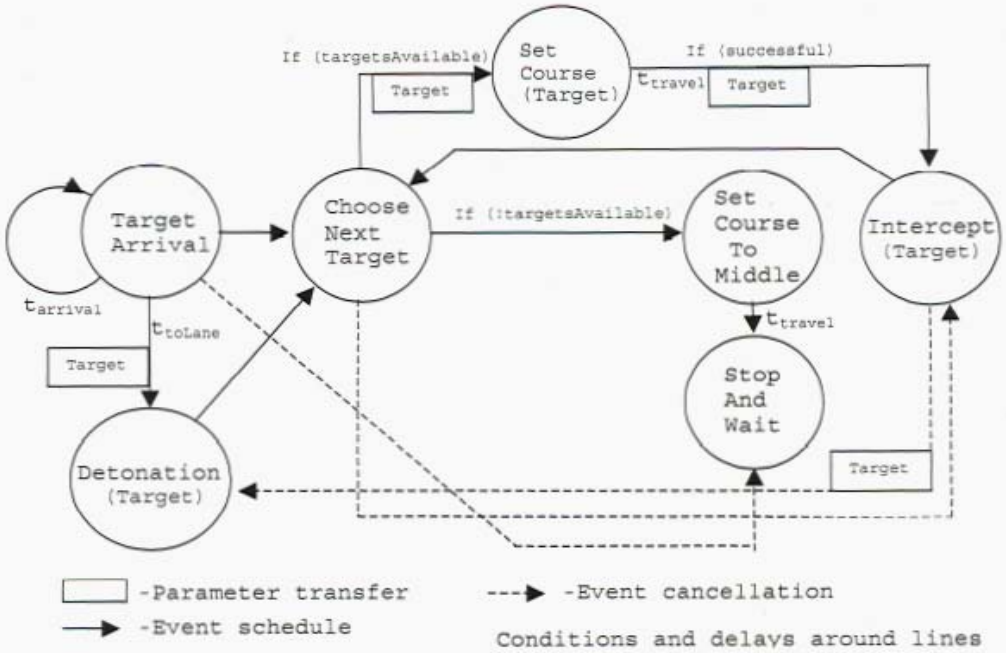

Figure 5 Simulation event graph

3.2.2 Results

The simulation was written in java language using simkit (Version 1.2.13) simulation package and Net Beans IDE 3.6 development platform. The ranges of the values inputted into the simulation appear in the table below:

Parameter	Min	Max	Increments
D (Coverage depth from each side)	10nm	40nm	5nm
N (# of patrol boats)	5	20	3
U (small boat arrival rate)	25 small boats/hour	75 small boats/hour	50

It is important to understand that the small boat arrival rate represents the overall small boat arrival rate into the area of interest and not only the hostile (red) boats arrival rate. As mentioned before the model does not distinct between hostile and neutral small boats, since they require similar maneuvers from the patrol boats.

The constant parameters used were: V_{pv} (max speed of patrol vessel) = 40 kts, V_{sb} (speed of small boat) = 30 kts, and Length of the protected area of the traffic lanes = 120nm.

The figures below present the success ratio, number of failures divided by the number of small boats arrived, as a function of the number of patrol vessels used when one patrol vessel is on each side of the traffic lanes. The lower arrival rate shows a clear relationship between the coverage depth and the number of boats needed to achieve a

specific success ratio. There seems to be no significant improvement in performance with increase of D over 20 for the higher arrival rate.

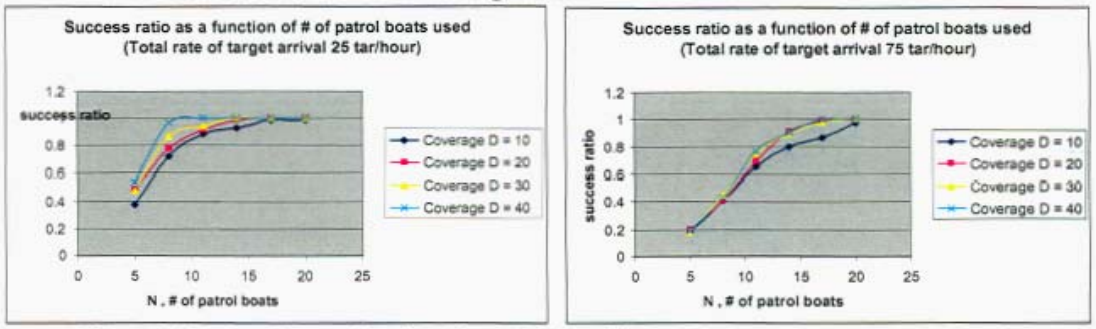

Figure 6. Success ratios as a function of number of patrol boats

Below are the same graphs for the tactic using one patrol vessel to protect both sides of the lane. There is a very weak relationship between the success ratio and the coverage depth. The is probably a result of the patrol boat constantly "leaping" from one side of the lane to the other with these rates of arrival, thus not utilizing the extra early warning given by a larger coverage depth. This method of employment seems less effective for the given rates of small boat arrival. The fact that the interceptions in this method are close to the lane itself makes it even less attractive for our purposes.

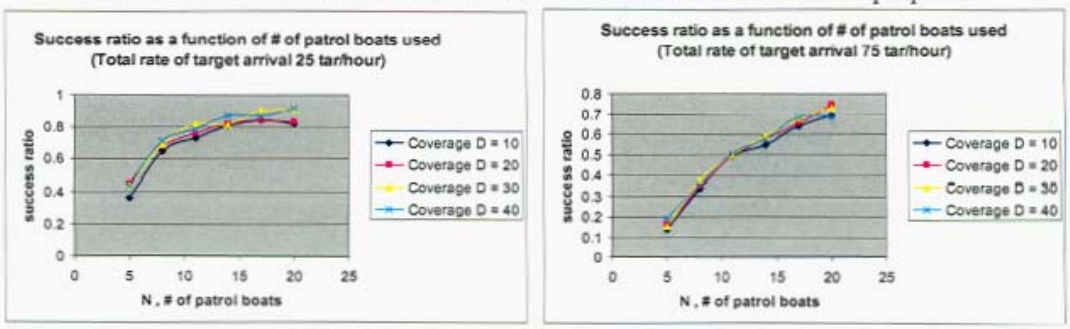

Figure 7. Success ratios as a function of number of patrol boats

The graph below compares the performance of the two methods of employment considered and shows that employing a boat on each side of the lane is superior in performance.

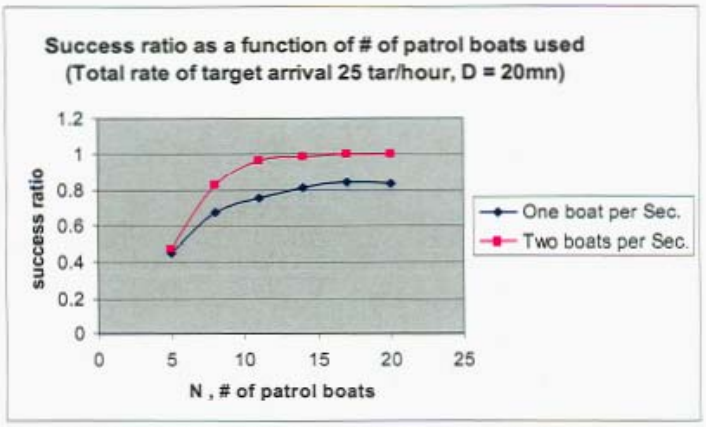

Figure 8. Success ratios as a function of number of patrol boats

The data obtained from the simulation was used to establish a relationship between coverage depth of the sensors and the number of patrol vessels needed to achieve a 95% success ratio. The curve derived is shown in the figure below for the two arrival rates simulated. It appears that for the high arrival rate, increasing the coverage depth above 30 nm does not contribute to lowering the number of patrol vessels needed. This might be attributed to the fact that the performance is restricted by the time it takes the patrol vessel to travel parallel to the shipping lane inside its area of responsibility and not by the amount of early warning time provided. In the lower arrival rate, at night for example, decrease in one patrol boat can be compensated by increasing the coverage depth by four nautical miles, which translates into an increase in area of 960 nm^2 for the entire approach area.

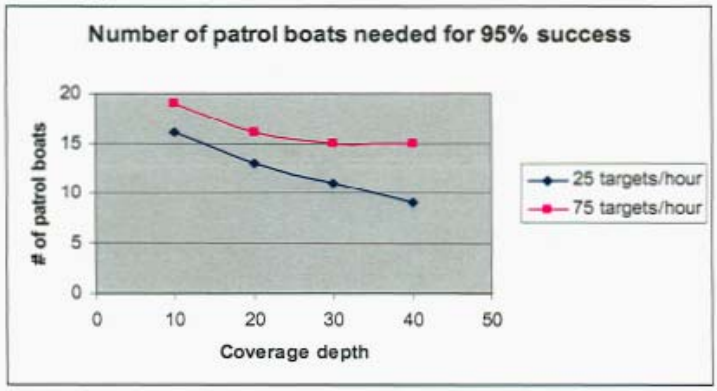

Figure 9. Number of patrol boats needed for 95% success

3.3 UAV Coverage of Area of Interest

3.3.1 Area Coverage

Integrating UAVs into Maritime Domain Protection requires an immense amount of planning and structure. The main measures of effectiveness for the sensor include coverage ratio and probability of detection. Sensor coverage ratio refers to the number of times a sensor visits a point in the assigned area during a specific time frame.

$$SensorCoverageRatio = \frac{sweepwidth * speedoverground * duration}{area \quad of \quad region}$$. Sensor coverage ratio provides a very simplistic means to calculate the area of a region to be covered by a single UAV. Given the assumption that small boats will proceed at 30 kts, the revisit time will need to be less than the amount of time it would take for a small boat to cross the boundary and reach the shipping lane. From the above simulation results, 20 nm is a reasonable value for D, which would imply that a small boat could reach the lane from the boundary in 40 minutes. This translates to a coverage ratio of six for a four hour patrol. Utilizing a UAV with sweep width 8 nm and speed over ground 70 kts, the resulting area of interest for a single UAV could be no more than 375 nm^2.

Assuming a straight line search to cover the entire area of interest translates into searching 120nm*(2D+5nm). Using the same 20 nm for D, the resulting total area of coverage would be 5400 nm^2. To achieve the desired revisit time, this would require 15 UAVs to be on station continuously. Using 15 UAVs only ensures that with a perfect sensor no small boat will be able to reach the traffic lane without being detected, but this gives little assurance that there will be enough early warning for a patrol vessel to react to a potential threat.

3.3.2 Barrier Patrol

A probabilistic analysis was made to determine the number of sensing assets necessary for patrolling along the area of interest. The probability of detection for a single small boat that arrives at a random point along the boundary was calculated. In both types of barrier patrol described below the patrolling UAV's are assumed to patrol outside the defined protected area so that any detection of a small boat made by them, will occur before it reaches the defined boundary. This idea is depicted in the figure below, where the UAV's are patrolling outside the protected zone and have a scan width of R_w.

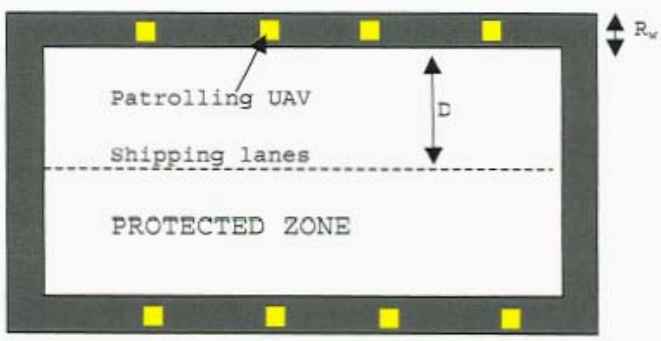

Figure 10. Boundary patrol

3.3.2.1 Circular Patrolling

In this scenario it is assumed that the UAVs are patrolling in a circular pattern with constant distances, d, between them. The patrolling route goes along one of the sides of the traffic lanes and comes back on the other side. Another assumption is that every small boat that was under surveillance for more than T_d has a fixed probability for its detection, p_d, and a reduced probability of detection, p_{dr}, if surveyed for less than T_d.

The time between visits for every point along the boundary in this case will be $T_r = (d - R_f) / V_c$. Where R_f is the forward looking range of the UAV sensor and V_c is its cruising speed. The time the UAV will survey each point will be $T_s = R_f / V_c$. The time it will take a small boat to cross the surveyed boundary will be $\tau = R_w / V_{sb}$, where R_w is the UAV sweep width and V_{sb} is the small boat speed.

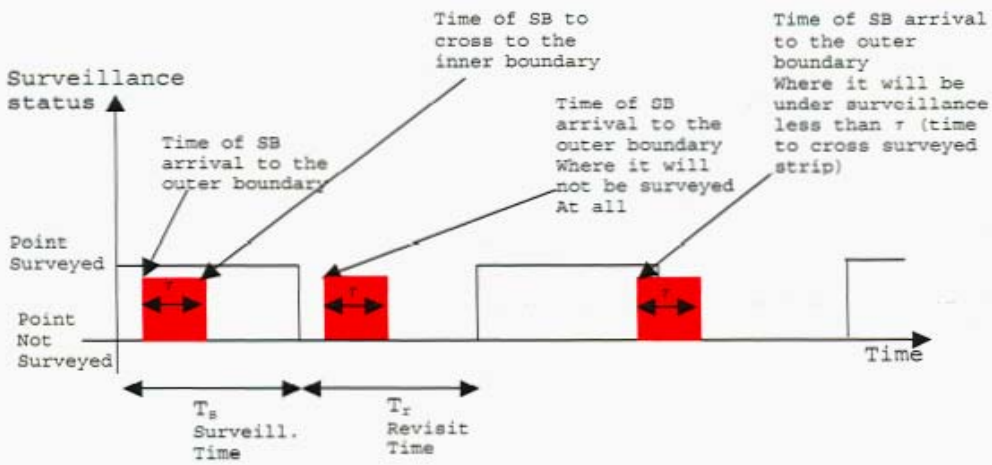

Figure 11. Surveillance time cycles over one point along the surveyed boundary.

The probability of detection of a boat entering at a random point of the boundary will be: $p_{detected} =$ p(the time boat surveyed T_d) p_d + p(0 < the time boat surveyed $\leq T_d$) p_{dr}, or, under the assumption that $T_d < \tau < T_r$ (see figure 11 above):

$$p_{detected} = \frac{2T_d}{T_s + T_r} p_{dr} + \frac{T_s + \tau - 2T_d}{T_s + T_r} p_d$$

In terms of the UAV parameters, this formula can be rewritten as:

$$p_{detected} = \frac{2T_d V_c}{d} p_{dr} + \frac{V_{sb} R_f + V_c R_w - 2T_d V_c V_{sb}}{d V_{sb}} p_d$$

The following graph shows this probability of detection as a function of the number of UAVs patrolling the boundary, with T_d=1 min, V_c=70 kts, V_{sb}=30 kts, R_f=10 nm, R_w=8 nm, p_{dr}=0.97, and d=0.5.

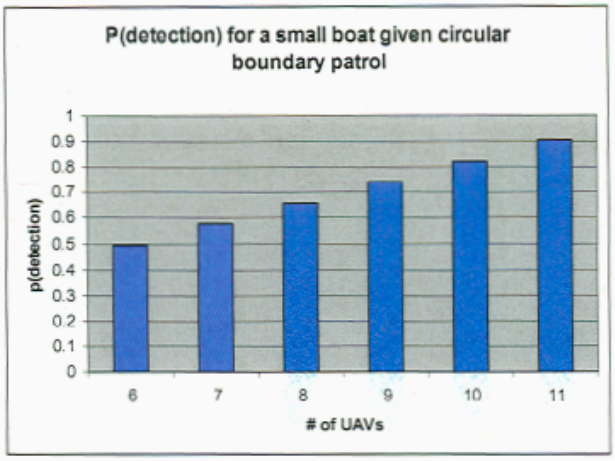

Figure 12. Pdet for circular boundary patrol

3.3.2.2 Sector Patrolling

Another barrier patrol alternative is dividing the boundary into sectors, each patrolled by a single UAV in a "back and forth" pattern. This alternative might be more efficient in UAV employment since no UAV time has to be allocated to covering the width of the straits. It is assumed that at the edge of its sector the UAV slows down to loitering speed, to ensure that the fringes of its sector will be surveyed for at least the minimal time for effective detection, T_d. In this alternative the shipping lanes are divided into sectors and two UAV's are patrolling each sector, one UAV at each side of the shipping lane. These sectors are not necessarily the same sectors that are mentioned in the reaction force employment.

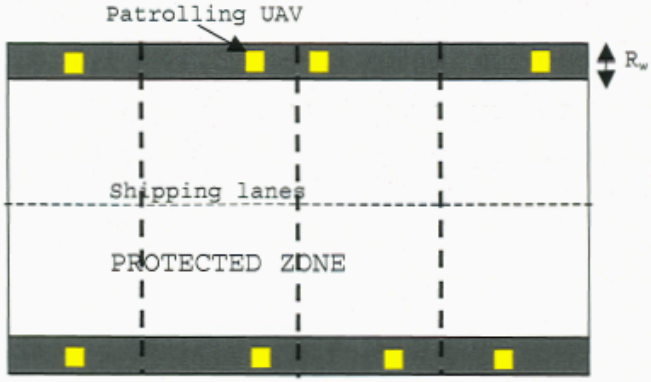

Figure 13. Illustration of sector patrol concept

For this scenario a slightly different approach was adopted for the analysis. A Surveillance Ratio (SR) was defined as the proportion of times the small boat would be under surveillance had it crossed the boundary, and the duration of the entire patrol cycle (see figure 11):

$$SR = \frac{T_s + \tau}{T_s + T_r}$$

Of course $T_r > \tau$ is assumed, other wise the surveillance ratio is always 1. For any given p_d, inherent probability of detection, the actual probability will be SR p_d. Different from the circular patrolling scenario, T_r and T_s are varying along the axis of patrol in the following manner :

$$T_s = \begin{cases} T_d + \dfrac{2x}{V_c} & x < R_f \\ R_f / V_c & R_f \le x < L - R_f \\ T_d + \dfrac{2(x - L + 2R_f)}{V_c} & L - R_f \end{cases}$$

Where x is the location along the patrol axis.
The revisit time will be:

$$T_r = \begin{cases} T_d + \dfrac{2(L - R_f - x)}{V_c} & x < R_f \\ T_d + \dfrac{2(L - R_f - x)}{V_c} & R_f \le x < L - R_f \text{ on the way right} \\ T_d + \dfrac{2(-L + R_f + x)}{V_c} & R_f \le x < L - R_f \text{ on the left} \\ T_d + \dfrac{2(-L + R_f + x)}{V_c} & Rx \ge L - R_f \end{cases}$$

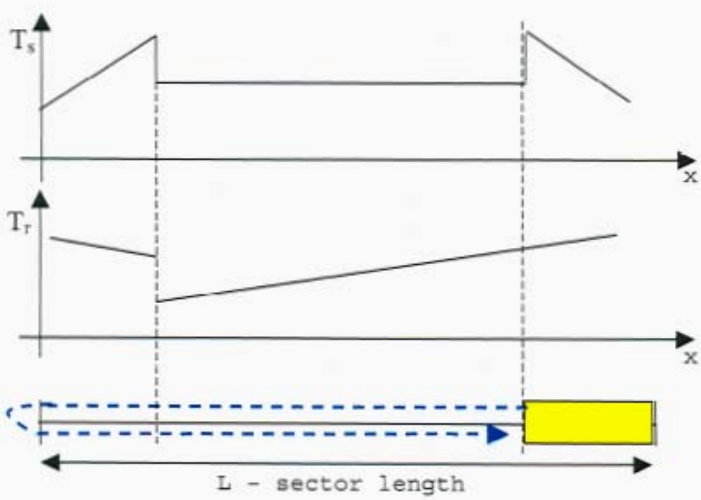

Figure 14 . the surveillance and revisit times for every point along the patrolled sector for a sensor moving from right to left and back.

The average of the SR over x is

$$SR = \frac{1}{2(L-R_f)}\left[\frac{T_d R_f + \frac{R_w R_f}{V_{sb}} + \frac{R_f^{\,2}}{V_c}}{T_d + \frac{L-R_f}{V_c}} + (R_f + \frac{R_w V_c}{V_{sb}})\left(\ln(T_d + \frac{2L-3R_f}{V_c}) - \ln(T_d + \frac{R_f}{V_c})\right)\right]$$

In the graph below are calculated values of SR for the same parameters specified in the previous part (circular patrol), only for the sector patrolling tactic. SR close to 90% can be achieved starting with around seven UAVs.

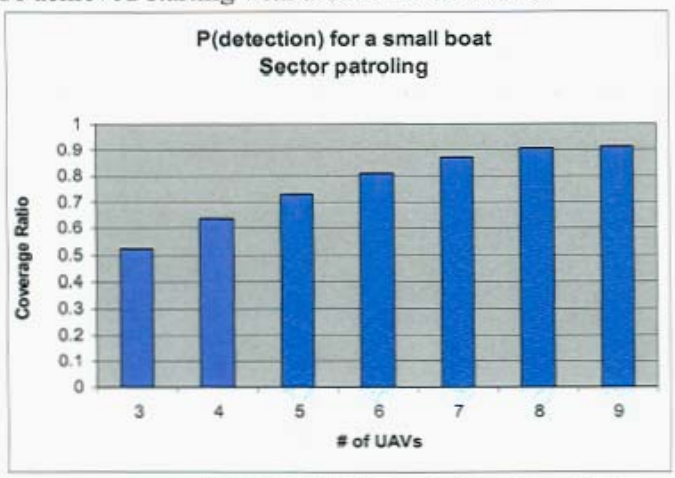

Figure 15. Pdet for sector boundary patrol

3.3.3 Convoy

Another way to require fewer UAVs is to further reduce the area of interest. This can be accomplished by placing HVUs in a convoy for transiting the Strait. Convoys reduce the AOI by creating concentrated groups of HVUs which results in places along the Strait that have to be covered and other places where there are no HVUs and therefore no need to provide sensor coverage in these areas. Convoys can be arranged to begin transit at specific times throughout the day, similar to the Suez Canal operations, or after a specific number, H, of HVU arrivals. Either method of assembling the convoys would result in a fixed number of vessels in the convoy. Choosing the fixed transit times would reduce the waiting time, but require some additional voyage planning considerations on the part of the merchants.

The number of vessels in the convoy should be chosen to minimize the number of UAVs needed. The most efficient use of assets would be to only have one convoy at a time transiting in each direction along the 120 nm length of the area of interest. The entire transit along this portion of the Strait would take approximately seven hours for vessels traveling at 18 kts. To account for possible delays, an eight hour transit is assumed. Choosing three transit times at eight hour intervals and using the estimated

HVU density of 75 vessels in each direction per day yields roughly twenty-five ships per convoy.

The formation for the convoy should also be as small as possible. Using only one UAV per convoy requires that the footprint of the UAV provide coverage of the transiting HVUs and also cover a sufficient area to provide early warning for the reacting force. Assuming an UAV with a sensor of range 8-10 nm forward and sweepwidth of 8 nm dictates the convoy configuration and early warning area into this total coverage area. The number of patrol vessels necessary will be such that a patrol vessel has sufficient early warning to intercept any incoming potential threat.

The maximum sensor coverage provided by the UAV requires that the reaction force be able to intercept a small boat in a given time, T, at the maximum range of the sensor. Therefore, T is based on the closure rate of the small boat and the convoy from all possible arrival points of the small boat.

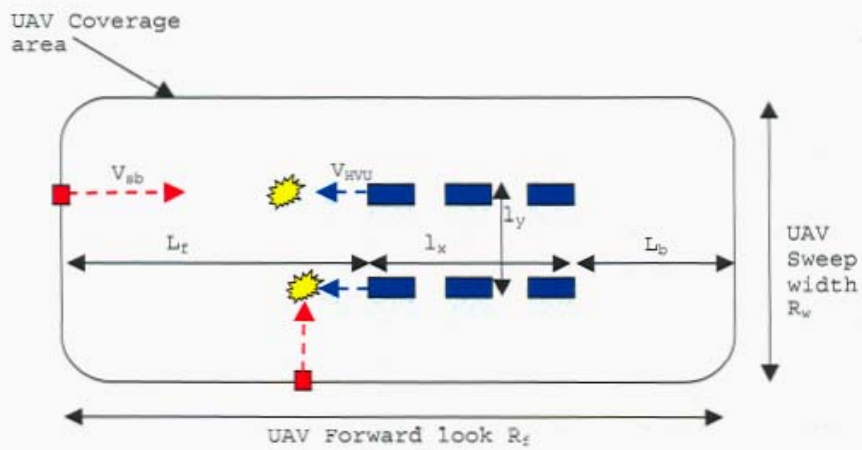

Figure 16. UAV footprint covering a single convoy, and the two worst case (in terms of reaction time) SB attacks from the front and side.

Considering the width of the convoy, $T = \frac{R_w - l_y}{2V_{sb}}$. It is assumed that the reaction times necessary for a small boat approaching from ahead of the convoy and one approaching from behind the convoy are equal. Therefore, $T = \frac{L_f}{V_{sb} + V_{HVU}} = \frac{L_b}{V_{sp} - V_{HVU}}$. The sum of the total length of the convoy plus the length forward of and behind the convoy must not exceed the maximum sensor range of the UAV: $l_x + L_f + L_f \frac{V_{sb} - V_{HVU}}{V_{sb} + V_{HVU}} = R_f$. Solving

for L_f yields: $L_f = \dfrac{R_f - l_x}{1 + \dfrac{V_{sb} - V_{HVU}}{V_{sb} + V_{HVU}}}$. Using the previously assumed speeds for small boats and HVUs, $L_f = \dfrac{R_f - l_x}{1.25}$. For example, a convoy of 24 HVUs in two columns with 500 yard spacing between columns and 500 yard spacing between vessels within a column yields T=7.25 minutes for a small boat ahead of or behind the convoy and T=7.75 minutes for a small boat approaching from the sides of the convoy. These times represent the worst case scenario for the shortest time from when a small boat initially enters the field of view of the sensor to impact with an HVU. Given a force that is able to react within these times, a UAV can effectively provide sensor coverage for protection of a convoy. Two patrol vessels will be sufficient to provide protection to this configuration of HVUs.

4. CONCLUSION

To provide Maritime Domain Protection (MDP) to HVUs against a small boat attack (SBA), it is not necessary to know the whereabouts of every vessel in the entire region of the Straits. It is possible to reduce the region into a smaller area of interest (AOI) in order to reduce the number of sensors required to adequately cover the region. In the approach area where the width of the Strait varies from 90 nm to 60 nm, spanning 120 nm in length, focusing mobile sensor assets on a well-defined area of interest can be an effective method of providing protection where no other viable sensor system exists.

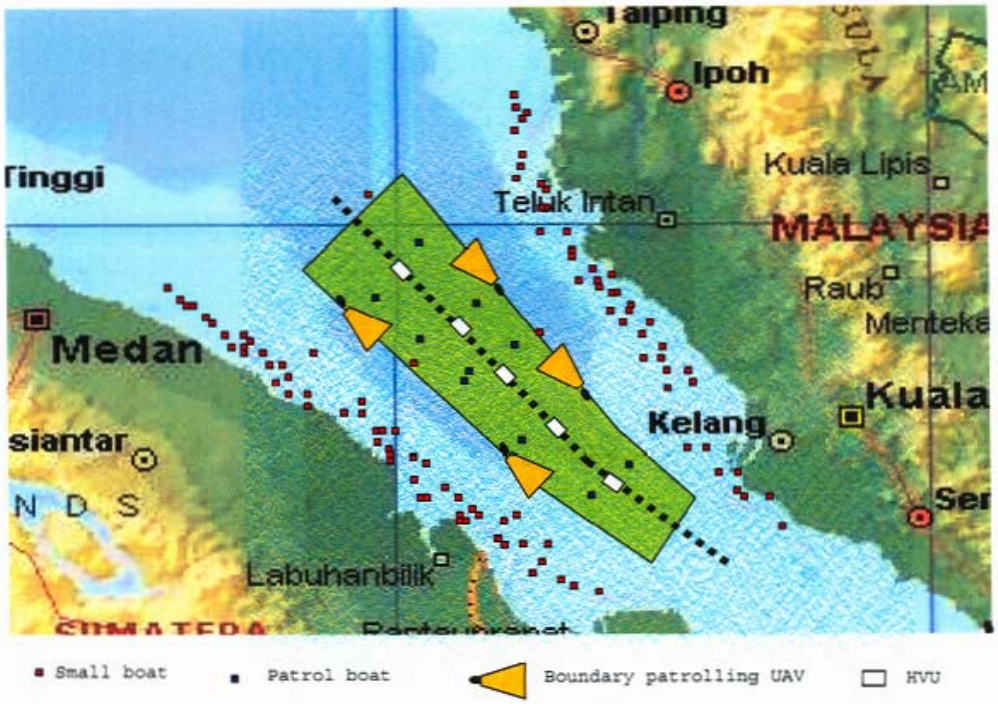

Figure 17. Illustration of a UAV based protection system in the approach area to the straits

Based on the above analysis, some insight is gained into the tradeoffs between the different elements of the subsystems within a protection system. Under the assumptions given in the analysis, a relationship between the patrol vessel characteristics, namely speed and quantity, and the number of UAVs required on station and their characteristics, namely speed and footprint, has been established. Given a specific area of interest, there are several possible combinations of UAVs and patrol boats to provide adequate coverage of the region. This relationship can be used to find the right balance between investing in the sensor system or investing in the force structure.

Convoys seem like the most effective means to facilitate a well-defined region for sensor coverage in order to provide protection to transiting HVUs using UAVs. Convoys would only require the use of one UAV per convoy at any time. This option, however, will have a great impact on the shipping industry. Transiting via convoy also poses the problem of where to stage HVUs that are rendezvousing for the next transit so as not to create a target-rich environment for an attacker.

The next best employment of UAVs is to conduct sector patrolling along the boundary of the area of interest. This tactic would require eight UAVs on station at any point in time to provide adequate coverage of the 5400 nm^2 AOI. Although this requires four times the number of UAVs on station compared to using convoys, this method of employment would not cause any disruptions or modifications to the flow of traffic throughout the Strait.

The model presented does not address all real world aspects of the protection mission. Once a vessel is detected and classified, the UAV proceeds with patrolling the area. In reality, however, the UAV may loiter over the small boat until a patrol vessel arrives on the scene to neutralize the potential threat. The discrimination of small boats is not addressed because it is assumed that any small boat approaching the shipping lanes is a potential threat. The adequacy of the sensor is also of import to the decision to employ UAVs. In poor weather conditions and at night the inherent probability of detection and range of the sensor are drastically reduced.

To effectively serve as the sensor platform in the area of interest, 24 hour coverage must be maintained by the UAVs. This requires relief on-station, which immediately doubles the number of UAVs to be procured. Mean time between failure (MTBF), mean time to repair (MTTR), and turn around time (TAT) between missions must also be considered. Ingress and egress time to/from the area of interest affect on station times. Autonomous aerial refueling could extend the time on station of the UAV, but the benefits of additional time on station would have to be weighed against the additional cost of using a refueling platform. A faster, longer-looking UAV with long on station times will increase the ability to protect a specific area of interest.

5. FUTURE RESEARCH

An optimization of the parameters of the subsystems can be conducted to determine the minimum number of assets needed given different specifications for UAVs. Based on the described tradeoffs between sensors and forces, a cost analysis can be conducted to determine an appropriate cost effective combination of assets.

IV. REACTIONARY FORCE FOR SMALL BOAT ATTACK

1. BACKGROUND

The Maritime Domain Protection (MDP) study group has developed a threat risk graph showing the likelihood of three forms of attack verses the consequences of the attack.[3]

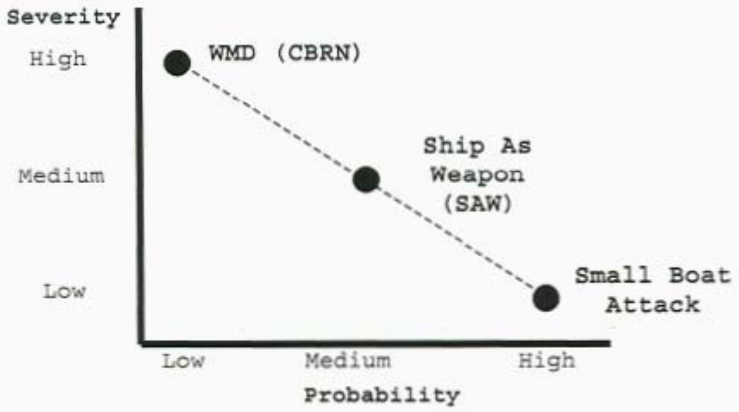

Figure 1. Threat Risk Comparisons

The inability of current maritime security systems to process and effectively counter terrorist threats is also highlighted, particularly in the form of Small Boat Attacks (SBAs), which present the most probable threat from economical, logistical and training perspectives. The crowded, shallow, and narrow passages along parts of the Straits of Malacca pose a high payoff to the terrorist community considering the consequences and the chances of success. A successful SBA, though having the lowest severity of consequences, will result in significant negative impact as it delivers the effect of choking up the shipping lines and potentially the closure of the Straits. The target rich environment in the water way network in and around the Southeast Asian waters, in particular the Straits of Malacca, presents an attractive breeding ground for low level crime, including pirates. Truly, the rising severity of consequences and lawlessness of some individuals and groups in that area has made the increasing probability of terrorist related crime too high not to address.

Is such a form of attack unheard of? No. The extensive research by the MDP study group on global events of terrorism has concluded that in just the last five years, this form of attack has been successfully conducted twice, first against the USS COLE while in port Aden, Yemen,[4] and again against the French tanker Limburg off the coast of

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[3] SEA7/TDSI Maritime Domain Protection Cross-Campus Integrated Project IPR2.0, 24th February 2005

[4] USS Cole (DDG-67) Tragedy & Honor, http://www.cargolaw.com/2000nightmare_cole.html

Yemen.[5] In both cases there were substantial damage to the hull of the ship, and in the case of the COLE there was loss of life.

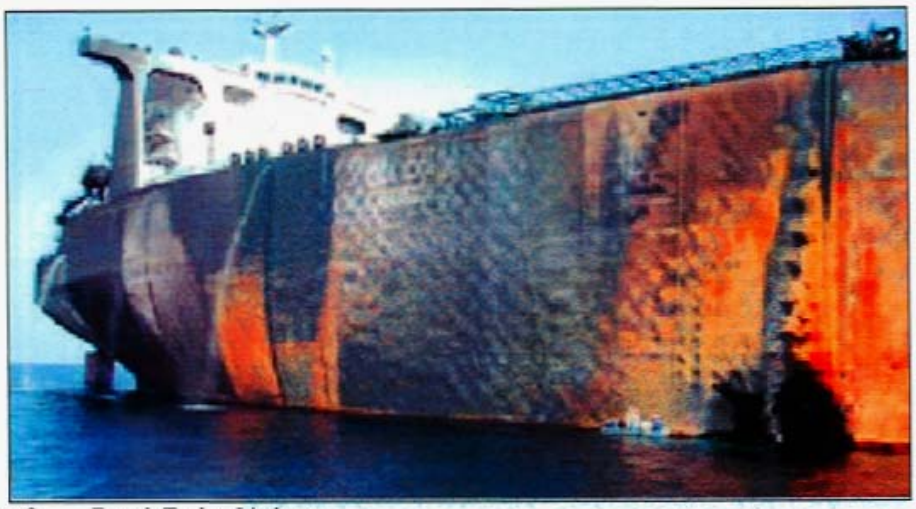

Figure 2. French Tanker Limburg

In the attack on the French tanker Limburg in the Gulf of Aden, Yemen in October 2002, a boat driven by two suicide bombers and booby-trapped with 1,150 kg of TNT, 150 kg of the highly explosive C-4 material, a number of detonators and other highly flammable materials rammed into the ship. Although the new double-hulled ship remained afloat, the force of the impact "pierced both hulls and penetrated 7-8 meters into the cargo hold, which was loaded with crude oil." If more attackers had been involved, or if the cargo had been more volatile, the outcome could have been far more severe.

The natural question in this regard is what are the potential impacts should the large volume of commerce in the narrow channel along the Straits of Malacca be choked due to small boat terrorist attacks? Are the current maritime protection processes and systems in the region capable of defeating or preventing such an attack?

2. PROBLEM STATEMENT

The task of quantifying traffic density is difficult as ships do not follow specific routes except at those portions of the Straits with traffic separation schemes. This challenging task is made harder with cross traffic as well as the presence of hundreds of fishing vessels and a high density of traditional small craft. In a cluttered maritime environment like this, monitoring all the vessels traversing the straits is an extreme challenge from the perspective of system, sensor and other resource requirements. To make matters worst, the hostile intent of a small terrorist vessel, in most cases, cannot be confidently ascertained until it is up close to its target. It is a very challenging problem to intercept and defeat hostile vessels charging at high speed given this short reaction time. The maritime protection force is therefore concerned with the force configurations and

[5] UK BBC, Monday 7 October 2002, http://www.bbc.co.uk/worldservice/learningenglish/news/words/general/021007_witn.shtml

alternatives that will ensure a certain level of success to neutralize the hostile boat before it successfully rams into its target, hereafter referred to as the High Value Unit (HVU). The definitions of a HVU vary widely with the contexts in discussion. Here, a HVU in this context is referred to as any maritime vessel on which damage or sinking will result in a loss of high economic value, a loss of many lives or even a significant adverse political or environmental impact. Examples of such vessels are bulk cargo carriers, LPG / LNG tankers, passenger ships and naval presence for peacekeeping operations.

3. SCOPE AND ASSUMPTIONS

It does not take much intuition for one to expect that the amount of force resources will increase with increasing number of HVUs to be protected. Then again, it is the objective of this project to evaluate the effectiveness of the various force alternatives in protecting the HVUs against SBA. More importantly, the project is focused to answer questions related to force configurations and system parameters that will be valuable to the system designers in guiding them in the design and development of the MDP reactionary force to ensure a pre-stated level of success. This study will focus on the modeling and analysis of three alternatives, the first two being the sea marshal option and the patrolling pickets option as proposed by the MDP Force group, and the third being a modification to explore a convoy escort option. Specifically, the OR Force group is interested in determining the number of sea marshal team or patrol-convoy pickets to be deployed in the Straits to ensure an acceptable probability of success given a SBA.

Perhaps the greatest challenge for maritime protection is the determination of hostile intent early enough for pre-emptive force to be employed successfully. This is also the reason why the group has decided to look into convoy-escort force alternatives where protected zones are established in an attempt to force the SBA to demonstrate hostile intent earlier than it would otherwise. However, having understood the importance of earlier detection of hostility, it should also be clear that much of the analysis is done under the assumption that hostile intent has been determined. It is the unhappiness with this assumption that drove the TDSI OR group to seriously investigate an escorted convoy option. While this option would require an unusual level of international cooperation, it would also allow for determination of hostile intent by proximity – shifting the tactical advantage to the defenders. In lieu of this, one could assume that there is a predecessor process that would perform the necessary target assessment before it is designated to the force component in the MDP system of systems approach with perfect target information.

Once a target is designated, the second assumption states there is no possibility of engaging a wrong target and the engagement models assume a cookie cutter design, that is the Probability of Kill for Single Engagement (PKSE) is 100%. It should also be noted that the numerous fishing and other vessels engaging in their normal activities along the Straits are not taken into account in any analytical computations except for the simple case that they are "obstacles" to the maneuvering of those vessels of interest. That is to say that the study assumes no collateral damage and does not probe into the effects of fratricide.

For the simplicity of model development and the lack of readily available data, the group recognizes that sea state has a significant effect on the weapon performance,

platform maneuverability and target performance, but does not consider such effects on the model outcome.

4. ANALYSIS METHODOLOGY

4.1 Agent-Based Modeling

The success of the MDP reactionary force to ensure security of the shipping traffic in the Straits depends on many interrelated factors, some controllable, others not. Some examples of controllable factors that will be explored in the study include the number of patrol or escort pickets and the number of HVUs to be protected. Uncontrollable factors would include the established location of the hostile boat and the degree of cluttering in the area of operations. These additional background factors are randomized to ensure that they do not contribute to the effects on the modeling outcomes.

The need to explore a wide range of experimental outcomes resulted from the considerably large number of factors, not even considering their interactions, prompting the use of a fast but low-fidelity computer model to execute repetitive runs for each possible design point. The agent-based computer models, referred to as "distillations" by the Project Albert community, has the following characteristics: transparency, speed, ease of configurability, and requirement of little training to use.[6] These distillation models are produced as an intentional complement to the very highly-detailed simulation models, which by the very fact that they are so highly-detailed and encumbered; do not permit the examination of a very wide range of possibilities and outcomes. Table 1 illustrates some of the pros and cons of various techniques.[7]

By running experiments on distillations that examine a large data space, analysts could seek to look into areas that traditional complex, high-fidelity, high resolution simulations could not or have not explored, with the ultimate goal of developing insights into the questions at hand. The Map-Aware Non-uniform Automata (MANA), developed by the New Zealand Defense Technology Agency, is widely used by the Project Albert team amongst the suite of distillation model tools. Based on the fact that there already exists a considerably large community within the OR curriculum which uses MANA for their research, the OR force group has decided to use it to build the scenarios representing different MDP force alternatives.

	Pros	Cons
Wargames	Provides a common tableau for discussion; enhances mutual understanding; allows the imagination to roam	Non-reproducible; often dominated by personalities; limited options; unrealistic opposition
Equations	Only one "run" needed; appeals to our background; ideal when	Validation almost impossible without a theory of war; sensitivity to initial

6 Project Albert Website. http://www.projectalbert.org

7 Horne, Gary, Beyond Point Estimates: Operational Synthesis and Data Farming, Maneuver Warfare Science 2001, USMC Project Albert, December 2001

	steady state solutions apply	conditions a problem; relations may not be functions of usual variables; binary events a problem; closed form solutions rare
Simulations	May be only way to get a high fidelity sample; ample validity difficult but doable; experimental data may contribute	Epimorphism onto space of outcomes problematic; validation of ensembles beyond current state of art; important variables may not be accessible; binary events are a major challenge
Distillations	Validation often trivial; can handle non-linearities, binary events, sensitivity to initial conditions, emergence; fun; accessible to all; adaptable to passively parallel machines; can create all the data need; can relate to intangibles and coevolving landscapes	Accreditation is a ridiculous issue; sampling possible but may require new statistics; visualization a challenge

Table 1. Pros and Cons of Various Modeling Techniques

4.2 Data Analysis

The data collected from the production runs on MANA provides an extensive source of experimental input into the next process of the analysis plan. Most of the data elements generated by MANA are not in the exact format and thus have to be massaged to the form desired for analytical purposes. The JMP Statistical Discovery software package has been chosen for its ability to manipulate the input data without a steep learning curve using friendly graphical user interfaces, and more importantly, for its superb power to handle hundreds of thousands data points. The analysis extracted essential parameters (or Measures of Effectiveness, a standard terminology in the field of Operation Research) from the data to determine the amount of force resources needed to commit in the protection of the HVUs given a pre-stated level of success.

In addition to the single point estimate of the force resources required to commit, the study also aimed to gain useful insights into the effect the number of HVUs to be protected has on these parameters. The experiment was accomplished using a full factorial design taking into account the fact that the total number of design points, though large, is manageable using the identified distillation model.

5. SCENARIO DEVELOPMENT

5.1 The SBA Scenario

The MDP force is primarily concerned with the provision of maritime protection along the narrowest part of the Straits of Malacca which stretches 300nm in length and 30nm in width as marked in the map as shown in Figure 3. Designed to demonstrate the ability for timely response of the maritime domain protection system, the SBA scenario is based on the attack on the French tanker Limburg off the coast of Yemen as discussed in Section 1 of this chapter. The SBA scenario as described in detail in the main report

entitled "Maritime Domain Protection in the Straits of Malacca" will be used as the basis for model formulations and analysis throughout the project.

The scenario is modeled with the two force alternatives proposed by MDP Force study group: the current baseline option of deploying sea marshals onboard the HVU to be protected and the patrolling picket option with the Patrol Vessels (PVs) designed by the TDSI Force group. The TDSI OR group has included in this project a modified alternative to investigate the effectiveness of a convoy escort.

Figure 3. Critical Area Along the Straits of Malacca

5.2 Force Alternative I: Sea Marshal

The sea marshal protection scheme, as defined by the MDP Force study group, is the first of the two force options to be investigated for its effectiveness in the defeat of a SBA. The program involves a five-man team armed with 5.56 and 7.62 mm small arms, and is air or surface deployable to the HVU and should have internal and external communications to the command and control centre. The sea marshals will embark the HVU before it transits through the Straits and disembark when it reaches the opposite end.

5.2.1 Model Formulation

The sea marshal model is perhaps the most trivial from the perspective of analytical complexity and mathematical formulation. The biggest assumption made to simplify the model is that if a boat is identified charging toward the HVU with sea marshals onboard, its hostile intent can be established with certainty (this assumption was discussed earlier in this chapter). The ability to defeat the threat without causing any damage to the HVU by the onboard sea marshals is almost certain given the fragility of

the attacking small boat. In other words, assuming hostile intent is determined outside the blast radius of the small boat and a vigilant sea marshal team is embarked, the probability of mission success in defeating the attack on this HVU is 100%. Therefore to achieve a mission success of 80% for protecting, say, 100 HVUs at any point in time, simple probability says that it is sufficient to just deploy 80 onboard sea marshal teams on the 100 HVUs.

5.2.2 Measures of Effectiveness

Following the argument, it is noted that the number of onboard sea marshal teams required to achieve 80% of mission success is 80% of the number of HVUs in the Straits to be protected at any point in time. However, one might have already anticipated that by grouping the HVUs close enough in a certain configuration and equipping the sea marshals with weapons of sufficient range and precision, it could well be possible that one sea marshal team could provide protection over a group of HVUs convoyed together in transit. This is another argument for the convoy-escort force alternative, which will be discussed in Section 5.4 later in the chapter.

5.3 Force Alternative II: Patrol Picket

A second force alternative proposed by the MDP Force study group is the patrol picket option. The protection scheme entails the use of a High Speed Vessel (HSV) mother-ship as a floating logistics and support staging base for the PVs, in this case, the TDSI Transports, operating in the Straits of Malacca in a combination of patrolling and HVU escort missions. Following an interview with the U.S. Navy SEAL Detachment from Naval Special Warfare Group and the Lead Instructor at the Inshore Boat Unit School in Cherry Point, North Carolina, the MDP Force group has concluded that the most efficient patrolling profile would be to split the entire area of interest into two segments of equal length, one in the northern half and the other in the south, and have each area independently patrolled by the PVs in an effort to deter small boat attacks, and to react in the event of an attack, as shown in Figure 4.

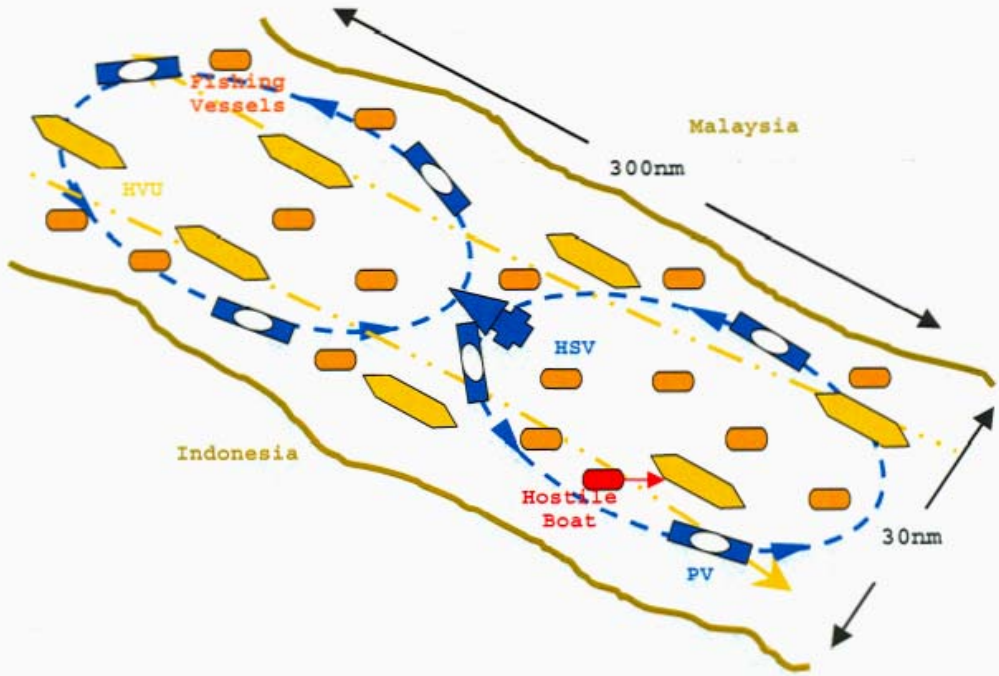

Figure 4. Patrol Picket Option

5.3.1 Model Formulation

As the entire area of interest is divided into two separate sections, each patrolled by an independent set of PVs, the distillation model is therefore setup to depict only one section of the Straits with an area of 150nm by 30nm waterways. The simulated area of operation is also partly restricted by the limit of a 1000 by 1000 grid system imposed by MANA. In order to achieve a resolution good enough to model close combat, the inter-grid spacing is set to 300 meters (approximately 0.15 nm); any smaller inter-grid spacing would reduce the area simulated and modeling of a sensible patrol pattern would not be possible.

The hostile boat in the model will start off by impersonating an "innocent" fishing vessel, indicated in the model as a green ship icon as are other legitimate shipping vessels in the vicinity. As a HVU sails within one nautical mile of the hostile small boat, the small boat will begin its approach and charge with a speed of 30 knots towards the HVU. It is at this moment that the small boat is established hostile and designated as a target to the nearest PV by some MDP predecessor process. This is indicated in the model as a red ship icon. The PV, which is initially patrolling in its patrol path with a cruise speed of 25 knots, will change its course and charge towards the hostile boat at a speed of 40 knots until the target is within its weapon range. The speed and weapon range used for the PVs in the model are extracted from the parametric study of the Patrol Ship designed by the

TDSI Force group[8]. A sequence of the model screenshots and scenario walkthrough for the patrol picket scheme developed in MANA is attached in Appendix A-1.

5.3.2 Model Parameters

The data farming feature in MANA is used to farm the set of excursions for each combination of the parameters (number of HVUs and number of PVs). The combinations present a total of 500 excursions, and for each excursion, 50 runs are executed, thus yielding 25,000 runs in total. The parameters are varied as tabulated in Table 2.

Parameters	Lower Limit	Upper Limit	Increment
Number of HVUs	1	50	1
Number of PVs	1	10	1

Table 2. Patrol Model Parameter Table

The HVUs in each excursion are placed randomly along the sea lanes with the only constraint that half of the HVUs is heading Southeast towards Singapore and the other half, Northwest towards the Indian Ocean. The starting positions of the PVs are also randomized along the patrol path with the restriction that they are approximately equi-distant apart.

One of the objectives for the analysis is to evaluate the change in number of PVs required to achieve the same level of mission success as the number of HVUs to be protected increases. The upper limit for the number of HVUs transiting the Straits is calculated based on the World Oil Transit Chokepoints Analysis brief by the Energy Information Administration in March 2004[9]. The brief reports the number of shipping vessels transiting the Straits of Malacca is no less than 50,000 per year. This figure translates to a typical day shipping traffic of approximately 140 vessels in the entire Straits, and therefore corresponds to 70 vessels in half of the Straits. Assuming that two-third of these vessels are classified as high value, this gives an estimate of 50 HVUs of interest to the maritime protection force. On the contrary, the upper limit for the number of PVs of 10 is determined empirically to achieve the desired level of success for the worst case.

5.3.3 Measures of Effectiveness

The Measure of Effectiveness (MOE) collected from the excursions of this model is the probability of success (SBA prevention) at each design point, that is, for each combination of the number of HVUs and PVs.

5.4 Force Alternative III: Convoy-Escort Picket

The escorting of a significantly large number of HVUs with on-board sea marshals might have caused the question "Is there a better and more efficient way than doing this?" in the minds of the maritime protection stakeholders. This is exactly the same reason the TDSI Operation Research group is interested in investigating the convoy-escort option to determine its efficiency over the sea marshal scheme. It is, however, not the intent of this study to establish the monetary worth of each option, nor is it the exclusion of one over the other, but to compare the options based on pure

8 Maritime Domain Protection Force Group Integrated Project Report, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, June 2005

9 World Oil Transit Chokepoint Country Analysis Brief, Energy Information Administration (EIA), March 2004. http://www.eia.doe.gov/emeu/cabs/choke.html

quantitative measures of the number of sea marshal teams needed versus number of escort pickets required. There may be other political or economical rationales that may warrant for the choice of one option over the other.

The convoy-escort protection scheme is inspired by the shipping model adopted for ships traversing the narrow Suez Canal of Egypt, a vital water way often called the "crossroads of Europe, Africa, and Asia" in that the route is used to transport goods to and from all three continentals. Ships transiting the narrow water passage along the Suez Canal have to adhere to strict rules of navigation and convoy timings[10] imposed by the Suez Canal Authority. All LPG/LNG tankers or large bulk carriers exceeding a certain size or loading arc mandated by the maritime authority to be escorted by escort tugs. In the case of the Straits of Malacca, the convoy-escort protection scheme will require all the HVUs arriving at both ends of the Straits to form a convoy and be escorted through the passage by a squad of Escort Vessels (EVs) as depicted in Figure 6.

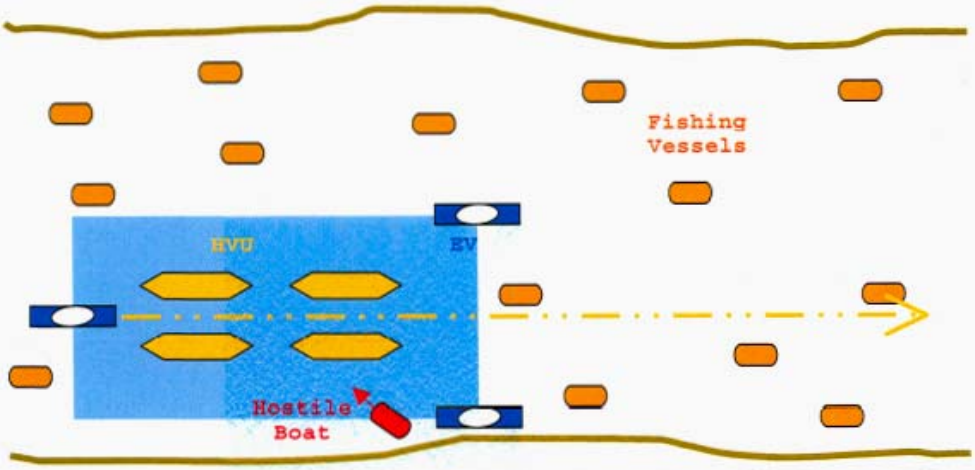

Figure 5. Convoy-Escort Picket Option

5.4.1 Model Formulation

In this model, the behaviors of the hostile boat and the EVs are modeled like those in the patrol picket model with similar platform and weapon parameters. However, in order for the EVs and HVUs to traverse in the given formation throughout their passage through the Straits, all the vessels will be sailing approximately at the same speed, which is the fastest speed the slowest vessels in the convoy. In the convoy-escort model, the EVs are set to sail with a speed of 25 knots, in tandem with the HVUs to be escorted.

While there is a lack of unclassified specific escort formations in the tactics manuals of the major naval forces, there exist several guidelines governing the planning of a maritime protection escort mission such as the safety distance between two vessels in

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10 International Maritime Services Co, Egypt, Suez Canal Information. http://www.imsalex.com/suez_canal.html

the convoy, the relative position of each escort ship depending on its role as well as the maritime geographical constraints in which the convoy is transiting. The escort formations for one, two and three EVs used in the model are shown in Figure 6. The front-biased formations are conceptualized based on the idea that it is more vulnerable at the front of a convoy as it is potentially harder to defend against threats coming from the front than the rear.

The choice of the specific HVU to attack is purely based on its proximity to the hostile boat. The hostile boat will continue to act "innocent" while waiting for the convoy to pass through it and only commence its course when a HVU is close within one nautical mile in range. The random placement of the initial position of the hostile boat and HVUs in the protection zone ensures that the attack is not solely targeted on HVUs on the outer circumference but also those on the inside of the formation.

Figure 6. Escort Formations for Convoy-Escort Protection Scheme

The size of protection zone is estimated based on the maximum number of HVUs to be accommodated and the safety distance between two HVUs while traversing in the convoy. A series of interviews with naval officers from both the U.S. Navy and the Republic of Singapore Navy has concluded that a good approximation of the safety distance between two HVUs should be no less than five-cable length (which is equivalent to 0.5 nm) away. Assuming one convoy per day per direction, to accommodate a maximum of 50 HVUs in a formation of six columns and nine rows, the protection zone is estimated to cover an extent of 4 nm in width and 7 nm in length.

5.4.2 Model Parameters

Similar to the data farming process that is used for the patrol picket model, the number of HVUs and EVs are varied as shown in Table 3. The combinations yield a total of 150 excursions, and 50 runs are executed for each excursion, thus giving 7,500 runs in total. The maximum number of PVs is limited to three, which is sufficient to provide the desired level of mission success.

Parameters	Lower Limit	Upper Limit	Increment
Number of HVUs	1	50	1

Number of PVs	1	3	1

Table 3. Convoy-Escort Model Parameter Table

5.4.3 Measures of Effectiveness

As in the case of the patrol picket model, the primary MOE collected for this model is the probability of success for each combination of the number of HVUs and EVs.

6. RESULTS AND ANALYSIS

After the process to formulate and validate the models, the computationally intensive run of the models follows to generate results. It is important at this point to recap the objectives of this study. As stated in the beginning of the chapter, it is the desire of this operational research effort to determine the amount of force resources needed to commit in the protection of the HVUs given a pre-stated level of success, and to draw important insights into the effects the numbers of HVUs and force alternatives have on the force resources. Finally, to set the stage for meaningful comparisons among the three force alternatives, the group has decided to look at parameters that will present 80% chance of mission success given an SBA attack in all the force options.

6.1 Analysis for Patrol Picket

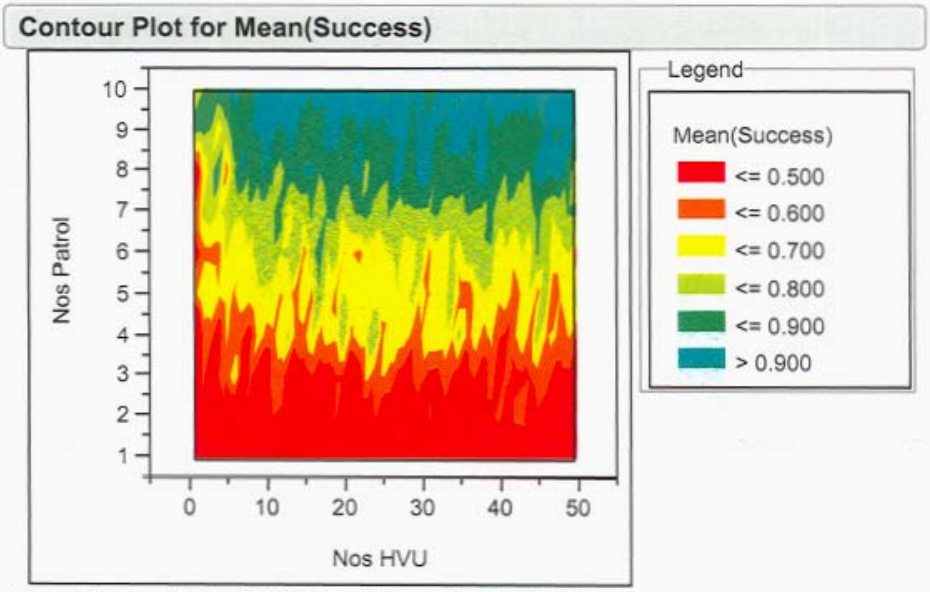
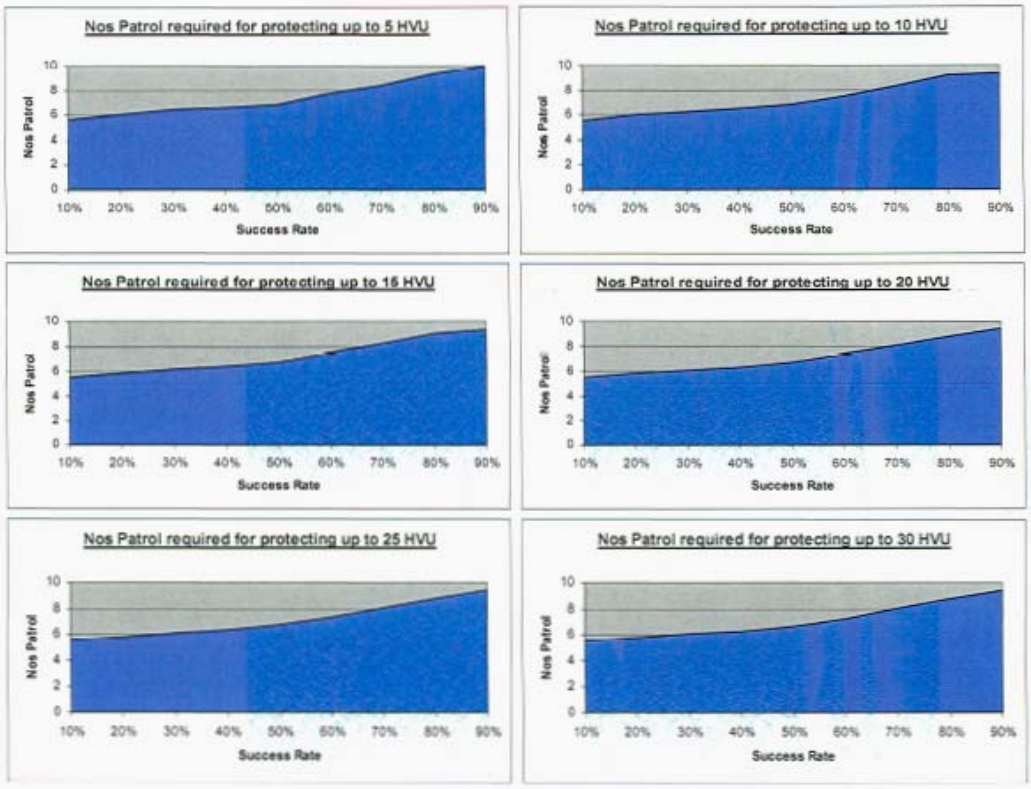


Figure 7. Contour Plot for Probability of Success for Patrol Picket

The interview with the U.S. Navy SEAL Detachment from Naval Special Warfare Group and the Lead Instructor at the Inshore Boat Unit School in Cherry Point has proposed the use of 3 PVs patrolling each segment of the Straits of Malacca. The results of the simulations have provided further insights into this proposal. Figure 7 shows the probability of success with 3 PVs given the platform and weapon parameters suggested by the TDSI Force group is at best 60%. While this might be sufficient from a deterrence standpoint, the TDSI OR group opines it to be ineffective in defeating a SBA attack

should it really occur. On the contrary, up to 9 PVs are needed for each segment in order to achieve at least 80% chance of success.

The relatively gentle slope for each range of the level of success suggests that the number of HVUs does not seem to have an effect on the number of PVs required for a specific probability of success, except when the number of HVUs is small, say lower than 10. The observation may appear counter-intuitive at first look, but on careful thoughts, the trend makes perfect sense as it is assumed that there is no consideration of concurrent SBA attacks; attacks occur independently and only one occurs at any point in time. The force response system is therefore mainly a force coverage optimization problem with interactions of related factors without taking into account of the protection demands from multiple sources. Hence, the number of HVUs does not significantly affect the number of PVs required. However, when the number of HVUs to be protected is small, the likelihood that a PV is in the neighborhood during an attack and close enough for timely reaction is scare, hence explained the larger number of PVs to achieve the same level of mission success. This may well advocate the effectiveness of the sea marshal option when the number of HVUs to be protected is small.



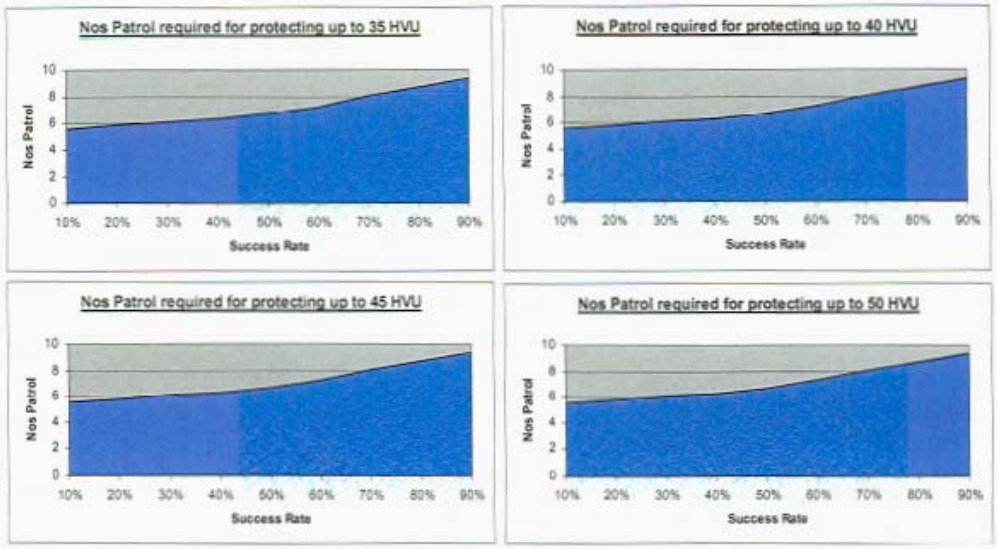


Figure 8. Graphs for Required Patrol Vessels

The graphs in Figure 8 suggest that it requires less additional PVs to contribute a given increase in the success rate at lower probabilities of success than at higher probabilities of success. At success rate of 50% and below, every increase in the number of PVs employed approximately increases the chance of mission success by 20%; at success rate above 50%, an increase in each PVs only increases the success rate by 10%. The trend can be extrapolated to predict that to achieve a success rate of close to a 100%, the number of PVs does not really increase beyond 10.

6.2 Analysis for Convoy-Escort Picket

The results for the convoy-escort picket option from the agent based model have presented an ideal solution. The graphs in Figure 9 indicate that with just one EV, it is sufficient to protect a convoy of maximum 50 HVUs transiting through the Straits of Malacca in each direction with 100% chance of success. The outcome may be astonishing to many; however, it reinforces the group's initial intuition. The offensive weapons on-board the EV as proposed by the TDSI Force group encompass the OTO Melara 76mm gun system with an effective range of 8.5 nm and the Otomat missile system with an effective range of 60 km (or approximately 30 nm)[11]. The Otomat missiles can also be launched at any direction without imposing on the ship's maneuvering constraints, hence providing equal engagement coverage in all direction with respect to the direction in which the ship is heading. This translates to the engagement range of 9 nm in the model, and together with the assumed PKSE of 100%, has well covered every corner of the protection zone which stretches only 4 by 7 nm. Thus with such superior weapon systems onboard, it is within expectation that one EV is sufficient to protect a single convoy with no chance of failure. While firing a 30 nm missiles may be problematic regarding rules of engagement, the 76 mm gun system has adequate range to cover the protection zone. This

11 Maritime Domain Protection Force Group Integrated Project Report, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, June 2005

ignores the HVU being in the line of fire, and is an argument for why more than one EV would be necessary.

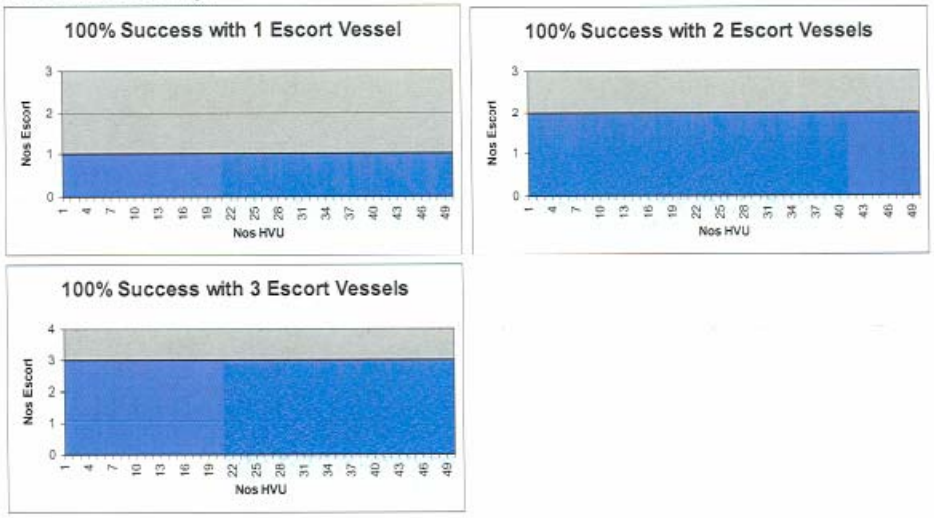


Figure 9. Graphs for Required Escort Vessels

7. CONCLUSION

The MDP Force OR study has concluded that to protect a maximum of 100 HVUs traversing the entire area of interest in the Straits of Malacca with at least 80% of mission success, there is a need for 18 PVs to patrol the Straits or 2 EVs to escort the HVUs: one escorting the southeast bound convoy; the other, the northwest bound. The number of HVUs to be protected in the model setup has shown to have no significant effect on the required number of MDP force vessels. However, the number of sea marshal teams deployed linearly increases with the number of HVUs of interest. Table 4 provides a summary of the size of force resources required for each option.

Nos HVU	**5**			**50**		
Force Alternatives	**Sea Marshal**	**Patrol Picket**	**Convoy-Escort Picket**	**Sea Marshal**	**Patrol Picket**	**Convoy-Escort Picket**
Nos Resources (At least 80% success)	4 teams of 5 men	18 PVs	2 EV	40 teams of 5 men	18 PVs	2 EV

Table 4. Force Resources Required Among Alternatives

It should be understood by the reader that the results in this study is largely a factor of several model parameters assumed, which include the effective weapon range and the maximum thrust speed of the force vessels, and the size of the protection zone of the convoy. For instance, the effective dimensions of the protection zone changes with the number of HVUs to be protected and probably the shipping intensity in the Straits. As the number of HVUs increases beyond 50 per day in each direction, it may no longer be feasible to have just one convoy, but more effective to segregate them into multiple

convoys. Similarly, a smaller engagement range or a lower thrust speed will imply that more force vessels must be staged to achieve the same force coverage with the same response capability. Therefore, the OR group cautions the reader not to focus on the absolute values of the analysis outcome but to understand the general observations from this analysis.

The reader is reminded again at this juncture that it is not the intent of the study to find the "best" force alternatives at the exclusion of others. In reality, the choice of each alternative is not solely based on the amount of resources required but depends on other factors such as geographical suitability and political implications. It is observed that while the sea marshal and the convoy-escort options provide the best protection capability and response, the patrol option is preferred for deterrence measure with reasonably low resources committed. However, to ensure satisfactory protection capability and a force response fast enough to cover the entire Straits of Malacca, the number of PVs to be deployed must be large and may not be justifiable for small number of HVUs. Nonetheless, the sea marshal option may not be implemented easily due to the need for central coordination of embarking and disembarking of the sea marshals, and more importantly, the political resistance for allowing sea marshals onboard HVUs of certain national origins. The sea marshal option is also not viable when the number of HVUs is large, which in this case, the convoy-escort option is more effective. It should be noted that in a high density maritime traffic environment like that in the Straits, a large convoy may not be geographically feasible and thus there is a need for many small convoys. This implies the number of required EVs will increase significantly and would make more sense from an economical perspective to use the patrol option instead.

8. FUTURE RESEARCH

Effects of Weapon Range and Probability of Kill for Single Engagement (PKSE). It is obvious now from the earlier discussion that the weapon range and PKSE affect the number of force vessels to be staged for a satisfactory level of mission success. While it is always possible to find a weapon of extended range and precision such as the Otomat missile system, one should take into account the operational feasibility of such weapon. In a cluttered environment such as the Straits of Malacca, it would take much risk of collateral damage to fire a Non Line Of Sight (NLOS) weapon on a small target beyond visual LOS. The group recommends further analysis on determining the significance of a degraded weapon range and PKSE would have on the force parameters presented in this study.

Effects of Available Response Range. While it is possible to determine the hostile intent of a small boat at a range of one nautical mile from its targeted HVU given accurate intelligence, the hostility in most cases will only be determined when it well within the assumed threshold. An extended study is therefore recommended to explore the effects a closer response range have on the probability of success and the number of MDP force elements required.

Effects of Convoy Formation. The convoy formation in this analysis for a maximum of 50 HVUs is fixed on 6 columns by 9 rows, which is practical for most part of the Straits with the exception of certain passages such as the Phillips Channel where the water depths are shallow and the width barely 1.5 nm. In such areas, it is required for the HVUs to transit in a single file. The change in the convoy formation, and hence the protection

zone, may fall outside the force coverage of the current escort formation and may suggest that more EVs are required to encapsulate the new protection zone. The group proposes a further study on the effects of the convoy formation on the force parameters.

APPENDIX I

Snap Shots OF MANA Models

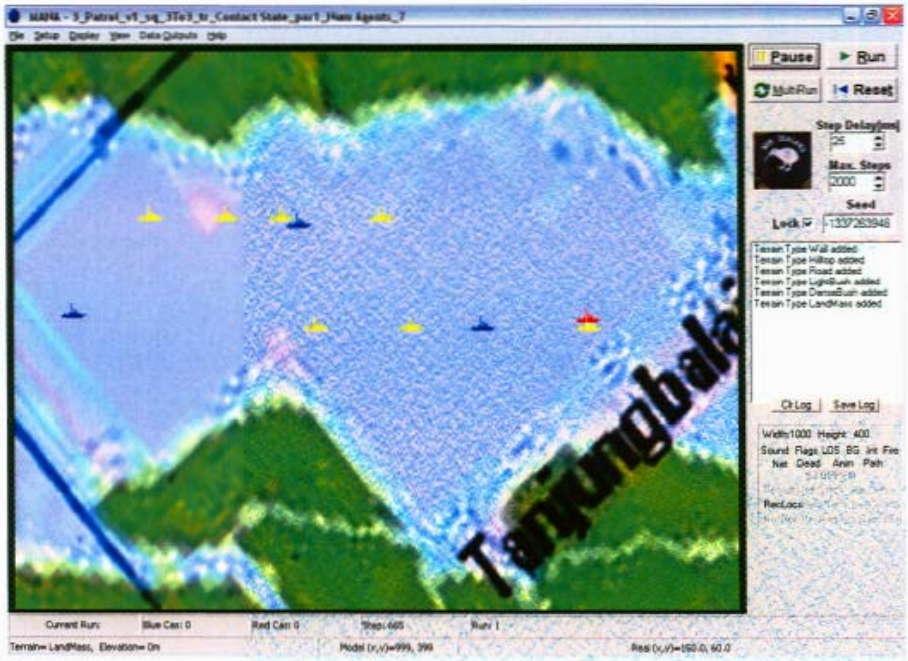
Force Alternative II. Patrol Picket

a. Start of Scenario

- One hostile boat impersonating as a fishing vessel (green ship icon)
- Seven HVUs – 4 sailing Southeast and 3 sailing Northwest (yellow ship icon)
- Three PVs (blue ship icon)
- 68 fishing boats (green ship icon)

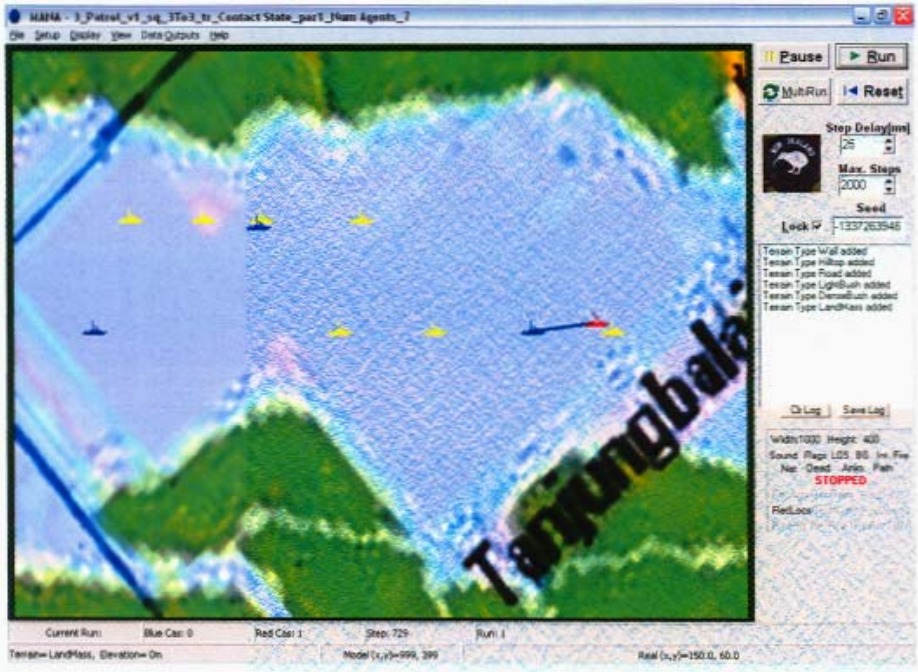
b. Hostile boat waiting for its target

- The fishing boats are removed from the screenshots to avoid cluttering the display.
- A HVU sails towards the hostile boat without knowing its intent.
- The hostile boat starts to exhibit hostile intent and charge towards the targeted HVU at a speed of 30 knots when it is within one nautical mile.
- The hostile intent is established by some predecessor processes, indicating by switching the hostile boat into a red ship icon.



c. Nearest Patrol Vessel intercepts and engages the hostile boat

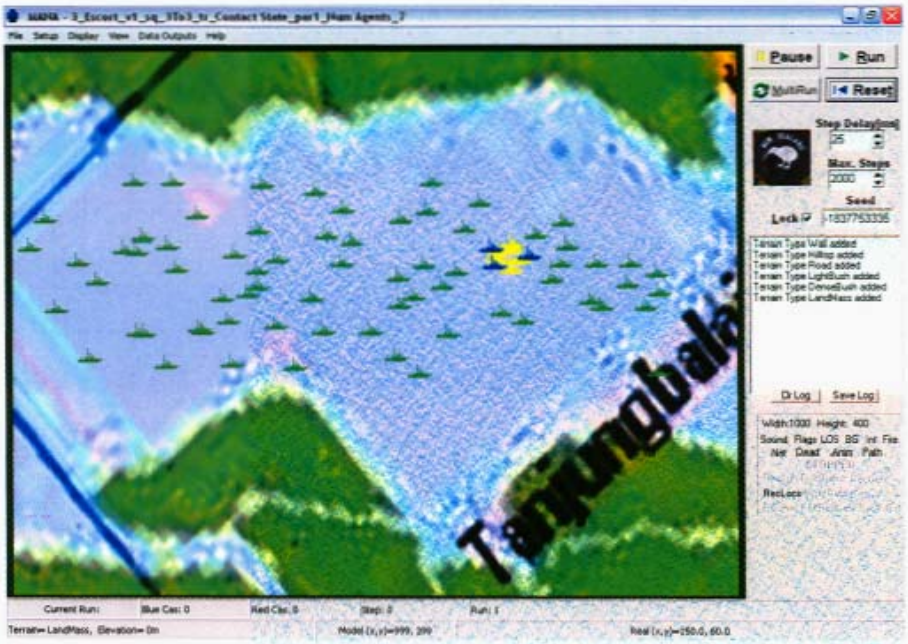
- The nearest PV attempts to speed up to 40 knots and intercept the hostile boat.
- The PV engages the hostile boat at 9 nm and defeats the hostile boat successfully before it rams into the HVU.



Force Alternative III. Convoy-Escort Picket

a) Start of Scenario

- One hostile boat impersonating as a fishing vessel (green ship icon)
- 68 fishing boats (green ship icon)
- Convoy comprises of seven HVUs sailing Northwest (yellow ship icon) and three EVs (blue ship icon)

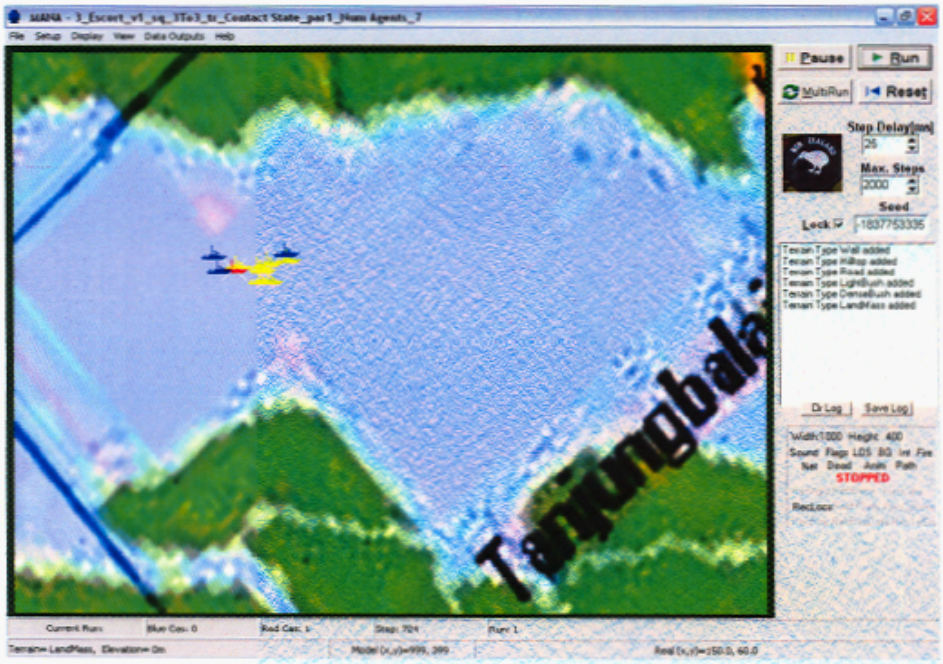


b. Hostile boat waiting for its target

- The fishing boats are removed from the screenshots to avoid cluttering the display.
- Convoy sails towards the hostile boat without knowing its intent.
- The hostile boat starts to exhibit hostile intent and charge towards the targeted HVU at a speed of 30 knots when it is within one nautical mile.
- The hostile intent is established by some predecessor processes or by proximity, indicating by switching the hostile boat into a red ship icon.

c. Nearest Escort Vessel engages the hostile boat

- The nearest EV engages the hostile boat within its weapon range of 9 nm.
- The EV defeats the hostile boat successfully before it rams into the HVU.



APPENDIX N: TDSI LAND SYSTEM SEARCH MODEL FINAL REPORT

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

INTEGRATED PROJECT
(TDSI Land System)
An Inspection Search Modeling of Cargo Container Ships

By
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CPT K.H. YEOH
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1

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1. INTRODUCTION

Geographically, the Straits of Malacca, Straits of Lombok and Sunda Straits had always served as the 'southern entrances' to the South China Sea. See Figure 1 below. A large volume of international maritime traffic transited this region annually. In 1993[1], $568 billion of long haul international seaborne shipments passed through these 'entrances', making up over 15% of all world's cross-border trade, excluding intra-regional trades[1]. Over half of the world's merchant fleet capacity (> 1/3 of world's ships) sailed through these Straits alone[1,2,3]. As a result, in light of its strategic and economic importance to many countries in the world, these Straits were also commonly viewed as 'chokepoints'.

By sheer deadweight tonnage of over 1000 DWT[2] merchant shipping alone, in 1993, the Straits of Malacca handled the highest flow of trade volume, amounting up to 1509 millions DWT, as compared to Straits of Lombok (297 millions DWT) and Sunda Straits (102.4 millions)[1]. The shipping traffic through the Straits of Malacca was also several times greater than the traffic along Suez or Panama canals. Some estimates put it that the Straits of Malacca alone carried about ¼ of the world's commerce and half of the world's oil[4]. Therefore, it was vital that there had to be continued undisrupted trade flow along the Straits of Malacca.

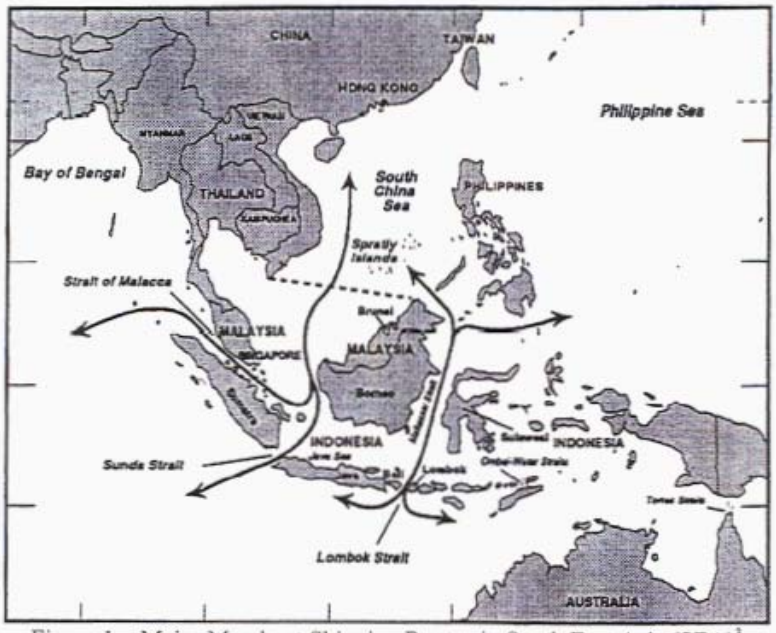

Figure 1: Major Merchant Shipping Routes in South East Asia (SEA)[3]

[1] Noer gave the assessment that the 1993 shipping and trade patterns were to be relatively stable, hence the data and facts presented would not deviate from its timeliness, except with likely growth of trade & traffic
[2] A measure of the vessel size/capacity, referring to the weight the vessel can carry in metric tons.
[3] http://nippon.zaidan.info/seikabutsu/1998/00362/images/022-1.gif, downloaded on 29 May 05

The recent heightened intensity and threats of terrorism around the world had led to an increased attention paid to ensuring port and maritime security. Maritime security along the Straits of Malacca was therefore of a priority concern to many nations.

2. MARITIME SHIPPING CONTAINER SECURITY

Today, the types and variety of merchant ships that operated along the Straits of Malacca was of a huge and diverse nature[4]. The types of shipments on board the ships were also of a varied nature i.e. oil, bulk cargo, cars, trucks, containers etc. Of particular concern was that, there had been a huge increase in the growth of the maritime shipping container use in the last decade. In 2003, approximately 90% of the world's cargos were moved by container[6].

Not surprisingly, containerized shipping made up a substantial percentage of the cargo that moved through the straits annually as well. Noer[7] in his work reported a total of 3611 container vessels out of a total of 41509 (8.7%) had transited through the Straits of Malacca in 1993. The Maritime Port Authority of Singapore[8] was also able to give a recent representative assessment of containerized shipping that passed through the Straits of Malacca by virtue of its geographical position. She reported in her 2004 Port Statistic that purely on vessels calls, 17333 out of the total 133185 vessels (13%) were cargo vessels and they were the 3rd highest grouping, next to tankers and regional ferries. And going by cargo tonnage alone, it had handled 223.5 million tonnes of containerized general cargo out of the total 393.4 million tonnes of cargo (57%) in that year.

In the United States, there was already a concerted effort and interest in advocating a balanced security approach towards countering terrorists targeting of various types of merchant shipping[9]. Nevertheless, great attention and efforts had also been paid towards curbing the weak link at maritime shipping container security due to the high volume of cargo transportation by container and the low inspection rate achieved by the U.S. Customs Service of only 2-3%[6] for more than 18 million containers entering the country annually. Therefore a critical weak link existed in maritime container shipments today.

3. THREATS & IMPLICATIONS

Due to the weak link in the maritime shipping container security, the possibility and danger of terrorism actions related to explosives, unconventional nuclear, biological and chemical attacks could not be discarded, and it posed a serious catastrophic threat to the well being of many nations. Besides, such acts could lead to severe disruption of shipping along the Straits of Malacca[7], which would lead on to a huge jump in shipping costs, freight rates and the adaptation of longer detour routes. There would also likely be a shortage of tanker capacity due to its current low excess capacity and trade would be delayed. Trades would also be blocked or halted due to possible port blockage. All these effects would lead on to further long term, and even unforeseen economic & political repercussions and fallouts worldwide[7,10].

---

[4] According to Merchant Ships Executive Overview dated 21 Jun 04, merchant ships could be classified generally into several types, namely cargo ships, gas carriers, tankers, super-tankers, passenger ships and sea/rover ships. Just of cargo ships alone, it could be further categorized into bulk carriers, container ships, roll on / roll off ships, automobile carriers, refrigerated ships, barge carriers, general cargo ships and heavy lift ships[5].

Currently, maritime piracy was already of a major concern along the Straits of Malacca. The International Maritime Bureau (IMB) in its 2004 piracy report warned that Indonesian waters and the Straits of Malacca remained the most dangerous shipping lanes in the world[11]. There were 37 pirate attacks in the Malacca Straits in 2004, up from 28 attacks in 2003[12]. The surge of piracy attacks was an alarming sign, as the linkage of piracy with terrorism acts must also not be discounted, particularly so when the use of maritime assets could form in support of or as weapons of terrorism.

4. CURRENT SECURITY MEASURES

4.1 Global Front

The United States remained today a major leading member in pushing and advocating for a balanced integrated approach towards curbing and curtailing the maritime container security issues worldwide, ever since Sept 11 2001. Major shifts and restructurings had taken placed within government agencies in order to take up the fight against terrorisms[6]. Under the U.S. Customs Service, some of the new security initiatives included the Customs-Trade Partnership Against Terrorism (C-TPAT) and the Container Security Initiative (CSI).

C-TPAT was a voluntary program meant as a joint government-business partnership to harness the cooperation of the trade community to improve cargo security while streamlining trade flow processes.

CSI was a cooperative working agreement between the U.S Customs Service with foreign governments and ports. It was established with the aims of setting international criteria for identification, screening/detection of high risks containers, and to develop the use of smart and secure containers. Today, a total of 20 countries had committed to participate in this effort, with a total of 37 operational ports at various stages of CSI implementations[13]. It accounted for about 2/3 of all container shipments into the States.

On a separate global front, in July 2004, the International Ship and Port Facility Security (ISPS) Code of the International Maritime Organization (IMO) was also jointly developed and globally implemented by 148 contracting parties/countries to the existing 1974 Safety of Life at Sea Convention (SOLAS), with the designated obligations discharging authority based in Hong Kong[14]. The ISPS was a comprehensive international shipping security regime or list of measures for governments, port authorities and shipping companies. It provided a consistent and standardized international framework for risk & threats/vulnerability assessment in order to ascertain the appropriate security levels and measures.

4.2 Regional Front

On the regional fronts, Singapore, Malaysia & Indonesia had stepped up naval patrols within their country boundaries along the Straits of Malacca ever since July 2004[11]. In 1992, the London-based International Maritime Bureau (IMB) set up a Piracy Reporting Centre stationed in Kuala Lumpur for the purpose of raising awareness, information sharing of reported piracy activities. It also entailed the role of working with national governments in the fight against piracy. Satellite tracking devices for ships, such as Shiploc Systems promoted by IMB, were already available to help in the recovery and

rescue of hijacked vessels. This was well proven during a recent hijacked case of a tug boat and barge in Dec 2004 along the Straits[15].

Multi-lateral naval exercises had been carried out with the emphasis on sharpening skills in handling maritime terror, for instance, the recent Western Pacific Naval Symposium involving 9 nations[16]. Coordinated patrols and surveillance systems between neighboring countries had also been deliberated and implemented. Project SURPIC, a sea surveillance system, was launched recently in May 2005 to allow both the Singapore and Indonesia navies a common real time sea situation picture of the Singapore Straits, enhancing command and control in reacting to piracy attacks & activities[4]. Other initiatives[17] included the Trilateral Coordinated Patrols of Indonesia, Malaysia and Singapore; the Five Power Defence Arrangements (FPDA) to include additional activities to address contemporary maritime security challenges; the Regional Cooperation Agreement on Anti-Piracy and Armed Robbery Against Ships in Asia (ReCAAP), initiated by Japan; and the maritime security issues dialogue in the ASEAN Regional Forum (ARF).

New technological application of unmanned surface vessels to complement maritime security missions as a critical enabler was also recently announced by the Singapore Navy. By the end of 2006, a new Harbour Craft Security Code would be implemented in Singapore, which required all small boats to install a transponder system for purpose of tracking of movements. Accompanying Sea Security Teams (ASSeTs) comprising had also been set up to provide rapid response in the event of terrorist or piracy attacks.

5. OBJECTIVES OF STUDY

In view of the current situation, particularly the need to plug the weak gap of maritime shipping security, SEA-7 integrated project was launched to design a conceptual systems of systems for the maritime domain protection of the Straits of Malacca. As part of SEA-7 overarching aim, a total ship inspection sub-system (TSIS) was formed[18]. It had the key aim of detecting and identifying dangerous materials to prevent use of a large cargo ship by terrorism. TSIS was further sub-divided into both land and sea components.

In order to fulfill the higher order of requirements in the SEA-7 integrated project, one of the critical areas that needed to be addressed in TSIS was the inspection search rate and its feasibility. However, several critical technological challenges existed with respect to the inspection capabilities of a large cargo ship, particularly its sensory detection capability and its employment of use. This thesis would attempt to provide an overview of the land/sea inspection technologies available and in the near future (5 years). It would define and conduct a preliminary study of an appropriate search model, and at the same time, explore the benefits and possibility of cooperative autonomous robotic systems in enhancing search.

6. MAIN ASSUMPTIONS

For the purpose of this study, the inspection of a maritime container ship would be assumed due to its prevalent used:

6.1 Environmental Setting

The setting used for our modeling study was based upon Panamax class of container vessel that were able to transport a range of 4000 ~ 8000 TEU (Twenty-foot Equivalent Unit).

6.2 Hardware

Numerous possible detectors equipment was available from commercially-off-the-sheft; however, broadly they could be categorized in to 2 types, which were either active or passive. Much of the research through open sources from Internet concluded with non-feasibility of employing active type detectors. As the immature stages of technologies for detectors that were available in the market currently. Thus, we have to tap onto the wealth of passive detectors that were available in the market, to maximize the output of our models.

6.3 Software

The software or programs used for our modeling were Microsoft Office – Excel, for the man-behind-loop concept, while Microsoft Visual Basic C++, was used for the autonomous robotics concept. The latter was adapted from a previous robotic simulation model developed from NUS (National University of Singapore) Cooperative Systems Laboratory[49,50]. The source code used was modified with new inputs and behaviors to suit our search scenario.

7. RADIOLOGICAL DETECTORS

7.1 Technology Classification

This section focuses on non-intrusive technologies targeted at inspecting shipping containers, specifically for weapons of mass destructions and special nuclear materials, biological and chemical substances. Non-intrusive technologies can be grouped into the following 2 categories:

7.1.1 Active systems – Technology that achieves detection through stimulating the object under inspection and detection of the resulting effects

7.1.2 Passive systems – Technology that detects unstimulated emissions from object being inspected.

The classification of some of the technologies discussed is given below in Table 1. Where applicable, the classification and definition is adapted from "Volume 6 – Report on Non-intrusive Detection Technologies" by COAC Border Security and Technical Advisory Group in June 2002.

Table 1: Technological Classification of non-intrusive technologies

Technology Classification			
Active Systems		Passive Systems	
Radiographic Inspection	Active Interrogation	Air/Trace sampling	Detecting Ionizing Radiation
- Gamma-ray - X-ray	Neutron: - Thermal Neutron Activation (TNA) - Fast Neutron Analysis (FNA) - Pulsed-Fast Neutron Analysis (PFNA) Others: - Acoustic	- Canine - Vapor/Trace Detection	- Radiation Detection

7.2 Technology Definition (Active Systems)

7.2.1 Radiographic Inspection

This is essentially an anomaly detection technique. The images reveal shapes, sizes, locations and densities. Commercial systems currently available are capable of throughput of several containers per minute. There is however great reliance on human inspectors and depends on the inspector's visual acuity and judgment.

7.2.1.1 Gamma-ray (γ-rays): By utilizing a radioactive element (usually Cesium^{137} or Cobalt^{60}) to produce gamma rays aimed at the object under inspection. The interaction of the rays with the object is

being detected and displayed as an image. Cs^{137} emits at 662keV and Co^{60} emits at both 1.2MeV and 1.3MeV radiation.

7.2.1.2 X-ray: By utilizing a radiation source and applying appropriate beam-forming, x-rays are being generated at the object under inspection. X-ray energies range from a low 120keV to a high 9MeV, and correspond to increasing penetration capability. To inspect cargo effectively, systems sized at 320keV minimum. Systems with energies below 320keV are useful for baggage and package inspection. Further classification of X-ray systems are as follows:

- Standard transmission systems – the transmission x-ray is directed through the cargo to a detector and presents an image to the operator that overlays all items in the beam path. Transmission systems operate at all energy levels without restriction

- Dual energy transmission – a higher energy x-ray and a lower energy spectra x-ray are used to interrogate the object and the difference between the 2 outputs is used to distinguish various materials. This is generally ineffective against large cargoes, as the low energy x-ray has less penetrative power.

- Dual View Transmission – standard transmission x-ray are directed from two (usually orthogonal) views of the object. The technique is not limited in energy level.

- Backscatter systems – standard x-ray transmission is employed together with Compton backscatter to create two or more views of the object under interrogation. Compton Backscatter detectors are placed on the same side as the illuminating source. Low Z materials scatter more and create brighter backscatter images and allow the distinction from high-z materials. Backscatter is useful at energies up to 500keV.

7.2.2 Active Interrogation

Active neutron interrogation allows for material specific identification. Intense fluxes of neutrons directed at inspection object can penetrate cargo and/or shielding and generates characteristic signals which can be detected. This technique allows for automatic material detection and does not rely on human interpretation.

7.2.2.1 Fast Neutron Analysis (FNA): High energy e.g. 14MeV, fast neutrons are created and directed at the object under inspection. The neutrons interact with the elemental constituents of the object and create gamma rays with energies characteristic of its elemental composition.

7.2.2.2 Pulsed Fast Neutron Analysis (PFNA): Nanosecond pulsed FNA are being created and directed at the object under inspection.

From the energy and time of arrival of the gamma rays in detectors, an elemental image of the object is created, which can indicate the presence of threat material containing defined concentrations of these elements. 3-d location of threat by time-of flight can be created.

7.2.2.3 Thermal Neutron Activation (TNA): Thermal neutrons are used to interrogate the object under inspection. With the absorption the thermal neutrons by the material, gamma rays are remitted. Sensors detect the energy of gamma rays and characteristic gamma rays identify the element.

7.2.2.4 Acoustics: An ultrasonic transducer is put into contact with the container and scanned. A sensor then detects the resulting reflection from objects inside and forms an image of them. The technology is useful only in liquid environments.

7.3 Technology Definition (Passive Systems)

Typically these systems may not be effective when object or substances are shielded or sealed.

7.3.1 Air/Trace sampling

7.3.1.1 Canine use: With its acute sense of smell, dogs are trained to alert inspectors when they detect contrabands and threat objects. The dogs are trained for specific materials and must be rested periodically to be effective.

7.3.1.2 Vapor Detection/Trace Detection: Air samples are being collected from or in the object/region under inspection and analyzed using a variety of spectrographic methods. Alternatively, a physical "wipe" collects particulate matter from the surface of the object and this wipe is analyzed. The results are used to determine the molecular nature of the material.

7.3.2 Detecting Ionizing Radiation

7.3.2.3 Radiation Detection: A detector measures the ionizing radiation (gamma rays, alpha rays, X-rays etc) and or other characteristic radiation such as neutrons naturally emitted from a radioactive substance.

Table 2: Technology Functional Matrix (adapted from "Report on Non-Intrusive Detection Technologies" by COAC)

	Time for inspection	Indicates potential presence of threat	Provides Material Discrimination	Identifies Specific Threat	Installation	Provides Electronic Record	Integrates with other Technologies	Cost
Active Systems								
Gamma ray	2-5 min/object	Yes	No	No	Mobile, fixed or relocatable sites. Fixed and relocatable site require local infrastructure of power, road access, personnel facilities and attention to radiation safety	Yes	Yes	$$$
X-ray	2-5 min/object							
Standard Transmission		Yes	No	No		Yes	Yes	$$$/ $$$$
Dual Energy Transmission		N/A	Not in high density cargos	N/A		Yes	Yes	NA
Dual View Transmission		Yes	No	No		Yes	Yes	$$$$ $
Backscatter w Transmission		Yes	Yes	No		Yes	Yes	$$$$
PFNA	90+ min/object	Yes	Yes	Yes		Yes	Yes	$$$$ $
TNA		Yes	Yes	Yes		Yes	Yes	$$$
Acoustic	2-5 min/object	Yes, in liquids	No	No	Portable/ desktop	Yes	Yes	$$
Passive systems								
Canine	0.5-1 min/object	Yes	Yes	Yes	Requires care, feeding and shelter, together with trained handlers	No	No	$
Trace Detection		Yes	Yes	Yes	Portable/ desktop equipment can be operated by battery or wall plug power	Yes	Yes	$
Vapor Detection		Yes	Yes	Yes		Yes	Yes	$
Radiation Detection		Yes	Yes	No		No	Yes	$

Cost: $: ≤$50k; $$: ≤$100k; $$$: ≤$1M; $$$$: ≤$5M; $$$$$: ≥$10M

7.4 Applicability of Technology to Marine Cargo Inspection

In general, all the inspection technologies discussed above are suitable for inspection of marine cargo containers. However, no single system has the capability to detect all possible threats. And even with the systems combined, there are still limitations on the detection capability given the complex nature of the object under inspection and the need to minimize inspection time.

Table 3: Pros and cons with non-intrusive inspection systems

Benefits and risk mitigation	Drawbacks/ Limitations
• Quick identification possible using radiation detection and trace detection for radioactive material and chemical substances that is unshielded and unsealed. • Containers can be cleared quickly with minimal disruption to flow of commerce • Reduced usage of man-power • Deterrence • Personnel performing inspection less exposed to potential threats	• Probability of detection not proven despite high costs of systems • Passive systems arguably ineffective against shielded radioactive source or sealed chemical substances • System footprint • Portability: current active (more effective) systems are portal and gantry based; ineffective (untimely) against weapons of mass destruction (WMD)

7.5 Technologies Applicable To Sea-Inspection

Based on current technology available, three alternatives are considered:

7.5.1 Platform-based off shore ship inspection (active systems): Platform is located offshore (substantial distance from port). Crane system unloads containers, passing them active detection systems on the platform for inspection. All containers can be inspected.

7.5.2 Ship based inspection (passive systems): "Inspection ships" have crane-mounted active inspection systems, with a reach to all containers. However, detector will only be able to inspect containers that are on the outer rim of the container stacks. Active systems are considered not applicable due the difficulty of placing detectors in appropriate position for effective detection.

7.5.3 Shipboard inspection teams (passive systems): Search teams board ships and inspect containers with passive detectors. The search team will be able to access tight spacing between container stack but may lack the reach to containers higher in the stacks. Active handheld systems lack penetrative power and may not be effective in searching container stacks.

A simple decision matrix is constructed to assess the options (Figure 2.4). The decision matrix is by no means a robust tool for consideration of alternatives but it does allow some basic understanding of the pros and cons of the various options.

Table 4: Decisions matrix for sea-inspection system

	Detectablility	Manpower requirements	Speediness	Thoroughness	Cost
Platform based	✓	O	×	✓	×
Ship based	×	O	O	O	×
Inspection teams	×	×	×	O	✓
✓ - Favourable	O - Average	× - Unfavourable			

7.6 Some Technologies Under Research

A few promising technologies currently under research will improve the detect ability of inspection systems

7.6.1 Active neutron interrogation: Developed by Lawrence Livermore National Laboratories (LLNL), suspicious containers would be bathed with neutrons. Fissile material, if present would produce fission reactions that are detectable and recognizable by the arrays of detector placed around the object of inspection.

7.6.2 Compton Backscatter Imaging: An AS&E system creates a pencil-beam of X-rays to interrogate suspect object. Backscatter images are detected by detector array placed on the same side as the X-ray source. It is good for low-z material (explosives) and has a detection range of 30 ft.

7.6.3 High-Sensitivity, Gamma-Ray Detection & Imaging Spectrometers: Under research in LLNL, high-sensitivity, high-spatial-resolution gamma-ray detectors accurately determines the path of gamma rays, allowing deduction of incident direction of gamma rays. This Compton camera concept can be realized in compact and potentially portable systems, providing omni directional sensitivity and isotope identification.

8. BIOLOGICAL DETECTORS

8.1 A Real Threat[25,26,27]

The ever changing global environment, the increasing proliferation of biological weapons technology, and its great lethality made biological warfare agent one of the most pressing security challenges faced today. The arena of interest was no longer only of military, but also in the civilian world. The means of delivery of biological agents was of a wide varied nature, ranging from simple means to sophisticated genetically engineered agents that might fool past current detection system capabilities. Its symptoms were of different natures compared to chemical agents, some of which might not even reveal its signs for several days, risking its spread. Its relatively basic levels of scientific and technological support and ease of manufacture through commercial means, made this threat even more real and dangerous.

8.2 Nature of Biological Attack & Agents[26]

The unique feature of biological weapons was that small amount of pathogen would often be enough to cause deadly infection in humans and other living things, even much less material than chemical weapons for the same equivalent devastating effect. It included incapacitating diseases such as Q fever & lethal communicable disease such as small pox, which could be spread rapidly within a short period of time. Symptoms might also take a few days to surface. In 1999, the US Center for Disease Control & Prevention (CDC) classified the range of biological agents into various categories of criticality by virtue of its health impact and dissemination potential for public health preparedness[28]. Category A, bearing the most critical impact, included variola major (smallpox), bacillus anthracis (anthrax), yersinia pestis (plague), clostridium botulinum (botulism), francisella tularensis (tularaemia) & filoviruses and arenaviruses (viral hemorrhagic fevers).

8.3 Biological Detection Challenges[25]

Currently, there existed no single biological sensor that could detect or identify all biological agents of interest. Biological Detection technology faced several technical challenges today, one of which was its requirement for great sensitivity of detection due to the lethality of the biological agents in small quantities. With current present technology, this led on to hikes in the cost, size, weight and power requirements. This was worsened with the fact that biological warfare agents were often difficult to differentiate from naturally occurring background materials or micro-organisms. The complex makeup of the agents further compounded to the issue. Henceforth, the huge gap between the limits of current equipment detection capability and lethal threat aerosol concentration still needed to be breached.

8.4 Current Systems[25]

Biological detection technologies were currently still in R&D stage and not fully proven, though new prototype systems were constantly being churned out into the market. Of recent, for instance, was the emergence of a portable micro-fluidic biological agent detection system[29] during the last US 24th Army Science Conference Proceedings in Dec 2004. Even though it had claimed that its system detection limit could be as low as 700 cells/ml with an assay time of 60 minutes for pathogenic cells and as low as 0.1

nanograms/ml with an assay time of 40 minutes for proteins and toxins, it was still far from the desired ideal instantaneous detection effect.

Also, most systems in the market were point detection systems that had yet to be fully deployed in the field (laboratory/field tests stage). They were often huge, complex, expensive and subjective to high false alarms rate. High costs of current existing systems would also be of great concern if they were to be affordable and widely employed. In most systems, limited numbers of biological agents were detectable and only after some exposure to it. Example of current systems include the biological mass spectrometer from Oak Ridge National Laboratory, the biological integrated detection system from the US Chemical Corps that could detect anthrax, plague etc, the nucleic acid analyzer from Lawrence Livermore[30] etc. Stand-off systems were however still in its infant stage of development.

The basic model for a biological point detection system consisted of a collector, a trigger, a detector and an identifier. Due to the micro size of the biological agents, a complex identification and detection process was necessary. This also ensued that most detection systems require substantial support requirements, often in the application of power, wet chemistry and sensitive reagents, and also sometimes specialized personnel in constant manning. Also, there were no clear means of detecting biological agents if they were being kept inside containers or packages, or if there were no leakages. Personnel operating the detection systems also faced a high level of danger, especially when they could not adequately detect and delimit the danger zones of the hazardous materials.

8.5 Research & Development (R&D)[25]

The current general trend and focus of R&D in biological detection technologies was to head towards an ideal detect-to-warn capability, particularly into fast, sensitive, accurate detection, and sample collection & processing. Efforts were also being channelled to produce an integrated system with reduced weight, automation, and field portability. If we went along with the technology forecast by Battelle[31] on the top 10 innovations in National Security and Defence, by 2012, there should be substantial leaps and advances in biological agent detection being fully integrated and non-invasive, and as easy & reliable to use as X-ray machines now. There would also be more dynamic growth in this arena, even much more than chemical detection market[27]. The U.S. Department of Homeland Security had projected that, if all went well, its two major research effort into designing bioagent autonomous networked detector (BAND) and rapid automated biological identification system (RABIS) would only complete its prototype testing and critical design phase by 2008[32]. Currently the efforts were still in her feasibility design phases. Therefore, with all the above constraints and limitations, it was not possible to project any big scale employment of any portable & useful biological detectors in the immediate future. As a result, this study would not go further into selecting any particular range of suitable biological detectors into its modelling.

9. CHEMICAL DETECTORS

9.1 Factors in Selecting Detection Equipment

A market survey of commercially available detection equipment in May 2000 identified 148 detection devices available to the military and first responders. With many different detectors and technologies available, the National Institute of Justice recommends examining 15 factors when choosing a detection device (see Table 5). The table below lists these factors. The most sensitive detectors tend to be most susceptible to false-positive alarms. Thus, for most practical applications, multiple detectors were needed to verify the findings of the initial detector.

Table 5: Factors for considerations of a chemical detectors

Factors to be Examined When Choosing a Detection Device		
1.	Agents detected	Determination of agents most likely to be encountered
2.	Sensitivity	Lowest concentration of CA that results in positive response; ideally, lower than levels necessary for injury to personnel
3.	Resistance to interference	Factors such as smoke, moisture, or other chemicals that prevent the device from accurately providing a response
4.	Response time	Time to collect, analyze, and provide feedback
5.	Start-up time	Time to assemble and deploy the device
6.	Detection status	Vapor, liquid, and/or aerosols
7.	Alarm capability	Audible, visual, or both
8.	Portability	Ease of transport, which encompasses weight and dimensions
9.	Power capabilities	Battery versus alternating current
10.	Battery needs	Quantity and type of batteries
11.	Operational environment	Extremes of conditions under which the device operates
12.	Durability	Amount of abuse the device withstands
13.	Procurement costs	Cost per device needed
14.	Operator skill level	Skill involved in using the device
15.	Training requirements	Number of hours and type of educational background required for operation

9.2 Portable versus Fixed

Either fixed or portable detection system, its main purpose was to inform and protect human, equipment and facilities. The devices were designed with various degrees of sensing rate and accuracy to support a wide array of applications / needs. But the greatest dilemma was question of which type would provide the right level of protection? It would never be practical / economical to place a fixed detection system in every potential release sites, nor having tedious man-hour of personnel stationing with portable detection system at these sites too.

9.2.1 Portable: Such detectors were relatively easy to operate, and would have a low initial cost and flexible. Minimal training required and could detect a large amount of known chemical agents. The best capability was it being portable as it name implied, thus allowing further investigation and confirmation false alarm. Its also designed to protect people in confined spaces or hazardous environments for a relatively short period of time

However, being "manned" devices, it would not be able to provide round-the-clock monitoring, due to its limited battery life. In addition, the average life span of the devices were only about 3~7 years, due to the harsh environment, theft, and abuse. There is a recurring cost of more frequent calibration, fixing abused units, and a shorter expected life.

9.2.2 Fixed: A fixed detection system on the other hand, provided 24/7 monitoring, alarming and an automated shutdown capability if dangerous conditions exist. While comparison of cost between portable versus fixed gas detection systems could be made, its essentially really looking at apples and oranges. It had greatly differing roles and cannot be substituted based on cost.

Fixed systems offer continuous monitoring, alarming and automated equipment shutdown for large areas or entire facilities to protect people as well as equipment and structures. Once installed, fixed systems provide years of reliable, low maintenance monitoring. The cost of a fixed system is often a significant capital expense.

9.3 Detection Techniques

There are currently numerous chemical detection techniques that were available in the market offered by many established company. However, there were essentially 3 main categories of such reliable techniques of detection.

9.3.1 Enzymatic Detection Techniques

The most common detector of all is the Chemical detection paper, as it is a very sensitive technique for detecting Chemical Agent (CA). Least sophisticated thus least expensive methods of detection. It is used commonly to detect liquids and aerosols for defining a contaminated area.

It comprised of 2 dyes soluble when in contact with any CA with a pH indicator integrated into cellulose fibers. The color would change accordingly to the type of agent encountered. The diameter and density of the spot could also be used to determine the droplet size of the CA and degree of contamination.

Chemical detection paper lacks specificity and would be prone to false alarm when contaminants such as antifreeze, and insect repellent were detected. Such readings were especially undesirable because it might cause unnecessary panic. Hence, another detection method was always advisable to be used in conjunction for better results.

M256A1 Chemical Agent Detection Kit

One example of such detection technique was M256A1, which was sensitive to lower concentrations of nerve agents. It was available commercially and used extensively during the Gulf War. This portable kit had the ability to detect nerve gas, mustard gas, and cyanide. It contains a package of M8 CA detection paper, instructions, and a vapor sampler.

The vapor sampler containing different substrates were crushed so that the liquids interact with strips of filter paper, chromatographic media, and glass fiber filter. Which were then exposed to the suspected surrounding for detection of possible vapor contamination. Upon detection of CA presences, the color would change to alert the user and typically this analysis would take about 10 minutes

Figure 2: M256A1 Chemical Agent Detection Kit

It could detect nerve gas concentrations of 0.005 mg/m^3, hydrogen cyanide concentrations of 11mg/m^3, and mustard gas concentrations of 0.02 mg/m^3. However, like any other enzymatic detection techniques, possible false alarm when in contact with substances like brake fluid, fume, etc. Hence, other methods of detection were needed to further confirm the suspected contamination.

9.3.2. Ion Mobility Spectroscopy

Ion mobility spectroscopy (IMS) technique detector was developed in numerous handheld and stand-alone detection devices to scan equipment and people for contamination.

This method of detection essentially involves drawing a gaseous sample into a reaction chamber to ionize the air molecules. These ionized particles were then passed through a weak electrical field to be identified by a ion detector, base on the time taken to move from the chamber to the detector. This was then compared to a clean air sample and if found being different and correspond to a certain unique types of agents, the alarm would sound off.

These systems were capable of detecting and distinguishing between nerve gas, mustard gas, and vesicants. Its sensitivity ranges from 0.03 mg/m^3 for nerve gases such as sarin to 0.1 mg/m^3 for mustard gas. IMS advantage was being less sensitive to contaminants, because of its reliance on a clean air sample for calibration.

M8A1, Automatic Chemical Agent Alarm, and Fixed Site/Remote Chemical Agent Detector

The military employs this M8A1 stand-alone detector, which allows continuously monitors the environment for hazardous vapors with up to 5 alarms that could be dispersed throughout an area. Its capable to detect nerve and blister agents of 0.1 mg/m^3 or greater concentration and sound off its alarm within 1-2 minutes.

Figure 3: M8A1, Automatic Chemical Agent Alarm, and Fixed Site/Remote Chemical Agent Detector

There were many commercial version of an IMS stand-alone detector, which could detects and identifies nerve, blister agents and offers superior reliability from interference. Upon detection of such contamination, information could be transmitted via radio, satellite, or hardwiring to the main control.

9.3.3. Infrared Radiation (IR) Detection Techniques

Infrared radiation (IR) was employed in several CA detectors that include long-range and point detectors. The technique essentially excites the molecules, as each agent carried it own unique pattern or fingerprint. Several different version of IR detection, include photo-acoustic infrared spectroscopy, filter-based infrared spectroscopy, forward-looking infrared spectroscopy (FLIR), and Fourier transforms spectroscopy.

9.3.3.1 Photo-acoustic infrared spectroscopy

Usually used in point detectors to identify CA vapors. Principally, when CA absorbs the IR radiation, temperature increases and gas expands. This phenomenon of gas expansion and contraction, depending on the modulation of the IR, were an audible signal in photo-acoustic spectroscopy.

The selectivity was dependant on the number of wavelengths passes through the suspected sample. The more wavelengths passes through, the lower false alarms detected. However, its sensitive to environmental variables such as external vibration, but if the devices were calibrated properly, detection should be accurate.

9.3.3.2 Filter-based infrared spectroscopy

This technology was similar to the earlier mentioned, which also based on comparing the amount of energy absorbed by the sample, but using several different wavelengths of infrared light. Series of filters were used to direct the beam through a predetermined path. Concentrations of each vapor component were then used to compile trends and identify the sample.

9.3.3.3 Differential absorption light detection and ranging

This technique using 2 pulses of laser transmitted towards the suspected CA cloud detecting the reflected IR. The difference in the intensity of the return signal (one pulse of frequency known to be absorbed by the CA, while the other not) was used to determine the concentration of the cloud, and the time of return determines the distance. This technique however was subjected to environmental noise but had been used effectively to track CA.

9.3.3.4 Passive infrared detection

FLIR and Fourier transform infrared (FTIR) were techniques that detect IR emitted from CA vapor. Its commonly used in stand-alone detection devices that would simply sound off its alarm when a CA cloud is detected. Both of these methodologies depend on the collection of infrared information; however, the processing was different.

One such detection device was the M21 RSCAAL, which was the first fielded standoff detector (wired from detector to main console). It could detect a vapor cloud from 5 km with a Pd of 0.87. It would continuously monitor the background and notes any changes in the spectral information, providing valuable information for troops in deployment area. However, the main limitation it had was being stationary, thus any rain / snow will obstruct the detection capability.

9.3.4 Other Detection Techniques

9.3.4.1 Photo ionization detection

Photo ionization detection depends on exposing the suspect vapor to UV energy powerful enough to ionize agent molecules. Like IR radiation, specific ranges of UV light ionize molecules in certain CA. An ion detector then registers the amount of ionized molecules. Thus, these detectors could determine the concentration and identity of the agent. Handheld detectors produced by RAE systems and Photovac were examples of detectors that used this technology.

9.3.4.2 Flame photometry

In this technique, a flame of hydrogen was used to burn a sample of air. The color of the flame is analyzed by a photometer for concentrations of sulfur and phosphorous (key components in nerve gas and mustard). Flame photometry is highly sensitive yet is prone to false-positive results by detecting other gases that contain significant concentrations of sulfur or phosphorus but were non hazardous. Certain analysis algorithms could be employed to make these detectors less prone to error. Gas chromatography could be integrated with flame photometry to make the detector more accurate.

9.3.4.3 Miniature Automatic Continuous Agent Monitoring System (MINICAMS)

This a hybrid system based on combining gas chromatography with flame photometry. A sample vapor was drawn into the machine and exposed to a heated pre-concentrator loop. Flame photometry would then measure these exudes. A typical cycle lasts 3-5 minutes, enabling continuous monitoring of the environment.

9.3.4.4 Surface acoustic wave detection (SAW)

This method relies on chemically selective coated piezoelectric crystals that absorb targeted gases. These detectors were able to identify and measure most CA simultaneously and were produced inexpensively, making them a popular choice. The absorption would cause the changes in the resonant frequency of the crystal that could measure by a microcomputer. An example of such device was the portable SAW MINICAD II, battery operated array detector that was available commercially. Its usually employed remotely to define areas of decontamination, and sometime also used for active detection by responders.

9.4 Types Of Selected Chemical Detectors

With the given knowledge and considerations laid for selection of a chemical detectors, in order of priority, following were some of the possible choice of detectors recommended.

9.4.1. SABER 4000

For applications where portability was required, this detector was one of the better hand held instrument that was independently capable of detecting and identifying more than 40 explosive, CA and even narcotic substances.

Figure 4: SABRE 4000 (Ion Mobility Spectrometry Technology)

Weighing only 7 lbs, including battery with 4 hours of operation duration. The portability allows immediate investigation on suspected packages, screen checked and abandoned luggage, at the receiving dock and in the mailroom, for traces of explosives, narcotics or chemical agents.

The device uses particle or vapor samples to analyze traces, thus allowing the user to match the most appropriate sample collection method to the suspected substances. It could identify a given CA sample as quick as only 10secs.

9.4.2. AP2C Chemical Warfare Agent Detector

This detector was based on the flame photo-spectrometer technique. It detects nerve and mustard agents and identifies Vx in liquid and vapor forms. It's highly sensitive which capable of detecting the presence of sarin at a concentration of 10 micrograms/m^3 in 2 secs. Suitable for initial reconnaissance, the AP2C also provides unique capabilities for mass screening and monitoring decontamination on casualties and equipment.

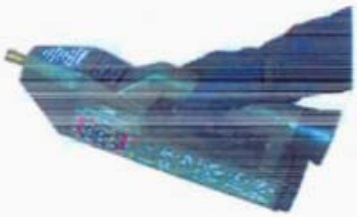

Figure 5: AP2C CW Agent Detector

Constructed to military specifications and was used by many military forces and civil defense agencies worldwide including France, Sweden, Israel, Australia, and federal agencies of the US government.

9.4.3 HAZMATCAD

This is a multi-functional, handheld, that detects and classifies both chemical warfare and toxic industrial chemical agents. When compared with other tools, it offers more capabilities with a faster response time and higher sensitivity at a lower cost. It uses both Surface Acoustic Wave (SAW) sensor and electrochemical cells. These combinations provide easy selectivity for both nerve and blister agents.

Figure 6: Model – HAZMATCAD / Plus

Weighing at 20 oz (including battery), the operating duration was up to 8 hrs as given in its specifications. Given concentration nerve / blister agent of 20 mg/m^3, the detection time needed was 20 secs.

9.4.4 APD 2000

A detector based on Ion Mobility Spectrometry (IMS) detection technique that detects chemical warfare agents, pepper spray and mace. This device could be power with 6 internal alkaline battery / rechargeable 'C' size battery. Weighing less than 3 kg and a small size of 10 x 9 x 28 cm, its able to provide detection of nerve and blister agent with high concentration on 10 mg/m^3 within 30 secs.

Figure 7: APD 2000 Hand Held Chemical Detector

This device is capable of data logging of all detection and monitoring events and sample preservation for future usage. It is also able to provide remote communication of alarm signals via radio frequency.

10.2 Types Of Selected Search Platforms

After having gone through the tedious round of deliberating on different types of available ROV in the market, using the above considerations guideline. Following were some of the identified search platform found to be suitable for our employment in order of suitability and choice.

10.2.1 Customised Magnetic MINTRAC

Inuktun made this ROV available, which feature having the platform custom fitted with their minitrac product, and further enhance it with magnetic capability under it belly for climbing on metallic surface. The appro. weight of this machine was less than 20 Ibs, with size of 381mm W x 508mm L x 10.16mm H. The speed attainable was 0-9 m/min.

Figure 8: Demostration of the ROV capabilities by the supplier

The platform could be operated through the integrated CCTV onboard. The limitation of this machine was the need to be powered with main, as the magnetic capability requires the continuous high power supply. Also base on the size of this platform, estimated number of detector mountable were probably only 2 detectors, any addition would prevent the employment of this platform for vertical movement.

10.2.2 NANO MAG

This platform was also available form Inuktun, which was designed to adhere magnetically to metal surfaces, for horizontal and vertical movement like the earlier highlighted ROV. Except, for this machine, the size was much small (105mm W x 157mm L x 49mm H), with speed of 0-1.5 m/min, which allows effective employment in areas too small or toxic for human inspection. The approximated weight of this system was less than 5 Ibs, which means, the limit of detectors allowed, would be reduced to only 1 detector.

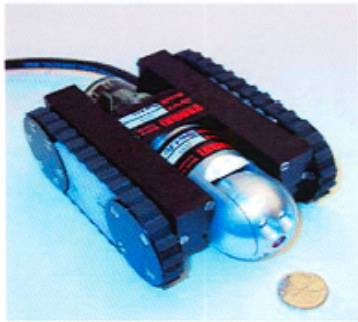

Figure 9: NANOMAG

10.2.3 PACKBOT

A rugged, lightweight robot designed to conduct Explosive Ordnance Disposal, HAZMAT, search-and-surveillance, hostage rescue, and other vital law enforcement tasks. PackBot by iRobot, could be rapidly configured into various employment needs with the right equipment.

Figure 10: PACKBOT by iRobot

With its compact profile and patented mobility platform (QuickFlip dual rotating flippers), it could operate with confidence on the toughest terrain - from the stairs, curbs, and rubble of urban terrain to the rocks and sand. Weighing less than 24 kilograms fully loaded, size of 405mm W x 879mm L x 409mm H, and speed of 2.2-3.7m/s, could be controlled remotely up to 1000m (line of sight – by radio frequency). It's capable of carrying a payload weight of up to 16kg, which means approximately up to 4 detectors.

However, superior it may sound, the greatest limitation lays on its inability to climb vertically, thus limiting its effective search capability.

10.2.4 Mobile Disruptor Vehicle

Being developed by Inuktun for the applications in bomb disposal, penetration of shielded packages, EOD (Explosive Ordnance Disposal). This is one powerful, reliable, precise control, easy to operate, lightweight and integrated with high-quality images machine.

Figure 11: Mobile Disruptor Vehicle used by EOD personnel.

The size of this platform is 355mm W x 610mm L x 420mm H, with speed of 9 m/min, and could be controlled remotely up to 330m (radio frequency). With the given size of this platform, the estimated numbers of detector mountable were 3 detectors.

Having such capable configuration, the greatest limitation was the inability to climb up a vertical wall. This lacking of inability renders its effectiveness for searching of potential treat at greater heights.

10.2.5 MINI-ANDROS II

This is the smallest member of the ANDROS family of mobile robots made by REMOTEC. The most unique feature of the Mini-ANDROS II is its small size and lightweight, which provide for unparalleled portability and versatility. These features allow for operation in very constrained areas.

Figure 12: MINI-ANDROS II used by responders for various operations.

Likewise to the earlier mentioned search platform, the size of is 355mm W x 650mm L x 325mm H, with speed of 5 m/min, and could be controlled remotely up to 330m (radio frequency). With the given size of this platform, the estimated numbers of detector mountable were up to 3 detectors.

Greatest limitation was the inability to climb up a vertical wall. This lacking of ability renders its effectiveness for searching of potential treat at greater heights.

11. MODELING

In this section, we would be looking at both the modelling which had been developed to look into the specific situation of a sea inspection, upon detection or informed of any potential suspected cargo / vessel. As this portion consisted a vast amount of information, it would be referenced to **Annex A** – Radiological Search & Modelling, & **Annex B** – Robotics Search & Model, of this document.

12. FINDINGS & RESULTS

12.1. Findings for Human Search Strategy

12.1.1 Optimum team size is 8-15

Figure App 1, shows the plots of search time against time size, with detection range of 4m, 6m and 8m. It is evident from the curves that the optimum team size corresponds to the section where the plots start to flatten out and is the range of 8-15 for a container stack that is 1 by 10 by 13.

12.1.2 Increasing the detection range and decreasing the soak time brings about substantial improvement to search time

Figure App 2, shows the plots of search time against detection range with soak times of 1, 2 and 4 minutes. Halving the soak time from 4 to 2 brings about 1.7 fold decrease in search time; while increasing the detection range from 4m to 8m brings about a 4-fold decrease in search time.

12.1.3 Non-linear relationship between search time and team size

With increasing team size, the improvement in search time decreases. Figure App 3 shows the decreasing gradient of the search time vs. team size plot.

12.1.4 Container stacking configuration: more favorable in terms of search performance to increase container breadth-wise

Starting with a container stack that is 10 containers wide by 10 containers tall, it is considered that the number of containers is increased 10 at a time either, row-wise or column wise.

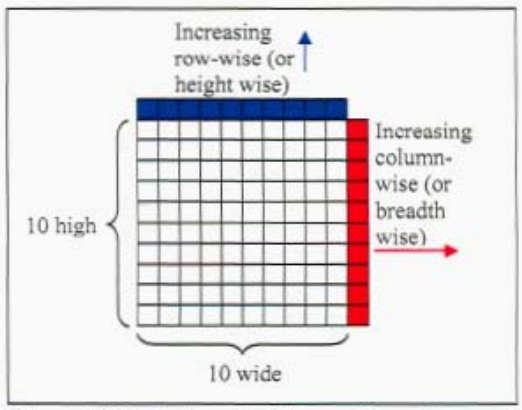

Figure 13 Container-stacking configuration

This is an intuitive observation. Given that the container height is larger than container width (8.5' vs. 8') and stack search speed is slower than deck search speed, it is obvious that it is faster to search the stack breadth-wise. Figure A4 supports this observation.

However, it is noted that with different detection range (a change from 4 to 5m), there are certain configurations in which an increase in stack height leads to a lower search time compared to an increase in stack width. Reference Figure A5, stacking with 10 containers wide and 11 containers high gives a search time of 0.49 hrs; which compares to a stacking configuration of 11 containers wide and 10 containers high with 0.47hrs search time (1.2 min different)

12.1.5 Coordinated human search strategy outperforms autonomous robotic search algorithm developed

Figure A6 shows the plot of human search time and autonomous search time for 18 TEUs. For the human search, the search time converges to the optimum search time with a team size greater than 4. For the autonomous search, the search time converges to human search times with team size 7.

12.2 Findings for Robotics Search & Modelling

12.2.1 The simulation of autonomous robotic systems was successfully achieved with a high probability of successful inspection of up to 86.7%, given a target source, as compared to an ideal human achievable rate of supposedly 100%. The disparity between autonomy and manned was therefore also clearly illustrated.

12.2.2 The autonomous robots could finish its inspection of 18 TEUs approximately between 5-7 min (Figure B13), which was comfortably below the maximum allowable limit of 10.1min.

12.2.3 The behavior of the robots was also a strong intrinsic function of its assumed input parameters and threshold values, and was closely tied to its use of sensors and communication systems.

13. RECOMMENDATIONS

13.1 Human Search modelling

13.1.1 Higher fidelity models and accurate information for the search parameters will be required for more precise estimation of search times.

13.1.2 Where it is possible to ascertain the types and material characteristics of cargo in the containers and detector information, the model can be further developed to work out probability of detection.

13.2 Robotics Search & Modelling

13.2.1 More detailed sensitivity studies would broaden the understanding of the various parameters that affected the overall success rate of the robotic inspection process.

13.2.2 Future attempts could also look into simulating larger number of TEUs, and attempting to identify a scaling factor that could project the inspection results to variable sized ships.

13.2.3 The influence of more than just 1 target would also be interesting and useful to investigate.

13.2.4 Other new cooperative robotic algorithms could also be designed and explored in order to narrow the present gap between autonomy and manned systems.

14. CONCLUSIONS

It was recognised that the current strategic threat along the Straits of Malacca was indeed real and it posed a great global security challenge. The vast amount of uncertainty and possibilities also made the various possible threat scenarios complex.

In order to fulfill the higher order requirements in the SEA-7 integrated project, this study had attempted to address one of the critical areas in their Total Ship Inspection Study (TSIS) - the sea inspection search rate and its feasibility. A broad overview of the several critical technological challenges with respect to the inspection capabilities of a large cargo ship was given, drawing particular note to its sensory detection capability, the platform capability and their employment of use. This led on to a conduct of a preliminary study of an appropriate search model, exploring the associated benefits and the possibility of cooperative autonomous robotic systems in enhancing search.

An effective Sea-Inspection system enabled by intelligence and technology will improve the probability of detecting any potential threat before its reaches its target. It was shown that the maturity of technology (detectors) is a key factor in the overall search rate, ultimately defining the effectiveness and feasibility of sea search operations. The complex threat scenarios had also pointed out the vast array of equipment that would be required to conduct such operations.

Though the search modelling has pointed out parameters that can contribute to better human search efficiency, with the current man-portable sensor technology, such searches are still manpower intensive and have significant limitations in detecting sealed or shielded CBN threats. Sea-inspection as a form of deterrence, though not quantifiable by the modelling, may be of value as an added cause of concern for any terrorist building up to or planning an attack.

The search modelling conducted highlighted the strength of human search strategy over current autonomous robotic search algorithm. It gave an appreciation of the team size needed to accomplish the human search task required by the SEA-7 studies.

In view of the strategic importance of the Straits of Malacca, it would certainly pay off reviewing this preliminary work for future research, to identify a better solution in tackling its current imminent threat problem.

ABBREVIATIONS

ASEAN	Association of South East Asian Nations
ASSeTS	Accompanying Sea Security Teams
ARF	ASEAN Regional Forum
COUGAR	Cooperative Unmanned Ground Attack Robots
COSY	Cooperative System
C-TPAT	Customs-Trade Partnership Against Terrorism
CSI	Container Security Initiative
DARPA	Defense Advanced Research Projects Agency
DWT	Deadweight Tonnage
FPDA	Five Power Defence Arrangements
ISPS	International Ship and Port Facility Security
IMO	International Maritime Organization
MULE	Multifunction Utility/Logistics Equipment
NUS	National University of Singapore
ReCAAP	Regional Cooperation Agreement on Anti-Piracy and Armed Robbery Against Ships
SEA	South East Asia
SLOC	Sea Lines of Communications
SOLAS	Safety Of Life at Sea Convention
TUGV	Tactical Unmanned Ground Vehicle
TEU	Twenty Foot Equivalent Units
TSIS	Total Ship Inspection Sub-system

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ANNEX A –
RADIOLOGICAL SEARCH & MODELLING

RADIOLOGICAL SEARCH & MODELLING

A.1 OVERVIEW

The search model was developed with the following objectives:

A1.1 Determine inputs for Sea Inspection team.

A1.2 Determine key search parameters that influence the efficient searching of container ships using man-portable detection systems.

A1.3 Experiment autonomous search strategies and compare its performance against coordinated human search strategies.

A.2 ASSUMPTIONS

Model assumptions are essential to limiting the model to a manageable scope. The assumptions made are as listed below.

A2.1 The focus of the search model is to derive search strategies, as such, homogenous search environment and search teams are assumed.

A2.2 The capability of the search entities and detectors are assumed as there are currently no man portable detectors designed for the searching of container stacks. Man portable detectors are readily available but are not designed to scale the height of container stacks. It is hence assumed that this capability exists.

A2.3 Due to the lack of precise detector performance specifications, the model search times will vary from actual search times.

A2.4 In view of its capability to inspect containers non-intrusively, a passive nuclear/radiological detector is being considered in the models. Man-portable active systems though available, lack the capability to penetrate cargo containers.

A.3 APPROACHES

Two separate models were being developed. For the human search model, Microsoft Excel was used and for the autonomous robotic search a Visual C++ simulation program was developed, which would be discussed and highlighted seperately.

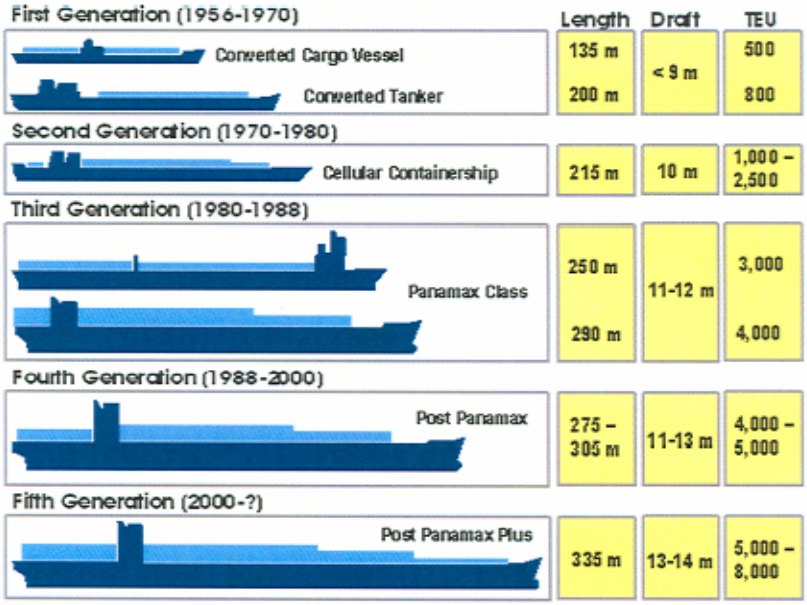
A.4 MODEL INPUTS

In developing the search models the following input parameters need to be defined.

A4.1 Search environment

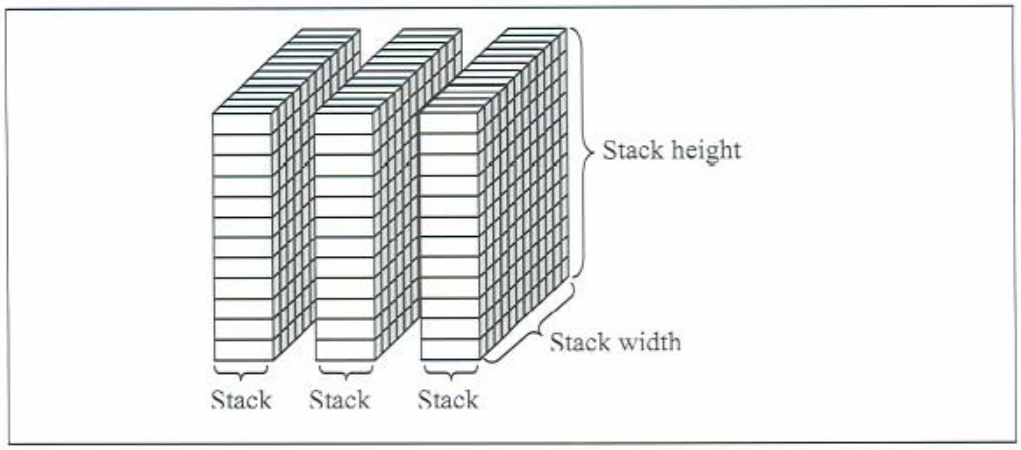
The model looks into the searching of container stacks on container ships. Panamax to Post-Panamax class container ships are being considered. Typically, each container stack is about 10-12 containers wide and 13-15 containers high. It is estimated that there are between 36 to 45 container stacks depending on size of container ship. Twenty-foot-equivalent-units (TEU) containers are being considered. The inputs required for the model are the total number containers and the container stack dimensions which is a function of container dimensions and the number of containers per stack.

Figure A1: Five Generations of Containerships



http://people.hofstra.edu/geotrans/eng/ch3en/conc3en/ch3c5en.html

Figure A2: Container stacking configuration considered in search model



A4.2 Search entities

Human and robotic search teams are being considered in the models. The inputs required for the search model are *deck search speed* and *stack search speed*. Deck search speed refers to the movement speed of the search entity/detector while inspecting containers horizontally along the width of the container stack; stack search speed refers to the movement speed of the search entity/detectors while inspecting the containers vertically along the height of the container stack.

In the model, the distinction between human search entities and robotic systems is only given by their difference in speeds. The other required inputs for the search entities, are the *team size* and the *number of teams*.

A4.3 Detector capability

A portable germanium detector used in an experiment in 1990 to detect soviet nuclear warheads, was being used a sort of baseline detector. It is assumed that current technology surpasses the capability of the said detector and can be taken as a conservative estimate.

The detection range of the detector is modeled reference the baseline detector by using Microsoft Excel. It was estimated that the detector will be able to detect 25kg of HEU with ¼ inch lead shielding at 4.2m. The detector model is covered in greater detail in the next section.

In the model, the key input parameter of the detector is the *detection range* and *detector soak time*. The detector is assumed to have a FOV of 180°.

Table A1: Inputs for search model

Search environment	Search entity	Detector
No of containers per stack No of container stacks Dimensions of container (length, breadth, height)	Number of teams Team size Deck search speed Stack search speed	Detection range Soak time

A.5 PASSIVE RADIATION DETECTOR MODEL

The detector model was developed based on the experimental results and documentation of an experiment carried out to measure gamma-ray emissions of soviet cruise-missile warhead[4].

A coaxial high-purity germanium detector was used in the experiment. The sensitive portion was cylindrical with volume 151cm3, and with diameter and length both at 5.9cm.

Certain radiation emissions from U-235 and Pu-239 radionuclides are unique and are most indicative of the presence of nuclear warheads. The most detectable emissions are the 186keV line for U-235 and the 414keV line for Pu-239. The emission for U-232 isotope at 2614keV is even more pronounced. U-232 is not naturally existent and is only present when uranium from reprocessed reactor fuel is used as feedstock during uranium enrichment process.

The intensity for gamma-ray emission, C is given by

$$C = SMF\varepsilon(\Omega/4\pi) \text{ counts per second (cps)}$$

where S is the decay rate per gram of parent isotope
M is the mass of the parent isotope
F is the external shielding factor
ε is the efficiency of the detector
Ω is the solid angle subtended by the detector.

Appendix A1 shows table and graph used to obtain the value of S, M and ε.

The external shielding factor F is given by

$$F = e^{-\mu_{sG} t}$$

where μ_{sG}^{-1} is the mean free path of gamma ray absorption
t is the thickness of the shielding material

The mean free path is μ_{sG}^{-1} given by

$$\mu_{sG}^{-1} = \left[\left(\mu / \rho \right) \times \rho \right]^{-1} \text{ cm}$$

where μ/ρ is the total attenuation coefficient
ρ is the density

From reference 4, the mean free path of lead and tungsten corresponding to 186keV and 414keV are given as follows:

Table A2: Mean free paths of lead and tungsten

Mean free path	186keV	414keV
Lead (cm)	13.5065	2.48565
Tungsten (cm)	17.9876	3.5126

Figure A3: Passive radiation detector model

detection time, t	1	
detector length	5.9	cm
detector diameter	5.9	cm

Container	
Shielding	0

Gamma (U235) 186keV Source		
weight of U235	142144.1	gram
Detector distance	10	m
area of detector, A	2.73E-03	m2
emission rate, SG	4.20E+04	gamma rays/g.s
efficiency, εG	0.6	
Ω/4π	2.77E-06	

	lead	tungsten
μsG-1	13.5065	17.9876
thickness of shield, rs	0.635	0.635
Fsg	0.000188	1.1E-05
additional shielding factor	1	
shielded, mean	1.87	0.108657
with additional shielding	1.87	0.108657
target value (opt)	1.87	

Gamma (Pu239) 414keV Source		
weight of Pu239	266.6859	gram
detector distance	10	m
area of detector, A	2.73E-03	m2
emission rate, SG	3.46E+04	gamma rays/g.s
Efficiency, εg	0.3	
Ω/4π	2.77E-06	

	Lead	tungsten
μsG-1	2.48565	3.5126
thickness of shield, rs	0.635	0.635
Fsg	0.206307	0.107475
additional shielding factor	1	
shielded, mean	1.582	0.824133
with additional shielding	1.582	0.824133
target value (opt)	1.582	

Gamma (U232) 2614keV Source		
weight of U232	1	gram
detector distance	136.3574	m
area of detector, A	2.73E-03	m2
emission rate, SG	2.68E+11	gamma rays/g.s
efficiency, εg	0.08	
Ω/4π	1.49E-08	

	lead	tungsten
μsG-1	0.49032	0.80095
thickness of shield, rs	0.635	0.635
Fsg	0.732455	0.601335
additional shielding factor	1	
shielded, mean	233.9607	192.0783
with additional shielding	233.9607	192.0783
target value (optional)	1.369	

coloured cells denote input cells

Inputs from SEA7 Sea-Inspection Group indicated the target nuclear source to be a 25kg HEU with ¼" lead shielding. The detection range for this source is estimated to be 4.2m.

Figure 3.1 shows the spreadsheet developed to calculate the intensity of the source given the detection time, source weight, detection range, detector efficiency, thickness of shielding and container shielding.

Using the passive detector model, Table 3.3 shows the estimated detection range of the detector corresponding to different weights of U235 and Pu239.

Table A3: Detection range and corresponding source weight

Detection range (m)	2	4	6	8	10
Wt of U235 (kg)	5.7	22.7	51.2	91	142.1
Wt of Pu239 (kg)	0.01	0.042	0.096	0.17	0.267

A.6 HUMAN SEARCH STRATEGY

For the benefit of time, a calculation-based, analytical approach is taken in the development of the human search strategy using Microsoft Excel. It is reasoned that as absolute values of search times, are not required, this simplified approach will suffice to give good estimate of actual search performance and allow meaningful comparison and understanding of the search parameters. During the calculation where simplifications are required, the calculation is modified so that it will err on the conservative side (i.e. derive a longer search time)

The following search parameters are investigated using the search model: detector soak time, detection range, number of search entities, number of containers and container stacking configuration.

The approach taken for the calculation of the search time(s) is as follows:

A6.1 Model Inputs

Search environment
No of containers (length, breadth, height) S_{ln} , S_{bn} , S_{hn}
No of container stacks, S_S
Dimensions of container (length, breadth, height) C_L, C_B, C_H (m)

Search entity
Number of teams, I_T
Team size, I_N
Deck search speed, v_d (m/min)
Stack search speed, v_s (m/min)

Detector
Detection range, D_R (m)
Soak time, D_T (min)

A6.2 Model Calculation

Stack length, $S_L = S_{ln} \times C_L$ m
Stack breadth, $S_B = S_{bn} \times C_B$ m

Stack height, $S_H = S_{hn} \times C_H$ m

Number scan intervals (length-wise), N_{sl} = INT (S_L/D_R) +1
Number scan intervals (breadth-wise), N_{sb} = INT (S_B/D_R) +1
Number scan intervals (height-wise), N_{sh} = INT (S_H/D_R) +1

Distance between scans (length-wise), $R_l = S_L/N_{sl}$ m
Distance between scans (breadth-wise), $R_b = S_B/N_{sb}$ m
Distance between scans (height-wise), $R_h = S_H/N_{sh}$ m

Movement time on stack, $T_{ms} = 2 \times ((N_{sb}-1)+(N_{sl}-1)) \times (S_H-R_h)/(v_s \times I_N)$ min
Movement time on deck, $T_{md} = (SL+SB)/v_d$ min
Total movement time, $T_m = T_{ms} + T_{md}$ min

Detection time, T_s = INT $(((N_{sb}-1)+(N_{sl}-1)) \times (N_{sh}-1)) \times (D_T/I_N)$ min
Total search time for each stack, $T_T = T_m + T_s$ min

Total search time for all stacks, T_{ST} = (INT $(S_S/I_T) \times T_T)/60$ hr

The effective depth, *Re*, the detector scans is given by

$$Re = \text{MIN}$$
$$\left(R_{el} = \sqrt{D_R^{\,2} - (\frac{R_l}{2})^2}\ ,\ R_{eb} = \sqrt{D_R^{\,2} - (\frac{R_b}{2})^2}\ ,\ R_{eh} = \sqrt{D_R^{\,2} - (\frac{R_h}{2})^2}\ \right)$$

Where R_{el}, R_{eb} and R_{eh} corresponds to the effective depth for the scans in the length, breadth and height of the container stack.

Given above equations: R_{el}, R_{eb} and $R_{eh} < D_R$

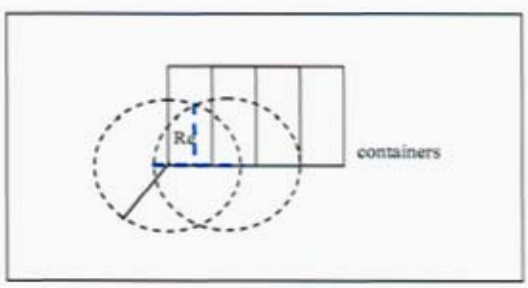


Figure A4: Detection range of detector during Inspection of containers

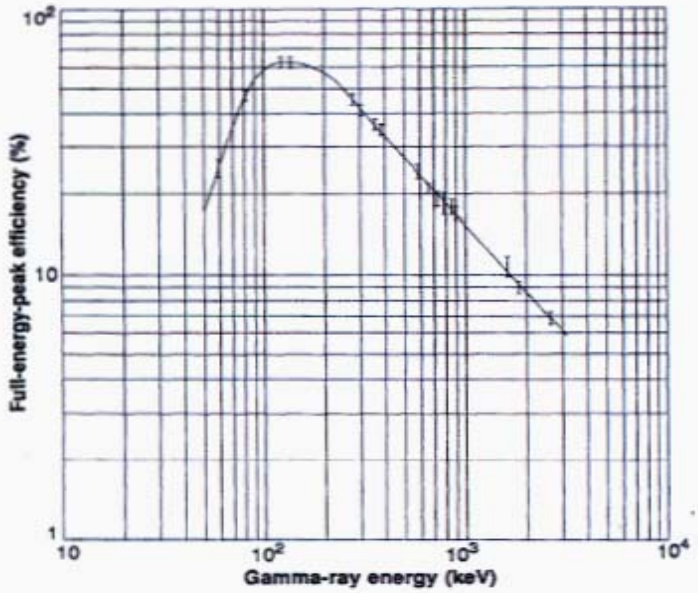
For D_R = 4m, $Re \geq$ 3.46m which is larger that than 3.043m (half the largest dimension of a TEU). The model does not account for the variation in shielding due to the presence of container wall and cargo along a scan path, when scanning from different positions outside the container.

APPENDIX 1 –
RADIOLOGICAL SEARCH & MODELLING

Table 3. The observed intensity, branching ratio, and decay rate of gamma-ray emissions observed in Fig. 2 that are due to isotopes of uranium and plutonium or their daughters (*14*).

Parent radio-nuclide	Expected energy (keV)	Observed intensity (counts/s)	Branching ratio (% per decay)	Decay rate $(g \times s)^{-1}$
$^{232}U^*$	583.02	0.190 ± 0.018	86.	2.31×10^{11}
	727.72	0.058 ± 0.018	6.65	4.97×10^{10}
	860.30	0.071 ± 0.013	12.0	3.22×10^{10}
	1620.66	0.030 ± 0.012	1.51	1.13×10^{10}
	2614.35	1.369 ± 0.031	99.79	2.68×10^{11}
^{235}U	143.79	0.118 ± 0.051	10.5	8,400
	163.38	0.102 ± 0.038	4.7	3,800
	185.74	1.870 ± 0.074	53.	42,000
	205.33	0.301 ± 0.062	4.7	3,800
$^{238}U^*$	1001.00	0.082 ± 0.014	0.65	81
^{239}Pu	332.81	0.137 ± 0.046	0.000505	11,600
	344.94	0.191 ± 0.061	0.00057	13,100
	375.02	0.862 ± 0.160	0.00158	36,300
	380.17	0.131 ± 0.071	0.000307	7,040
	382.68	0.160 ± 0.073	0.00026	6,000
	392.99	0.373 ± 0.090	0.00056	12,800
	413.69	1.582 ± 0.064	0.00151	34,600
	422.57	0.139 ± 0.027	0.000119	2,730
	451.44	0.318 ± 0.036	0.000192	4,410
	640.15	0.083 ± 0.025	0.0000079	181
	645.98	0.113 ± 0.025	0.0000145	333
	652.18	0.075 ± 0.024	0.0000064	147
	756.42	0.051 ± 0.018	0.0000034	77
	769.37	0.158 ± 0.020	0.0000110	252
$^{241}Pu^*$	662.43	0.116 ± 0.043†	0.00036	174,000
	722.47	0.131 ± 0.026	0.00013	92,000

APP.A2 **EFFICIENCY OF PORTABLE GERMANIUM DETECTOR**



Fetter et al 1990

APP.A3 RESULTS FOR HUMAN SEARCH MODELING

Figure App 1: Variation of search time with team size and detection range

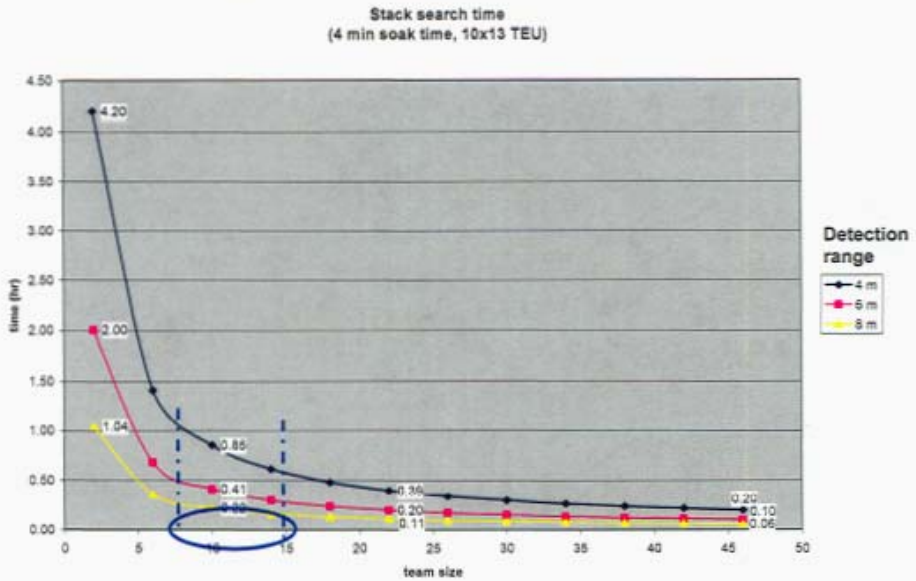


Figure App 2: Variation of search time with detection range and soak time

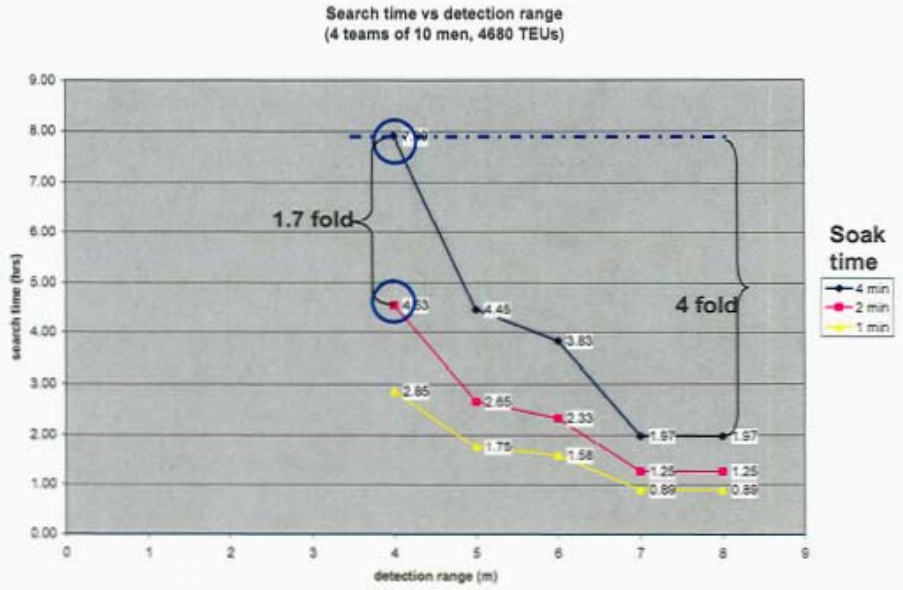


Figure App 3: Variation of search times with number of teams

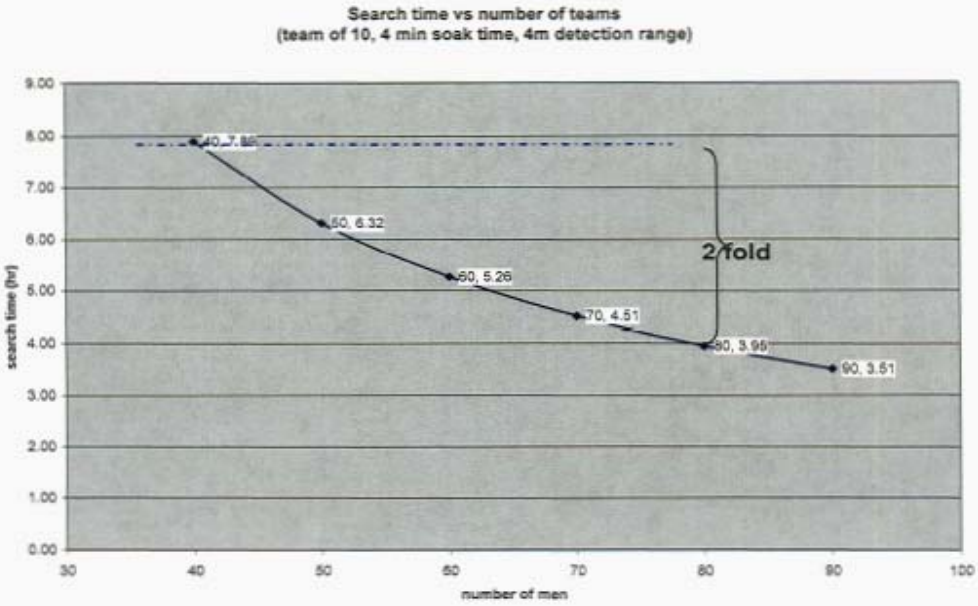
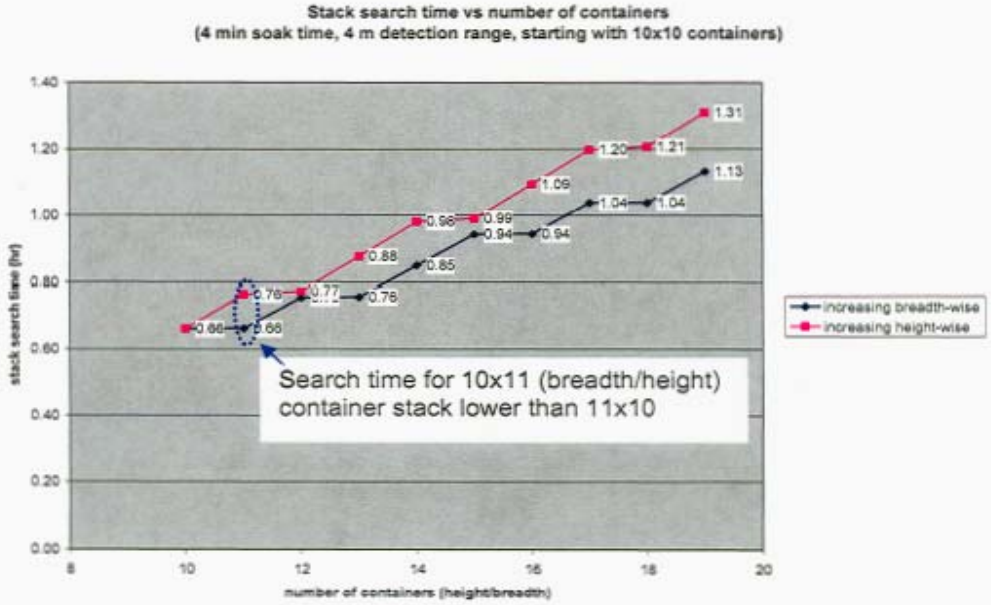


Figure App 4: Variation of search time with container configuration (4m detection)



APP - A4

Figure App 5: Variation of search time with container configuration (5m detection)

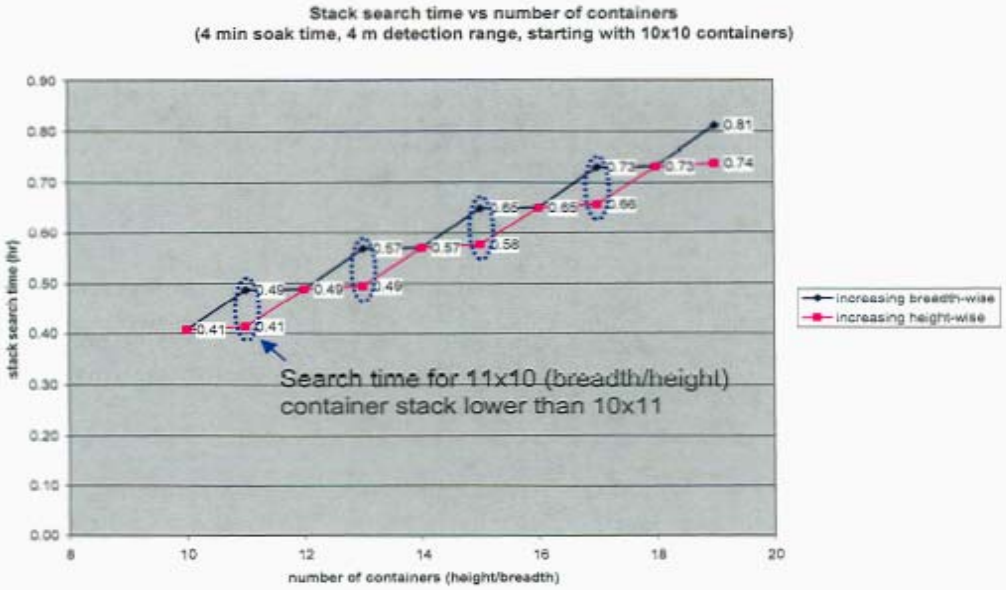
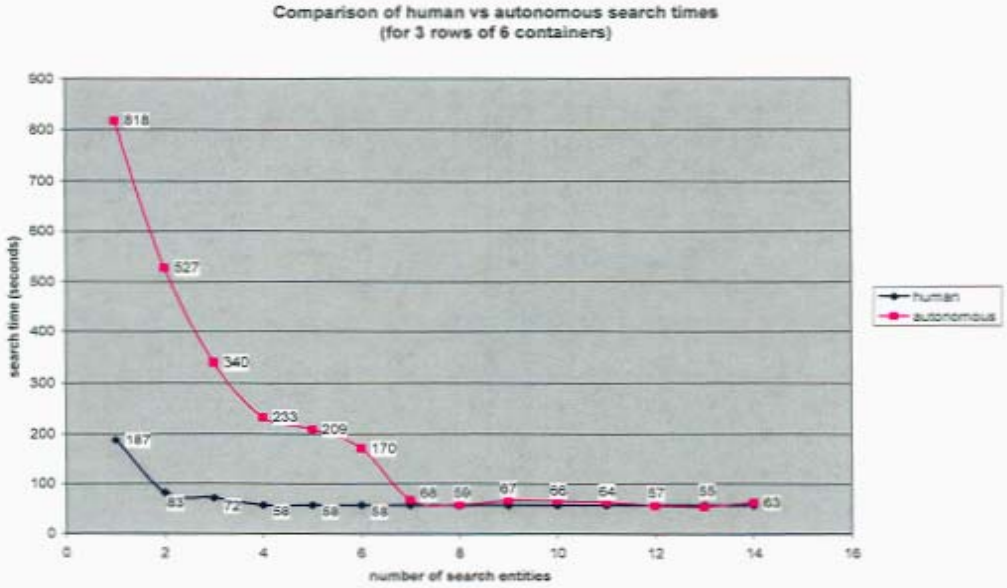


Figure App 6: Comparison of human vs. autonomous search times



APP - A5

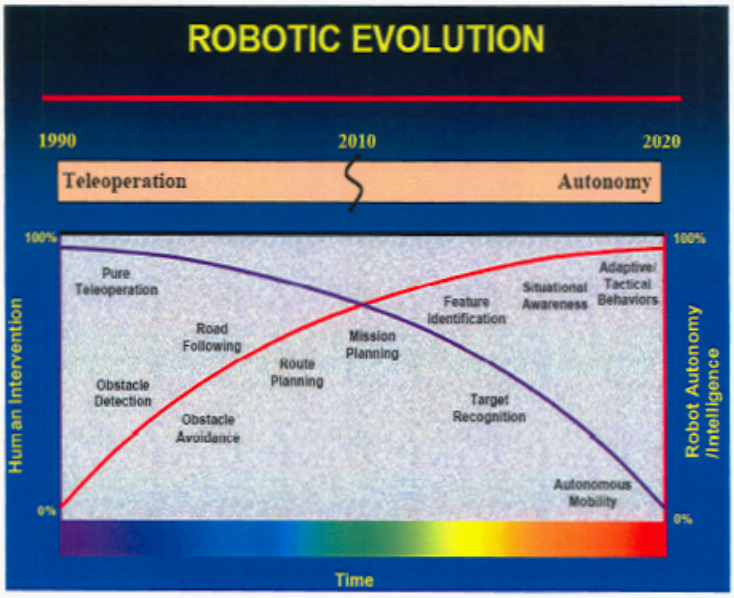
ANNEX B –
ROBOTICS SEARCH & MODELLING

ROBOTICS SEARCH & MODELLING

B.1 OVERVIEW

Many commercial and military applications had in recent times witnessed a marked surge of interests and activities in the fields of robotic technology and research. The recent use of Packbots[33] in mine-clearing and reconnaissance operations by the US Army in the Afghanistan & Iraq conflicts had laid down a significant milestone in the robotics arena. ActivMedia Robotics[34], a global commercial leader in the design of intelligent mobile systems, had also recently launched PatrolBots, an enterprise robots specialized in security and building automation. Both Toh[35] and Phey[36] in their research work had provided a concise literature survey of robotic platforms currently available and researched upon e.g. US COUGAR program, Gladiator TUGV, MULE vehicle, robotic technology in Mine Countermeasure applications etc. The widespread exploratory robotic research activities and their level of successes made the future of robotics look promising.

Figure B1: Robotics Evolution Projection of US FY2004 Joint Robotics Program Master Plan



Coupled with the rapid advances of artificial intelligence and robotic technologies, the efficient and cost-effective use of multi-robot systems adopting unmanned autonomous behavioral or collective approaches had also attracted many research and governmental organizations by virtue of its significant potential dividends of undertaking many tasks currently undertaken by humans. The US Defense Advanced Research Projects Agency (DARPA), being one such leading example, had been funding several robotic research projects. One of which being the Centibots Project[37], aiming at deployment of up to 100 unmanned cooperative autonomous robots for missions such as urban surveillance. The US Joint Robotics Program also viewed robotics as the key to their US Army Future Combat Systems (FCS)[38], leveraging itself on Collaborative Technology Alliance to strive towards insertion of robotics capabilities into force formation in the near future. In fact, their current projection was to achieve full autonomy by 2020 as depicted in Figure B1 above.

B.2 OBJECTIVE

It was with this motivation that the authors decided to embark on a preliminary exploratory study of adopting unmanned autonomous robotic platforms to carry out the inspection tasks required on board the container ships. Key focus would rest on the *autonomous search strategy and algorithm* as compared to human search capability. The overall scope of study comprised of:

B2.1 An adaptation of an existing Visual C++ robotic simulation model by courtesy of the National University of Singapore (NUS) Cooperative Systems Laboratory (COSY Lab).

B2.2 An appreciation of the search/comb time required and the probability of successful inspection would be defined and computed by running the simulation model.

B2.3 The various factors and variables that would affect the overall search efficiency of the autonomous robots would be analyzed and a brief sensitivity analysis study would be carried out.

B2.4 The results obtained could serve as a good lower-bound benchmark for the SEA Team to input its designated inspection team search rate into their overall modeling.

B.3 ROBOTICS IN SEARCH SCENARIOS

The idea of using robotic platforms to conduct unmanned search of items was not a new one. Much research work had been carried out, in particular, to support the use of multiple robot systems to search and dispose unexploded ordnance deemed too dangerous for men i.e. Packbots. McLurkin[39] in his paper stretched this idea further by exploring the ideas of using a community of autonomous robots to clear minefields. He described several simple community structures between robotic platforms, the desired search strategy, and the employment of cooperative behaviors to enhance search time. This brought about the potential dividends of enhanced system scalability, robustness and operator survivability. Some of his ideas would be incorporated into this study and its results would be analyzed.

Groups of robots performing coordinated actions to work towards achieving a common task presented unique challenges, particularly when they were to perform autonomously. The biological inspiration of nature in robotics had always been a popular driving theme, in particular ants and bees[40,41,42,43,44]. The seemingly complex yet simple behavior of each individual biological creature that could amount to a cooperative emergent behavior provided several insights to workable algorithms that can be input into the robots. The authors would attempt to inject similar behaviors into the simulation model to produce the desired cooperative behaviors.

B.4 OPERATING ENVIRONMENT

The search scenario of a container/cargo ship proved to be an interesting and challenging one purely by virtue of its tight constraint of maneuvering space. Container/cargo ships currently came in various types, shape and sizes, ranging from as small as a few hundred Twenty Foot Equivalent Units (TEU) size to post-Panamax class of 9,000 TEUs. Within the next 5 years, Ultra Large Container Ships (ULCS) (50m breadth) carrying up to 12,000 TEU would also be expected[45]. Due to the tight packing of the containers, the spacing in between containers turned out to be very narrow for any human operator to maneuver through easily[46]. Inspection tasks would therefore be hindered due to the inaccessibility. Also, due to the tall stacking of the containers one upon the other (see Figure B2 & B3 below), it would be extremely difficult or virtually impossible for human operators to be able to inspect/scan the container at close range without any aids. Deployment of small autonomous robotic platforms would therefore be an ideal attractive solution. However, this also had its own several limitations, which would be discussed later.

Figure B2: Typical Stowage Profile Layout of a Cargo Ship[47]

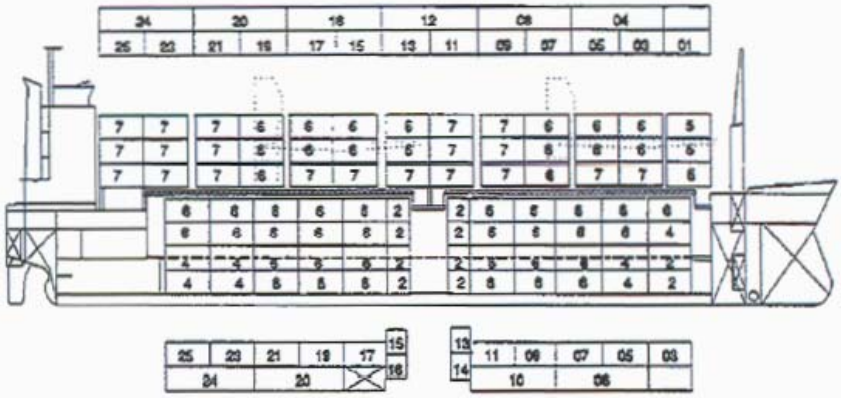


Figure B3: Typical Container Ship[48]

B.5 EXISTING SIMULATION MODEL

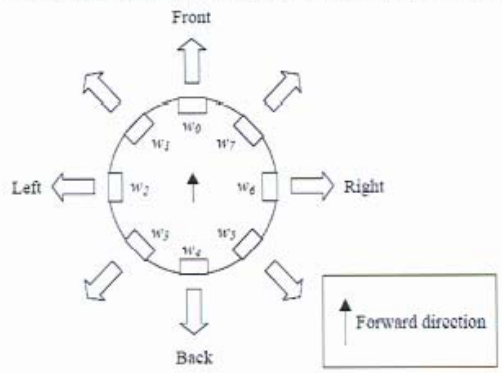
The robotic simulation model obtained from NUS COSY Lab was originally developed by Yee[49,50] for the purpose of simulating scenarios of encircling dynamic targets using multiple autonomous robotic platforms. The robotic simulation was based on a behavior-based algorithm and only three basic behaviors were adopted, namely obstacle-avoidance, target tracking and target circumnavigating. Object oriented Visual C++ Programming Language was used in the coding with incremental time-step simulations and the model allowed add-on provisions to improve or change the behaviors of the simulated robots.

B5.1 Behavior Based

Ronald Arkin[51] had defined robotic behavior as simply "a reaction to a stimulus", similar to biological behaviors in animals. He put forward two ways of having behavioral coordination, namely competitive and cooperative methods. The 1st behavior required a priority based hierarchical behavioral network that advocated preferential behaviors by virtue of its designed status i.e. winner-takes-all network. The 2nd behavior allowed a fusion of behaviors and permitted the combined output of more than one

behavior. This simulation model had both of these methods already operating together within its architecture.

Figure B4: Schematic of Simulated Robotic Platform (Courtesy of Yee[49])



Each of the simulated robots had a simple outlook, circular in shape and its size was to be user-defined. It was mounted with only light and sonar sensors on 8 equally spaced directions as shown in Figure B4 above. Each of the 3 robotic behaviors was determined by weighting inputs that were pre-assigned for each of these 8 mounted sensors. Positive activations of these sensors would then dictate the final behavior that the robots would behave, by reacting to changes in the sensory environment and summing up all the positive activations with its weightings i.e. cooperative effort. On the other hand, these 3 intrinsic robotic behaviors also had a fixed hierarchical preferential state within its decision-making architecture i.e. competitive, as shown in Figure B5 below.

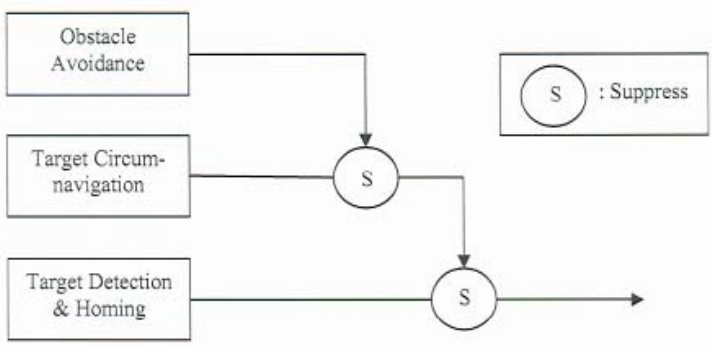


Figure B5: Subsumption Coordination of Previous Robotic Behaviors[49]

B.6 MODIFIED SIMULATION MODEL

The robotic behaviors in the existing simulation model were however inadequate to resolve the search problem encountered. This was due to the presence of sharp abrupt turnings and openings within the containers, akin to a simple columnar maze. This resulted in a need for the robotic platforms in its movements to possess added intelligence and coordination efforts among them in order to complete the search within reasonable timings.

The following section will describe the simplified assumptions made in pursuit of developing an autonomous search algorithm, and also highlight the model configurations adopted during the modifications of the earlier simulation model:

B6.1 Assumptions

B6.1.1 Modeling Environment.

Due to the wide variety of container ship configurations and the level of detailed study required, it would not be feasible to simulate in detail the exact configurations. Rather, a 2-dim 18 TEUs *deck* configuration of 20 foot containers were assumed, as shown in Table 1 and Figure B6 & B7 below. The choice of the TEU size was also limited by the size of the simulation screen that would project the robots to be reasonably viewable by users. The model drew upon the dimensions of a small container ship of 266 TEUs capacity for a conservative estimation.

Ship DWT / tonnes	Inter-Container Gap / cm	TEU	Walkway Gap / cm	Remarks
3284	64.8	266	40.5	20ft containers; small ship
7285	89.6	588	55.98	40ft containers; small ship
20380	96.8	1472	83	Medium ship
63163	207	4743	Nil	Large ship

Table B1 Survey of Container Ships Deck Layout (Wijnolst)

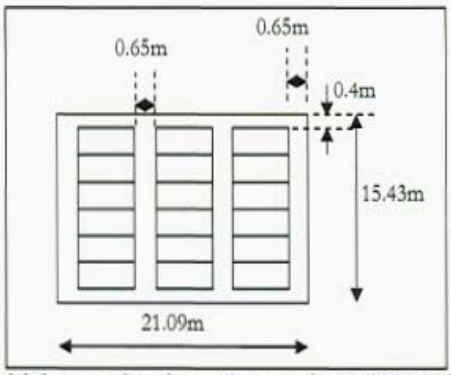


Figure B6: Simplified Schematic Simulation Layout of a 18 TEU (20ft container type) Deck

Figure B7: Sample Screen View of Simulation Model Run

The simulation run was driven primarily by simulating time steps. The time step was set to represent 0.03 seconds of real time. The robots would move in accordance to its interactions with the surrounding and other robots. The simulation floor was also divided up into equal size trail marker square (to be explained later). On the simulation screen, for display, debug and behavior output purposes, every robot figure would display a maximum of 4 sets of figures on the screen: *Robot ID* on the right; *Number of Other Robots Detected* on the left; *Number of Scanning Robot Detected* on the top; *Scanning Time Steps that had lapsed so far* on the bottom.

B6.1.2 Robot Configurations

B6.1.2.i Each robot was 2-dimensional, circular in shape and its size was user-defined. The overall robot configurations were upgraded as shown in Figure B8 below. It illustrates the overall makeup of the robot and its assumed sensors and communication aids. Besides the original sonar sensors makeup, 2 IR transmitters, 1 IR receiver and 1 trail marker sensor were installed onto the robotic platform for added communication aids to improve cooperative efforts.

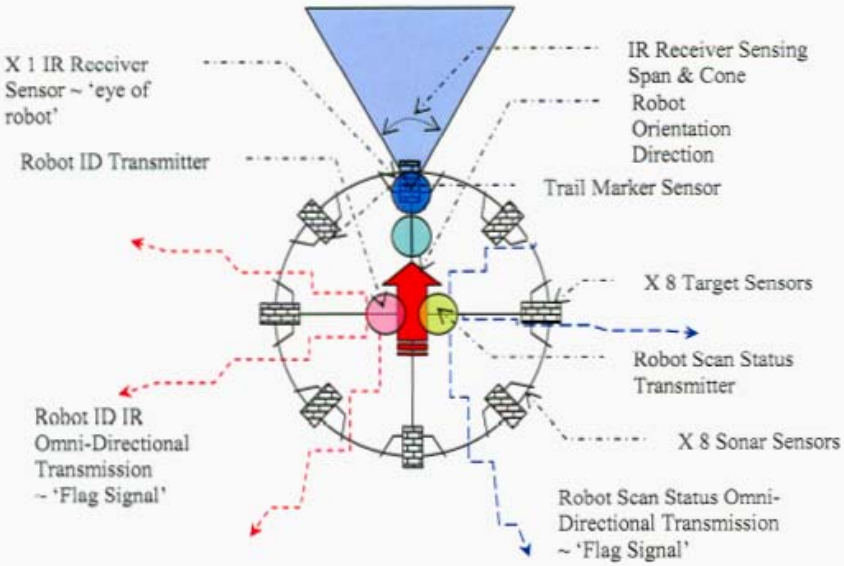


Figure B8: Robot Schematic Configurations in Simulation Model

B6.1.2.ii No design considerations for its payload, power and locomotion drive systems. The robot could rotate freely at a point and translate linearly in a defined direction with its ideal locomotion drive systems.

B6.1.3 Sensor Characteristics

B6.1.3.i The target itself and the target sensor modeled was a generic one. No distinction was made to differentiate the various possible types of target sensors that could be used for the various possible dangerous items i.e. nuclear / biological / chemical /explosives, except for its user-input definition of its target sensors maximum sensing range. The detection of a suspected target source was instantaneous the moment a defined threshold level had been attained. The robot would halt and commence its scanning process till the user defined maximum scan time was up. This was incorporated so as to simulate the necessity of a sensor scanning process using current existing detector technology.

B6.1.3.ii Each robot would be equipped with ideal sensors capability with no time lag (instantaneous sensing), no size fitting, no performance deterioration nor power consumptions considerations. Upon detection of a source, the robot would halt and commence scanning of the suspected source till an user-defined target scan time limit was reached.

B6.1.3.iii No detailed physical consideration was given for the practicality of laying trail markers. It was assumed that the concept was practically achievable, and every defined square area had a counter that could be updated whenever a robot entered it. In reality, the authors envisaged this could probably take the form of an IR beacon deployed at critical junctions and/or points, laid by leading robots in the search.

B6.2 User Input Design Parameters

Table B2 below lists the range of user input design parameters that were required as inputs for the simulation model. An input data file was also required to capture scenarios parameters.

Input Data File Scenario Parameters					
General					
Simulation Area Dimensions	No. of Trail Marking Divisions	No. of Obstacles	Dimensions of Obstacles		
Target Source					
No. of Source Targets	Type of Target (Static/ Moving)	Dimensions of Target	Initial Position of Target	Speed of Target	
Robot Specifications					
No. of Robots	Type of Robot	Robot ID	Initial Positions of Robot	Dimensions of Robot	Initial Orientation of Robot
Speed of Robot	Angular Velocity of Robot				
Model Embedded User Adjustable Design Parameters					
General					
Maximum Search Time Limit	Robot Trek Density Threshold	Robot Cluster Density Threshold	Scanning Robot Density Threshold	Simulation Time Steps	Weightings of Behaviors
Sensor Parameters					
Target Scan Time	Max. Target Sensing Distance	Target Sensory Span Angle	Max. Sonar Sensor Range	Sonar Sensor Span Angle	IR Receiver Max. Sensing Range
IR Receiver Span Angle	Max. IR Transmitter Range				

Table B2: List of Model Design Parameters

B6.3 Robotic Behaviors

In order to enhance the cooperative behaviors of each individual robots, additional behaviors were added into its hierarchical rule-based decision making structure, while modifying the previous original 3 behaviors. Both the basic obstacle avoidance and target tracking behaviors were retained by the authors, while the target circumnavigating behavior was discarded due to its unsuitability for the operating environment. Figure 9 below illustrates the enhanced behaviors created:

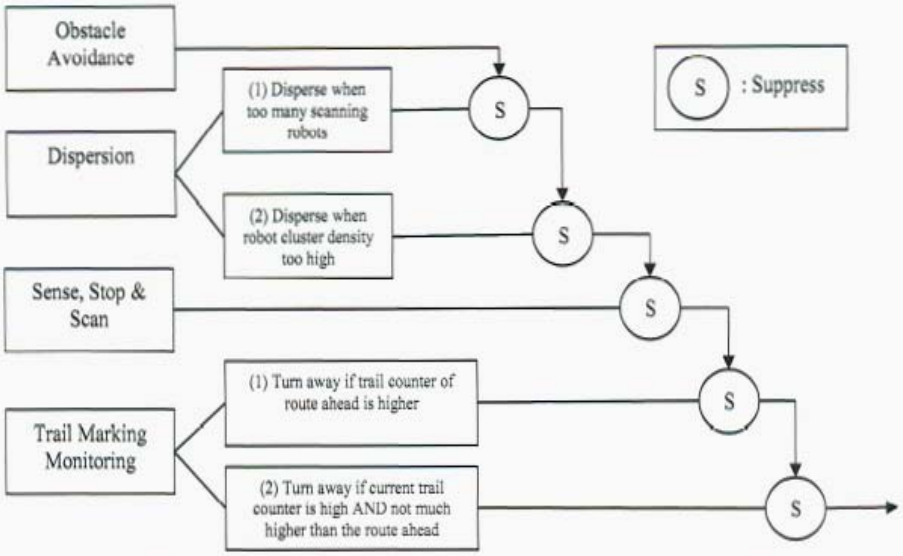


Figure B8: Subsumption Coordination of Modified Robotic Behaviors

Table B3 below summarizes the various sets of weightings applied to each of these behaviors, taking reference from Figure B4 & B8 above, and adapting from previous simulation model[17]. Each of these weighting values was multiplied with 360^0 to obtain the desired angular change to the orientation of the robot upon activation of the sensor in that direction. A summation average of weightings would be computed upon multiple activations of sensors.

Table B3 Weightings Applied to Various Individual Robotic Behaviors (anti-clockwise direction = '+')

		Behaviors										
		Obstacle Avoidance		Dispersion				Sense Stop & Scan	Trail Marking Monitoring			
Direction	Weights			(1)		(2)			(1)		(2)	
Front	w_0	0.25	$+90^0$	0.5	$+180^0$	0.5	$+180^0$	0	0	0	0	0
	w_1	0.625	$+225^0$	0	0	0	0	0	-0.875	-315^0	0	0
Left	w_2	0.75	$+270^0$	0	0	0	0	0	-0.75	-270^0	-0.75	-270^0
	w_3	0.875	$+315^0$	0	0	0	0	0	-0.625	-225^0	0	0
Rear	w_4	0.25	$+90^0$	0	0	0	0	0	0	0	0	0
	w_5	0.125	$+45^0$	0	0	0	0	0	-0.375	-135^0	0	0
Right	w_6	0.25	$+90^0$	0	0	0	0	0	-0.25	-90^0	-0.25	-90^0
	w_7	0.375	$+135^0$	0	0	0	0	0	-0.125	-45^0	0	0

Weightings applied were critical to defining the desired behaviors of each robots upon any change of environment. Slight variations of the weightings could create an entirely different behavior.

B6.4 Obstacle Avoidance

The weightings were adapted from the previous simulation model, with modifications to only w_0 (front) and w_4 (rear) to both 0.25, instead of the original 0.5 and 0 respectively. This was to generate behaviors that would rotate the robot to turn in 90^0 rotations upon hitting obstacles. Such behaviors would be useful in the environment of the container ship where sharp turns and corners were common. The robots would also treat other neighbouring robots as obstacles upon detection by the sonar sensors.

B6.5 Dispersion

The behavior of dispersion was injected essentially to keep the individual robots from being clustered too close to one another. The robots could also use this behavior to form teams between themselves. The activation of the behavior hinged on 2 conditions: when in the presence of a certain defined number of scanning robots in the vicinity (scanRobotDensity), or when the number of neighbouring robots were higher than a defined threshold level (robotClusterDensity). This sensing could only be picked up by the robot's front IR receiver sensor, which acted like its 'eyes'. This was necessary so as not to overload the robot with too much information, less its behaviors became too erratic. The robot would then turn 180^0 away. Figure 9 below illustrates this behavior briefly where 12 robots could split up into 3 groups.

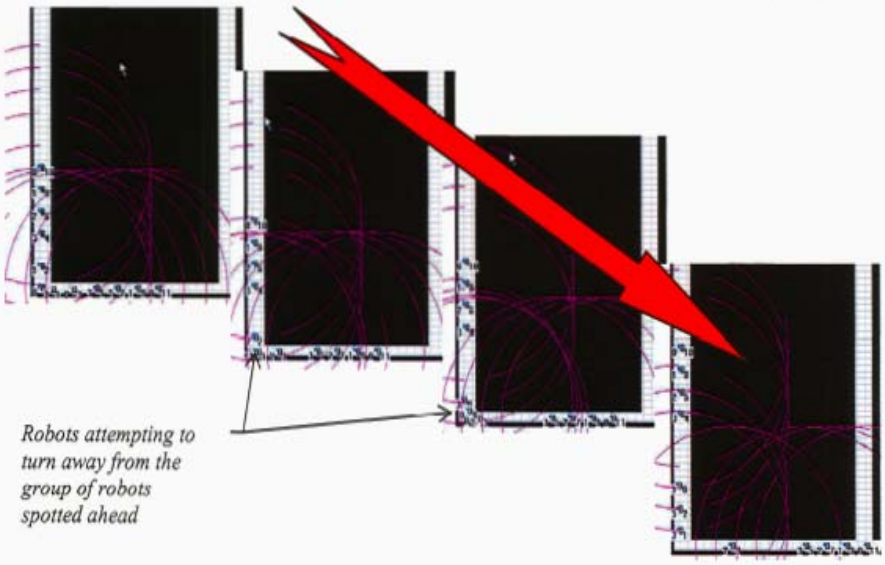


Figure B9: Dispersion Behavior of 12 Robots – Cluster Density Threshold of 3

B6.6 Sense, Stop & Scan

This robotic behavior would assume that its target sensing capability could pick up traces of the target even while on the move. Upon sensing the target within its sensing range, it would halt and commence its scanning process to confirm the presence of the target source till a user-defined specific time period was over. It would still remain halted after the scan. While scanning, the robot would broadcast its scanning status. Other on-coming robots upon receiving this status signal would react by turning 180^0 away (dispersion). See Figure B10 below.

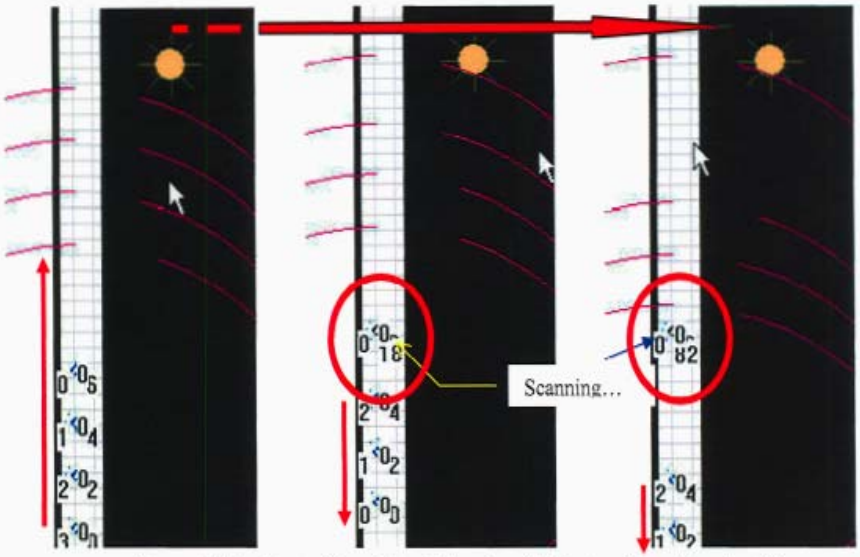


Figure B10: Sense, Stop, Scan Behavior of Robots – Scan Density of 0

B6.7 Trail Marking Monitoring

In order to further enhance search capability, it would be critical that updates of situations could be relayed down to individual robots. This could be achieved by performing trail marking operation as the robots moved through the environment[7]. In this way, the robot would always strive to venture into areas that were new or less frequently visited. Such method was inspired by how ants communicate and move to its source of food by sensing and following trails of the strongest traces of pheromone.

The simulated environment was equally divided into rectangular areas. Each designated specific areas would have a counter that jumped by 1 whenever a robot entered it. In this way, any oncoming robots would be able to know how many robots had passed through this area, and react accordingly. The decision criteria that the robots followed would be as follows, and would occur whenever there was an opening at that instance to another long corridor:

The robot would always turn away if the trail marking counter was higher ahead in the next area; if not, it would also turn away if the current counter (robotTrekDensity) was high and its difference with the counter ahead was not too big (< robotTrekDensity). The robots would turn into the 1st open corridor clockwise from its orientation. Note that the main idea of the 2nd sub-criteria was to make sure that if the robots kept coming back to the same spot, making the counter high, this would likely mean that it needed to move on ahead and they would be allowed. Figure B11 below demonstrates such behavior.

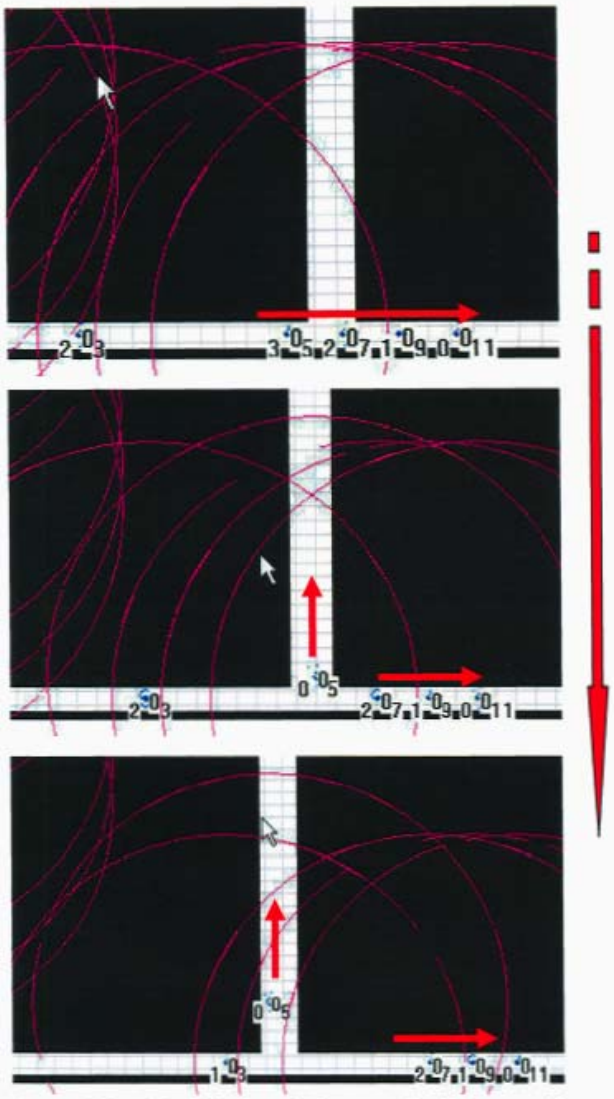


Figure B11: Trail Marking Behavior – Trek Density of 3

B6.8 Model Output

The simulation model was able to generate an environment for the autonomous cooperative behaviors and movements to be duly exhibited. From the simulation screen, the amount of time-step, the physical coverage of the robots and the target sensing behaviors could be easily observed. The target to be sensed could also be located randomly on the simulated area to be detected and scanned by the robots. Due to its rudimentary nature as a test platform, the level of user-friendliness was limited. The data displayed had to be written down manually and an excel spreadsheet was generated to analyze the results.

B6.9 Simulation Runs & Analysis Study

Using the model architecture designed, a series of simulation runs were conducted to evaluate the model and to derive useful results and findings from the behaviors of the simulated autonomous robots. The design constraint, input parameters used and the types of simulation runs would be described as follows.

B6.9.1 Design Constraint ~ Maximum Allowable Inspection Time

One of the key requirements laid down by SEA-7 Sea-Inspection Study was that each container ship inspection would allow a maximum of 6 hours of physical search time. Naturally, this would translate to a maximum time limit permissible for the robots to search the 18 TEUs in the simulation model. For conservatism, a futuristic Ultra Large Container Ship of size of 12 000 TEUs[45] would be assumed to estimate the maximum allowable time for 18 TEU deck size configuration.

Given from Wijnolst[46], a 63,163 DWT container ship, with a length of 299.96m and breath of 37.10m, had approximately a deck size of 36 columns of 10 rows of 20ft size containers. Scaling this linearly to an Ultra Large Container Ship, this would mean a maximum inspection time of **10.1 min** per 18 TEUs given a 6hrs period. This time constraint would serve as the cut-off limit to assist in the determination of a successful inspection during the simulation run.

B6.9.2 Base Line Input Parameters

A set of base-line input parameters was assumed to lay the foundations for a proper evaluation of the model, as follows below. Some of these input parameters would be altered during the sensitivity analysis simulation runs and these would be highlighted later.

Base Line Input Parameters	Value or Range of Values
Time Step	0.03s
Number of Trail Matrix Areas	70
Maximum Time Constraint	10.1min
Number of Targets	0 – 1
Robots Configurations	
Number of Robots	1 – 15
Speed of Robots	0.6 m/s
Diameter of Robots	15cm
Robot Scan Time	4min
Robot Sonar Minimum Reaction Distance	10cm
Robot Sonar Span	15deg
Robot Target Sensor Detection Range	4m
Robot Target Sensor Span	45deg
Robot Scan Transmitter Range	4m
Robot Long Range Detection Range	0.40m
Robot ID Transmitter Range	4m
Threshold Values	
Robot Trek Density	3
Robot Cluster Density	3
Scan Robot Density	0

Table B4: Simulation Run Base Line Input Parameters

Appendix 2 illustrates a sample input data file and documents the initial positions and orientations of the robots assumed. All the robots had their initial start points located at the lower left corner of the search area. Some of the above values were assumed after studying its effect on the robotic behaviors and carrying out sensitivity analysis (to be discussed later), while other minor observations were as follows:

B6.9.2.i Diameter of Robots. Due to the tight constrictions of the deck space (~ 40cm), it was found out that the maximum permissible robot size was in the vicinity of 15cm, with a minimum sonar reaction distance of 10cm. Anything beyond would constrict the movement of the robots and resulted in rise of frequent collisions.

B6.9.2.ii Speed of Robots. The speed of robots were assumed to be 0.6m/s, for the sole purpose of being approximately close to human walking speed, so as to draw comparisons in subsequent studies. Obviously, raising the speed of robots would quicken the inspection time, but in reality the probability of detection would drop. Due to the lack of information source in this aspect, the study did not incorporate such considerations.

B6.9.2.iii Robot Scan Time. The arbitrary scanning time of 4min was selected for this analysis in congruence with the human modeling study done earlier. That was based on the selected germanium detector versus a specified nuclear target source of 25kg HEU with ¼ inch lead shielding (specified by SEA-7 Study).

B6.9.3 Types of Simulation Runs

2 main types of simulation runs were conducted, namely (1) runs without targets with variations of robotic behaviors, (2) runs with 1 target and variations of number of robots.

B6.9.3.i Runs with Variations of Robotic Behaviors (no targets)

These runs were conducted with the purpose of studying & quantifying the significance of the modified robotic behaviors. 3 separate runs were carried out to capture the time needed to *fully comb the area* while varying the number of robots. The 1st run was purely the generic robotic behavior of the original model, the 2nd run incorporated the trail-marking algorithm, while the 3rd had the additional dispersion behavior. *Table B5* summarizes the results.

The definition of *time to comb* was defined as the time required for the robots to physically move over the entire deck area within the 18 TEUs. Run (1) did not see any of the robots being able to fully comb the deck area with just its generic behaviors, with all the robots observed moving along its perimeter. Runs (2) & (3) showed the marked improvements in the search capability with the added behaviors. There was observed a point of diminishing return of the comb time in increasing the number of search robots for the 18 TEUs for both runs, roughly in the region of 7 robots & above. Figure B12 below illustrates the comparisons between Run (2) & (3).

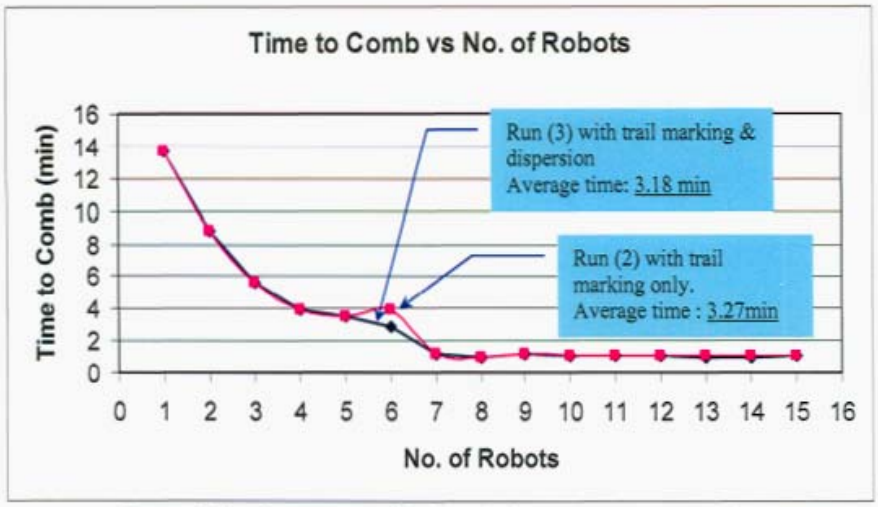


Figure B12: Comparison of Robotic Behaviors in Time to Comb 18 TEUs

Based on the average time-to-comb of both Runs (2) & (3), Run (3) with the full modified behavior showed an improvement of 2.88% in the timings. Though the magnitude of improvement was not huge in this case for 18 TEUs, it nevertheless would have its advantage, especially when the number of robots increased and the search area got larger than just 18 TEUs. Note also that the timings obtained were well below the 10.1 min design limit for > 1 robot.

(1) Pure Generic Behaviors			
No. of Robots	Time Step	Time (sec)	Time (min)
1	∞	∞	∞
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

(2) With added Trail Marking only			
No. of Robots	Time Step	Time (sec)	Time (min)
1	27279	818	13.64
2	17559	527	8.78
3	11322	340	5.66
4	7786	234	3.89
5	6999	210	3.50
6	7850	236	3.93
7	2277	68	1.14
8	1956	59	0.98
9	2229	67	1.11
10	2197	66	1.10
11	2190	66	1.10
12	2150	65	1.08
13	2147	64	1.07
14	2111	63	1.06
15	2111	63	1.06

(3) With added Trailing Marking & Dispersion			
No. of Robots	Time Step	Time (sec)	Time (min)
1	27279	818	13.64
2	17559	527	8.78
3	11322	340	5.66
4	7768	233	3.88
5	6977	209	3.49
6	5668	170	2.83
7	2275	68	1.14
8	1957	59	0.98
9	2244	67	1.12
10	2197	66	1.10
11	2192	66	1.10
12	2149	64	1.07
13	1884	57	0.94
14	1831	55	0.92
15	2111	63	1.06

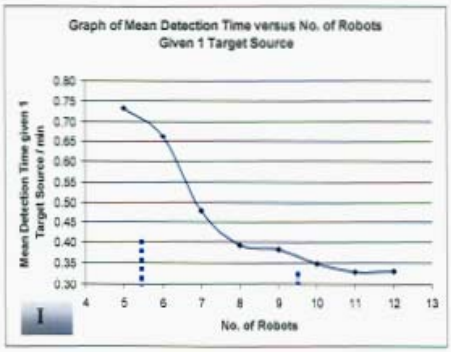
Table B5: Simulation Runs Results for Comparisons of Cooperative Behaviors

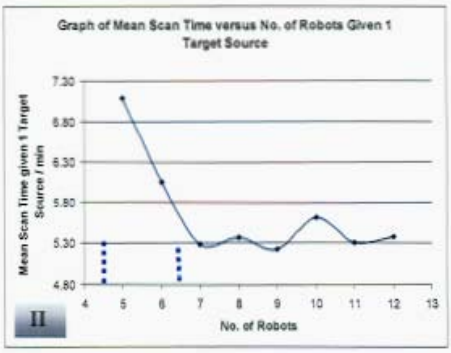
B6.9.3.ii Runs with 1 Target Source with Varying Number of Robots

A Monte Carlo simulation of randomly siting the target source was done on the simulation screen, and the number of robots released to search it was varied. A total of 30 simulation runs were carried out for each set of number of robots, making sure that each column of 6 TEUs had 10 target sites randomly simulated.

An inspection criterion was also designed as such:

Successful Inspection
= Successful Comb ∩ Successful Scan ∩ Successful Detect ... [1]





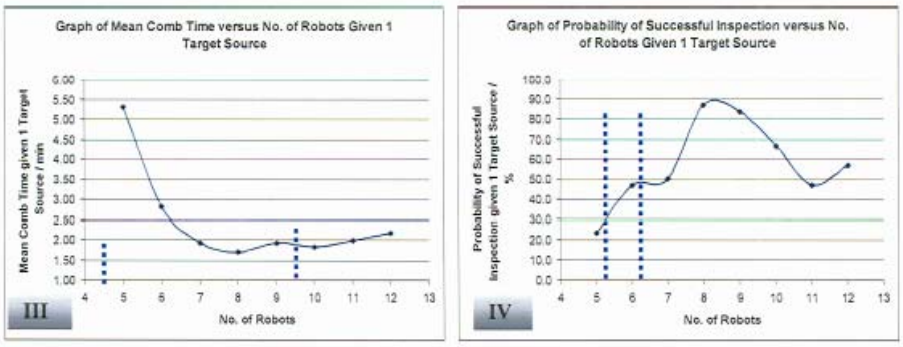


Figure B13 Graphical Representations of Results from Searching 1 Target Source

For a successful inspection to take place, all 3-sub criteria must be fulfilled during the simulation runs within the specified design time limit. For a successful scan, there must be at least 2 or 3 robots that could map their sensing envelopes and locate the target source. A successful detection would be fulfilled as long as any robot first sensed the target presence. The timings and the outcome of each of the sub criteria were noted down during the simulation run. Appendix 2 documents the range of data set obtained for the simulation runs, with the range of robots spanning from 5 up to 12.

From the data collected, the following findings and relations were found as shown in Figure B13.

It was cleared from the results obtained that the employment of **8-9 robots** proved to be the most efficient in terms of inspection success (83.3%-86.7%) and the timings required. It was found that though the increase in the number of robots have the edge of reducing the search time, the element of space congestion and collisions would also become more pronounced, leading to a deteriorations in the percentage of a successful comb. This explained why Graph IV in Figure B13 had a maxima curve.

A human conducted inspection should theoretically give a 100% inspection success if all things were ideal as it was for the robotic environment, and communications & coordination were efficiently carried out within the time span laid. Therefore, these simulation results, particularly Graph IV, also provided an appreciation of the level of robot autonomy achievable with respect to human intelligence.

B6.9.4 Sensitivity Analysis

It was clear that all the design input parameters played a strong influential role to the derivation of the final results. To succinctly sum up, the following functional relation should hold for this simulation model designed:

$$\mathbf{P(Successful\ Inspection) = F(\ N_B, N_{col}, N_{row}, TD, CL, SD, IR_{rge}, IR_{FOV}, SO_{rge}, SO_{FOV}, SO_{Lrge}, SO_{rge}, Tgtrge, N_{sq}, t, (x,y)_i, V_{rob}, N_{tgt}, R_{size}, (x,y)_{tgt}\ )} \quad \ldots [2]$$

where N_B : Number of robots
N_{col} : Number of TEU columns
N_{row} : Number of TEU rows

TD	:	Trek density threshold
CL	:	Cluster density threshold
SD	:	Scan density threshold
IR_{rge}	:	IR sensor range
IR_{FOV}	:	IR sensor field of view
SO_{rge}	:	Sonar sensor range
SO_{FOV}	:	Sonar sensor field of view
SO_{Lrge}	:	Sonar sensor long range threshold
SO_{det}	:	Sonar sensor detection range
Tgt_{rge}	:	Target sensor range
N_{sq}	:	Number of trail marking areas
t	:	Time Limit
$(x,y)_i$	:	Initial position of each robots
V_{rob}	:	Velocity of robots
N_{tgt}	:	Number of targets
R_{size}	:	Robot's size
$(x,y)_{tgt}$	:	Target positions

To fully analyze all these influences would require a long-term investment of time and effort. Therefore, for the purpose of this study, in order to just provide a brief insight to the influence of some of these factors into influencing the final results, simulation runs of the time-to-comb for 8 robots were carried out in variations with these factors as follows

B6.9.4.i Variation of Trek Density

The value of trek density would influence when the robots would react to turn into open corridors available at junctions, and would therefore influence how the robots would split up and how efficient the robots could search a particular area. Figure B14 below illustrate the findings obtained from the simulations runs:

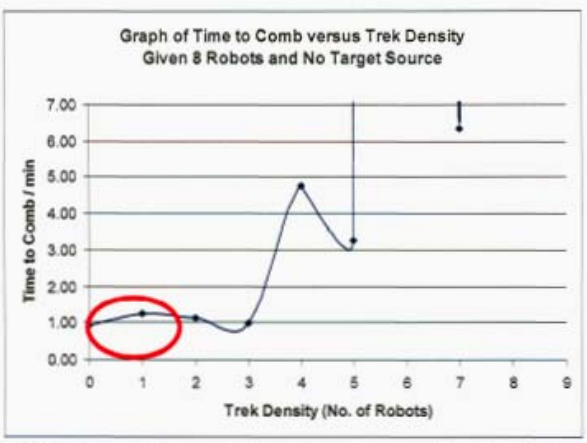


Figure B14 Graph of Time-To-Comb versus Trek Density (8 Robots/No Targets)

A clear upward trend in the combing time was observed if the trek density were too large with respect to the number of robots. Clearly, this result was also a function of how the TEU were laid out in the ship. The detailed functional relationship between these

variables would be out of the scope of this study. Nevertheless, the results showed that a Trek Density of 2-3 provided a good low combing time. Hence the assumed value of 3 for the simulation run described earlier. See Table B4.

B6.9.4.ii Variation of Cluster Density

Cluster Density would affect how efficient the robots could spread out. It would therefore also be a strong function of the number of robots, and how the TEUs were laid out. Figure B15 below shows the influence of the cluster density on the time-to-comb. The results showed that its influence was minimal, leveling off when the density was more than 3. The slightly high value at low cluster density could be the additional time spent attempting to split off from one another.

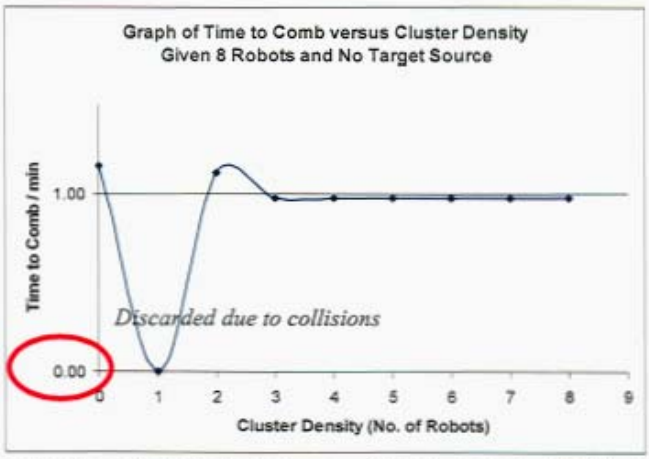


Figure B15 Graph of Time-To-Comb versus Cluster Density (8 Robots/No Target)

B6.9.4.iii Variation of Sonar Sensor Span

The span of the sonar sensor would have a marked effect on the search behavior of the robots. This was because of the tight sharp corners and openings of the deck area that required more directional sensing of the sonar in order for the robots to pick it out correctly. Figure B16 below shows the results. An optimum value of 15 deg was earlier selected based on this result.

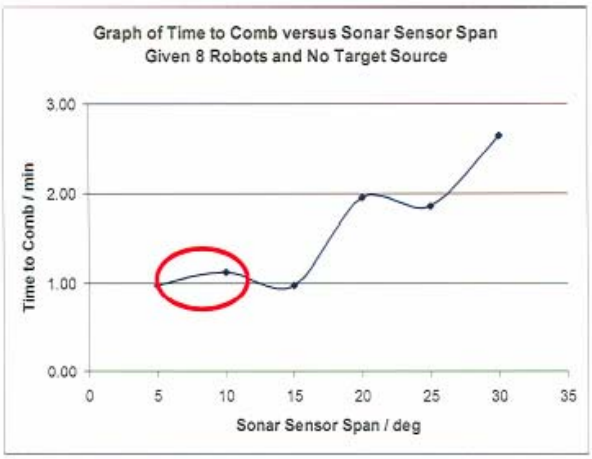


Figure B16 Graph of Time-To-Comb versus Sonar Sensor Span (8 Robots/No Target)

B6.9.4.iv Variation of Sonar Long Range Threshold

This value had to work hand-in-hand with the sonar sensor span. Similar to the sonar sensor span, due to the tight space constraint and the presence of sharp corners, the range threshold was crucial in order for the sonar to determine the presence of an open corridor to make a decision to turn correctly. The threshold needs to be of a certain minimal value. Yet, if the value was too high, it would become too insensitive to react as well due to the sonar span. Therefore, the sonar span had to be small if the threshold value was high. Figure B17 shows the outcome of the variation of this threshold value.

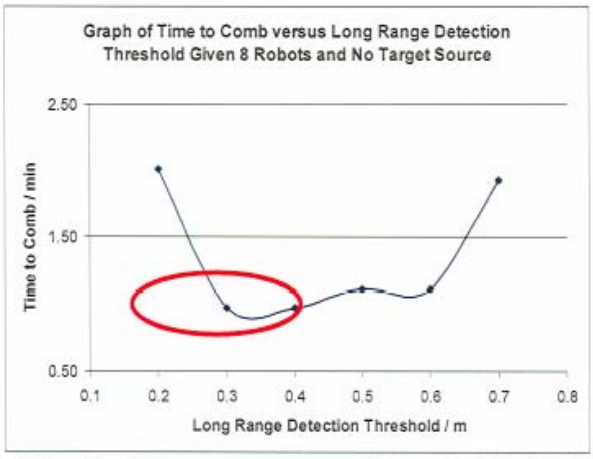


Figure B17 Graph of Time-To-Comb versus Long Range Detection Threshold (8 Robots/No Targets)

A minimal relationship was observed and the value of 0.4m was therefore assumed in the earlier simulation runs.

APPENDIX 2 –
ROBOTICS SEARCH & MODELLING

APP.B1 SAMPLE INPUT DATA FILE FORMAT ~ 15 ROBOTS / 1 TARGET SOURCE

```
drawing_area_dim(real)_{xmin,ymin,xmax,ymax}
0.0 0.0 21.088 15.63

drawing_area_divisions_{ndiv}
70

no_of_obstacles
22

no_of_targets
1

no_of_robots
15

obstacles_(ID,nside,x(1),y(1),...,x(n),y(n),r-only_for_nside<3)
1     4     0.0     0.0     21.088  0.0     21.088  0.1     0.0     0.1
2     4     20.988  0.0     21.088  0.0     21.088  15.63   20.988  15.63
3     4     0.1     15.63   21.088  15.63   21.088  15.53   0.1     15.53
4     4     0.0     0.1     0.1     0.1     0.1     15.63   0.0     15.63

5     4     0.75    0.5     6.846   0.5     6.846   2.9384  0.75    2.9384
6     4     0.75    2.9384  6.846   2.9384  6.846   5.3768  0.75    5.3768
7     4     0.75    5.3768  6.846   5.3768  6.846   7.8152  0.75    7.8152
8     4     0.75    7.8152  6.846   7.8152  6.846   10.2536 0.75    10.2536
9     4     0.75    10.2536 6.846   10.2536 6.846   12.692  0.75    12.692
10    4     0.75    12.692  6.846   12.692  6.846   15.1304 0.75    15.1304

11    4     7.496   0.5     13.592  0.5     13.592  2.9384  7.496   2.9384
12    4     7.496   2.9384  13.592  2.9384  13.592  5.3768  7.496   5.3768
13    4     7.496   5.3768  13.592  5.3768  13.592  7.8152  7.496   7.8152
14    4     7.496   7.8152  13.592  7.8152  13.592  10.2536 7.496   10.2536
15    4     7.496   10.2536 13.592  10.2536 13.592  12.692  7.496   12.692
16    4     7.496   12.692  13.592  12.692  13.592  15.1304 7.496   15.1304

17    4     14.242  0.5     20.338  0.5     20.338  2.9384  14.242  2.9384
18    4     14.242  2.9384  20.338  2.9384  20.338  5.3768  14.242  5.3768
19    4     14.242  5.3768  20.338  5.3768  20.338  7.8152  14.242  7.8152
20    4     14.242  7.8152  20.338  7.8152  20.338  10.2536 14.242  10.2536
21    4     14.242  10.2536 20.338  10.2536 20.338  12.692  14.242  12.692
22    4     14.242  12.692  20.338  12.692  20.338  15.1304 14.242  15.1304

targets_(ID,type,x,y,radius,speed)
1     0     10.5    7.5     0.25    0.0
```

robots_(ID,type,x,y,orientation,speed,angularvelocity)

1	9	0.35	0.5	90	0.6	0
2	9	0.7	0.35	0	0.6	0
3	9	0.35	1.25	90	0.6	0
4	9	1.45	0.35	0	0.6	0
5	9	0.35	2.0	90	0.6	0
6	9	2.2	0.35	0	0.6	0
7	9	0.35	2.75	90	0.6	0
8	9	2.95	0.35	0	0.6	0
9	9	0.35	3.5	90	0.6	0
10	9	3.7	0.35	0	0.6	0
11	9	0.35	4.25	90	0.6	0
12	9	4.45	0.35	0	0.6	0
13	9	0.35	5.00	90	0.6	0
14	9	5.20	0.35	0	0.6	0
15	9	0.35	5.75	90	0.6	

APP.B2 **SIMULATION RUN OF 1 TARGET SOURCE WITH 5 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	0	0	1732	0.866	17435	8.7175	0	0	0
2	1	0	0	417	0.2085	10934	5.467	0	0	0
3	1	1	0	764	0.382	16329	8.1645	0	0	0
4	1	1	0	603	0.3015	10830	5.415	0	0	0
5	1	0	0	6287	3.1435	14287	7.1435	0	0	0
6	1	0	0	308	0.154	11180	5.59	0	0	0
7	1	0	0	1451	0.7255	10102	5.051	0	0	0
8	1	0	0	1940	0.97	9940	4.97	0	0	0
9	1	0	0	236	0.118	11129	5.5645	0	0	0
10	1	1	1	883	0.4415	18923	9.4615	10923	5.4615	1
11	1	1	1	1582	0.791	16555	8.2775	8555	4.2775	1
12	1	0	0	308	0.154	8308	4.154	0	0	0
13	1	1	1	906	0.453	12788	6.394	11000	5.5	1
14	1	1	0	602	0.301	19103	9.5515	0	0	0
15	1	0	0	1112	0.556	10055	5.0275	0	0	0
16	1	1	0	1596	0.798	11562	5.781	0	0	0
17	1	1	1	428	0.214	17503	8.7515	9503	4.7515	1
18	1	0	0	56	0.028	9060	4.53	0	0	0
19	1	0	1	1439	0.7195	22991	11.4955	14991	7.4955	0
20	1	1	0	1	0.0005	8004	4.002	0	0	0
21	1	1	1	697	0.3485	10492	5.246	5786	2.893	1
22	1	1	0	1	0.0005	8004	4.002	0	0	0
23	1	0	0	1988	0.994	9988	4.994	0	0	0
24	1	0	0	6460	3.23	14460	7.23	0	0	0
25	1	0	1	202	0.101	23725	11.8625	15725	7.8625	0
26	1	1	1	966	0.483	18816	9.408	10816	5.408	1
27	1	0	0	1608	0.804	9793	4.8965	0	0	0
28	1	0	1	6401	3.2005	20868	10.434	12868	6.434	0
29	1	1	1	1782	0.891	13881	6.9405	5881	2.9405	1
30	1	1	0	1163	0.5815	15476	7.738	0	0	0
Percentage (%)	**100** (%)	**46.7** (%)	**33.3** (%)	Mean:	**0.73**	Mean:	**7.08**	Mean:	**5.30**	**23.3** (%)
				Variance:	**0.79**	Variance:	**3.87**	Variance:	**2.83**	
				Std Dev:	**0.89**	Std Dev:	**1.97**	Std Dev:	**1.68**	

APP.B3 **SIMULATION RUN OF 1 TARGET SOURCE WITH 6 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	0	0	1693	0.8465	12434	6.217	0	0	0
2	1	1	1	5138	2.569	14964	7.482	6964	3.482	1
3	1	1	0	1576	0.788	9588	4.794	0	0	0
4	1	1	1	1439	0.7195	9677	4.8385	4706	2.353	1
5	1	1	1	1427	0.7135	9808	4.904	2270	1.135	1
6	1	1	1	604	0.302	12265	6.1325	4265	2.1325	1
7	1	0	0	9	0.0045	8048	4.024	0	0	0
8	1	1	1	199	0.0995	18829	9.4145	10829	5.4145	1
9	1	1	0	1	0.0005	8004	4.002	0	0	0
10	1	1	1	4962	2.481	15205	7.6025	7205	3.6025	1
11	1	1	1	500	0.25	16473	8.2365	8473	4.2365	1
12	1	1	0	627	0.3135	10490	5.245	0	0	0
13	1	1	1	1553	0.7765	12403	6.2015	6794	3.397	1
14	1	1	1	156	0.078	13235	6.6175	5235	2.6175	1
15	1	1	0	333	0.1665	16326	8.163	0	0	0
16	1	1	1	4	0.002	11335	5.6675	5253	2.6265	1
17	1	1	0	1238	0.619	9876	4.938	0	0	0
18	1	1	0	370	0.185	11370	5.685	0	0	0
19	1	0	0	83	0.0415	9029	4.5145	0	0	0
20	1	1	1	808	0.404	10315	5.1575	3790	1.895	1
21	1	1	0	1505	0.7525	9861	4.9305	0	0	0
22	1	1	0	1374	0.687	10086	5.043	0	0	0
23	1	1	0	1586	0.793	14335	7.1675	0	0	0
24	1	1	0	1682	0.841	12289	6.1445	0	0	0
25	1	0	0	1118	0.559	9118	4.559	0	0	0
26	1	1	0	1104	0.552	11984	5.992	0	0	0
27	1	1	1	5158	2.579	14962	7.481	6962	3.481	1
28	1	1	1	494	0.247	11715	5.8575	3900	1.95	1
29	1	1	0	1545	0.7725	9622	4.811	0	0	0
30	1	1	1	1502	0.751	9711	4.8555	2414	1.207	1
Percentage (%)	**100** (%)	**86.7** (%)	**46.7** (%)	Mean: Variance: Std Dev:	**0.66** **0.49** **0.70**	Mean: Variance: Std Dev:	**6.05** **1.82** **1.35**	Mean: Variance: Std Dev:	**2.82** **1.41** **1.19**	**46.7** (%)

APP.B4 **SIMULATION RUN OF 1 TARGET SOURCE WITH 7 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	1	0	1523	0.7615	10694	5.347	0	0	0
2	1	1	1	218	0.109	11073	5.5365	6989	3.4945	1
3	1	1	0	1	0.0005	8005	4.0025	0	0	0
4	1	1	0	1	0.0005	8005	4.0025	0	0	0
5	1	1	1	1677	0.8385	10540	5.27	2562	1.281	1
6	1	1	1	1479	0.7395	9712	4.856	3376	1.688	1
7	1	1	0	1530	0.765	9594	4.797	0	0	0
8	1	1	1	589	0.2945	13362	6.681	5362	2.681	1
9	1	1	1	234	0.117	11021	5.5105	6912	3.456	1
10	1	1	1	1413	0.7065	11823	5.9115	3823	1.9115	1
11	1	0	0	1487	0.7435	9487	4.7435	0	0	0
12	1	0	0	967	0.4835	8967	4.4835	0	0	0
13	1	1	1	1527	0.7635	9629	4.8145	1629	0.8145	1
14	1	0	0	96	0.048	8096	4.048	0	0	0
15	1	1	1	1530	0.765	10706	5.353	2706	1.353	1
16	1	1	0	200	0.1	8477	4.2385	0	0	0
17	1	0	0	1322	0.661	9322	4.661	0	0	0
18	1	1	1	1457	0.7285	10760	5.38	2760	1.38	1
19	1	0	0	1028	0.514	9028	4.514	0	0	0
20	1	0	0	1600	0.8	9685	4.8425	0	0	0
21	1	1	1	719	0.3595	10412	5.206	2954	1.477	1
22	1	1	1	793	0.3965	12275	6.1375	4275	2.1375	1
23	1	1	0	447	0.2235	12380	6.19	0	0	0
24	1	1	1	1389	0.6945	10004	5.002	2071	1.0355	1
25	1	1	0	424	0.212	12477	6.2385	0	0	0
26	1	1	1	137	0.0685	9626	4.813	4286	2.143	1
27	1	1	1	1266	0.633	11941	5.9705	3941	1.9705	1
28	1	1	1	607	0.3035	10846	5.423	3941	1.9705	1
29	1	1	0	1458	0.729	9699	4.8495	0	0	0
30	1	0	0	1518	0.759	9518	4.759	0	0	0
Percentage (%)	**100** (%)	**76.7** (%)	**50.0** (%)	Mean:	**0.48**	Mean:	**5.28**	Mean:	**1.92**	**50.0** (%)
				Variance:	**0.09**	Variance:	**0.50**	Variance:	**0.63**	
				Std Dev:	**0.29**	Std Dev:	**0.71**	Std Dev:	**0.79**	

APP.B5 **SIMULATION RUN OF 1 TARGET SOURCE WITH 8 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	1	1	660	0.33	9651	4.8255	4258	2.129	1
2	1	1	1	742	0.371	12269	6.1345	4269	2.1345	1
3	1	1	0	311	0.1555	12461	6.2305	0	0	0
4	1	1	1	551	0.2755	10892	5.446	2898	1.449	1
5	1	0	0	415	0.2075	8415	4.2075	0	0	0
6	1	1	1	1000	0.5	10086	5.043	2056	1.028	1
7	1	1	1	146	0.073	16805	8.4025	8805	4.4025	1
8	1	1	1	569	0.2845	9680	4.84	4226	2.113	1
9	1	1	1	606	0.303	9410	4.705	2039	1.0195	1
10	1	1	0	1	0.0005	8005	4.0025	0	0	0
11	1	1	1	12	0.006	9658	4.829	4501	2.2505	1
12	1	1	1	1476	0.738	9792	4.896	1939	0.9695	1
13	1	1	1	592	0.296	9416	4.708	2039	1.0195	1
14	1	1	1	4	0.002	8005	4.0025	4129	2.0645	1
15	1	0	0	313	0.1565	8313	4.1565	0	0	0
16	1	1	1	1623	0.8115	9803	4.9015	1803	0.9015	1
17	1	1	1	1329	0.6645	9946	4.973	1803	0.9015	1
18	1	1	1	1176	0.588	11809	5.9045	3809	1.9045	1
19	1	1	1	875	0.4375	9300	4.65	3969	1.9845	1
20	1	1	1	1199	0.5995	11855	5.9275	3855	1.9275	1
21	1	1	1	1428	0.714	9685	4.8425	2034	1.017	1
22	1	1	1	1120	0.56	10176	5.088	2176	1.088	1
23	1	1	1	585	0.2925	10848	5.424	2848	1.424	1
24	1	1	1	1304	0.652	11705	5.8525	3705	1.8525	1
25	1	1	1	817	0.4085	12326	6.163	4326	2.163	1
26	1	1	1	1391	0.6955	9999	4.9995	1999	0.9995	1
27	1	1	1	648	0.324	10419	5.2095	2419	1.2095	1
28	1	1	1	249	0.1245	14492	7.246	6492	3.246	1
29	1	1	1	679	0.3395	12257	6.1285	4257	2.1285	1
30	1	1	1	1702	0.851	9777	4.8885	1822	0.911	1
Percentage (%)	**100** (%)	**93.3** (%)	**86.7** (%)	Mean: Variance: Std Dev:	**0.39** **0.06** **0.25**	Mean: Variance: Std Dev:	**5.37** **0.87** **0.93**	Mean: Variance: Std Dev:	**1.70** **0.67** **0.82**	**86.7** (%)

APP.B6 **SIMULATION RUN OF 1 TARGET SOURCE WITH 9 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	1	0	1	0.0005	8005	4.0025	0	0	0
2	1	1	1	660	0.33	9651	4.8255	4256	2.128	1
3	1	1	1	1098	0.549	10176	5.088	2176	1.088	1
4	1	1	1	570	0.285	10834	5.417	2834	1.417	1
5	1	1	1	1154	0.577	9154	4.577	2146	1.073	1
6	1	1	0	1510	0.755	9570	4.785	0	0	0
7	1	1	0	1505	0.7525	9536	4.768	0	0	0
8	1	1	1	1316	0.658	11672	5.836	3672	1.836	1
9	1	1	1	420	0.21	16307	8.1535	8307	4.1535	1
10	1	1	1	1774	0.887	11980	5.99	1774	0.887	1
11	1	1	1	606	0.303	10406	5.203	2831	1.4155	1
12	1	1	1	1456	0.728	10908	5.454	2908	1.454	1
13	1	1	1	1644	0.822	12086	6.043	4086	2.043	1
14	1	1	1	903	0.4515	12035	6.0175	4035	2.0175	1
15	1	1	1	1386	0.693	9925	4.9625	2040	1.02	1
16	1	1	1	4	0.002	9670	4.835	4233	2.1165	1
17	1	1	1	641	0.3205	9335	4.6675	2026	1.013	1
18	1	1	0	1	0.0005	8005	4.0025	0	0	0
19	1	1	1	228	0.114	9559	4.7795	3979	1.9895	1
20	1	1	1	797	0.3985	9118	4.559	4340	2.17	1
21	1	1	1	807	0.4035	12182	6.091	4182	2.091	1
22	1	1	1	661	0.3305	9363	4.6815	2012	1.006	1
23	1	1	1	4	0.002	8005	4.0025	4176	2.088	1
24	1	0	0	369	0.1845	8369	4.1845	0	0	0
25	1	1	1	604	0.302	9405	4.7025	2013	1.0065	1
26	1	1	1	168	0.084	11101	5.5505	10356	5.178	1
27	1	1	1	695	0.3475	12269	6.1345	4269	2.1345	1
28	1	1	1	387	0.1935	11187	5.5935	6913	3.4565	1
29	1	1	1	924	0.462	12051	6.0255	4051	2.0255	1
30	1	1	1	676	0.338	9322	4.661	2018	1.009	1
Percentage (%)	**100** (%)	**96.7** (%)	**83.3** (%)	Mean:	**0.38**	Mean:	**5.22**	Mean:	**1.91**	**83.3** (%)
				Variance:	**0.07**	Variance:	**0.75**	Variance:	**1.07**	
				Std Dev:	**0.26**	Std Dev:	**0.86**	Std Dev:	**1.03**	

APP.B7 **SIMULATION RUN OF 1 TARGET SOURCE WITH 10 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	1	1	620	0.31	9608	4.804	2630	1.315	1
2	1	1	1	1549	0.7745	10566	5.283	2566	1.283	1
3	1	1	1	1362	0.681	9922	4.961	1922	0.961	1
4	1	1	1	1497	0.7485	9791	4.8955	1791	0.8955	1
5	1	0	0	164	0.082	8164	4.082	0	0	0
6	1	1	1	507	0.2535	9443	4.7215	2020	1.01	1
7	1	1	1	295	0.1475	12783	6.3915	4783	2.3915	1
8	1	1	1	670	0.335	9302	4.651	2034	1.017	1
9	1	0	0	1093	0.5465	9880	4.94	0	0	0
10	1	1	1	573	0.2865	9351	4.6755	1998	0.999	1
11	1	1	0	112	0.056	11063	5.5315	0	0	0
12	1	1	1	777	0.3885	12565	6.2825	4565	2.2825	1
13	1	1	0	1350	0.675	10028	5.014	0	0	0
14	1	1	1	327	0.1635	9561	4.7805	2010	1.005	1
15	1	1	1	860	0.43	12401	6.2005	4401	2.2005	1
16	1	1	1	557	0.2785	9605	4.8025	2701	1.3505	1
17	1	1	1	689	0.3445	12566	6.283	4566	2.283	1
18	1	1	0	1	0.0005	8005	4.0025	0	0	0
19	1	1	1	1128	0.564	18161	9.0805	10161	5.0805	1
20	1	1	1	462	0.231	16034	8.017	8034	4.017	1
21	1	1	1	562	0.281	13968	6.984	5968	2.984	1
22	1	1	1	1293	0.6465	9911	4.9555	2008	1.004	1
23	1	0	0	1	0.0005	8001	4.0005	0	0	0
24	1	1	0	1	0.0005	8004	4.002	0	0	0
25	1	1	0	140	0.07	17200	8.6	0	0	0
26	1	1	1	1168	0.584	10085	5.0425	2800	1.4	1
27	1	0	0	344	0.172	10952	5.476	0	0	0
28	1	0	0	437	0.2185	10781	5.3905	0	0	0
29	1	1	1	1252	0.626	10156	5.078	3230	1.615	1
30	1	1	1	1084	0.542	10156	5.078	2156	1.078	1
Percentage (%)	**100** (%)	**83.3** (%)	**66.7** (%)	Mean:	**0.35**	Mean:	**5.60**	Mean:	**1.81**	**66.7** (%)
				Variance:	**0.06**	Variance:	**1.79**	Variance:	**1.27**	
				Std Dev:	**0.24**	Std Dev:	**1.34**	Std Dev:	**1.13**	

APP.B8 **SIMULATION RUN OF 1 TARGET SOURCE WITH 11 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	1	1	74	0.037	11038	5.519	12100	6.05	1
2	1	1	1	620	0.31	9703	4.8515	4243	2.1215	1
3	1	1	1	544	0.272	9728	4.864	4315	2.1575	1
4	1	1	1	59	0.0295	11124	5.562	3797	1.8985	1
5	1	1	1	1444	0.722	9886	4.943	1788	0.894	1
6	1	1	1	1296	0.648	9953	4.9765	1953	0.9765	1
7	1	0	0	4	0.002	8005	4.0025	0	0	0
8	1	1	1	705	0.3525	12532	6.266	4532	2.266	1
9	1	0	0	591	0.2955	8591	4.2955	0	0	0
10	1	0	0	569	0.2845	8569	4.2845	0	0	0
11	1	1	0	1	0.0005	8005	4.0025	0	0	0
12	1	1	1	836	0.418	11842	5.921	3842	1.921	1
13	1	0	0	47	0.0235	8782	4.391	0	0	0
14	1	1	0	291	0.1455	12617	6.3085	0	0	0
15	1	1	0	1	0.0005	8005	4.0025	0	0	0
16	1	1	1	215	0.1075	14147	7.0735	6147	3.0735	1
17	1	1	0	1337	0.6685	9951	4.9755	0	0	0
18	1	0	0	1517	0.7585	9517	4.7585	0	0	0
19	1	0	0	1	0.0005	8079	4.0395	0	0	0
20	1	0	0	643	0.3215	8643	4.3215	0	0	0
21	1	1	0	1336	0.668	9985	4.9925	0	0	0
22	1	1	1	472	0.236	9699	4.8495	1983	0.9915	1
23	1	1	0	380	0.19	12634	6.317	0	0	0
24	1	1	1	412	0.206	9744	4.872	1980	0.99	1
25	1	0	0	758	0.379	8816	4.408	0	0	0
26	1	1	1	1282	0.641	9900	4.95	1974	0.987	1
27	1	1	1	1119	0.5595	10043	5.0215	2239	1.1195	1
28	1	1	1	851	0.4255	12391	6.1955	4391	2.1955	1
29	1	0	0	1297	0.6485	9511	4.7555	0	0	0
30	1	1	0	928	0.464	9878	4.939	0	0	0
Percentage (%)	**100**	**70.0**	**46.7**	Mean:	**0.33**	Mean:	**5.30**	Mean:	**1.97**	**46.7**
	(%)	(%)	(%)	Variance:	**0.06**	Variance:	**0.62**	Variance:	**1.83**	(%)
				Std Dev:	**0.25**	Std Dev:	**0.79**	Std Dev:	**1.35**	

APP.B9 **SIMULATION RUN OF 1 TARGET SOURCE WITH 12 ROBOTS**

No. of Runs	Detected	Scanned	Combed	Time Step Detect	Time (min)	Time Step Scanned	Time (min)	Time Step Combed	Time (min)	Success
1	1	1	1	578	0.289	12309	6.1545	5245	2.6225	1
2	1	1	0	1	0.0005	8005	4.0025	0	0	0
3	1	1	1	642	0.321	12490	6.245	5745	2.8725	1
4	1	1	1	1679	0.8395	11374	5.687	1688	0.844	1
5	1	1	1	1121	0.5605	10030	5.015	2030	1.015	1
6	1	0	0	242	0.121	8735	4.3675	0	0	0
7	1	1	0	1430	0.715	9521	4.7605	0	0	0
8	1	1	1	675	0.3375	10211	5.1055	3502	1.751	1
9	1	1	1	806	0.403	12722	6.361	4722	2.361	1
10	1	1	1	828	0.414	11990	5.995	3991	1.9955	1
11	1	0	0	1	0.0005	8210	4.105	0	0	0
12	1	1	0	237	0.1185	11248	5.624	0	0	0
13	1	0	0	210	0.105	9000	4.5	0	0	0
14	1	1	0	1	0.0005	8005	4.0025	0	0	0
15	1	1	0	1	0.0005	8005	4.0025	0	0	0
16	1	1	1	373	0.1865	12048	6.024	4205	2.1025	1
17	1	1	0	501	0.2505	11056	5.528	0	0	0
18	1	1	1	1479	0.7395	11671	5.8355	3671	1.8355	1
19	1	1	1	1626	0.813	11524	5.762	3524	1.762	1
20	1	1	0	1352	0.676	9891	4.9455	0	0	0
21	1	1	1	688	0.344	8806	4.403	4148	2.074	1
22	1	1	1	605	0.3025	13098	6.549	5098	2.549	1
23	1	1	1	4	0.002	11262	5.631	4067	2.0335	1
24	1	1	1	1049	0.5245	11798	5.899	3798	1.899	1
25	1	1	1	1200	0.6	9979	4.9895	2029	1.0145	1
26	1	1	1	170	0.085	10142	5.071	2156	1.078	1
27	1	1	0	1394	0.697	9565	4.7825	0	0	0
28	1	1	1	656	0.328	12166	6.083	4166	2.083	1
29	1	0	0	194	0.097	8194	4.097	0	0	0
30	1	0	1	11	0.0055	21801	10.9005	13801	6.9005	0
Percentage (%)	**100** (%)	**83.3** (%)	**60.0** (%)	Mean:	**0.33**	Mean:	**5.38**	Mean:	**2.16**	**56.7** (%)
				Variance:	**0.07**	Variance:	**0.58**	Variance:	**1.73**	
				Std Dev:	**0.27**	Std Dev:	**0.76**	Std Dev:	**1.32**	

APPENDIX O: TDSI INFORMATION ASSURANCE REPORT

Appendix A

IA MECHANISMS

The following are fundamental mechanisms that can be applied to secure the networked MDP systems.

Application Hardening

Hardening application is a security feature designed to prevent exploitation of various types of vulnerabilities in software applications. Vulnerabilities are mostly introduced by programmers that fail to check properly the input data entering into the application. If an application contains vulnerability, it can be exploited by an attacker to take over the control of the computer on which the vulnerable application is running. Application hardening feature offers defense mechanism to recognize and stop these action.

Application hardening is done with application-specific procedures and together with host hardening.

Biometrics

Biometrics is technology that uses the human unique physiological or behavioral features to establish authentication and identity of the person. Some of more established biometric techniques are

- **Fingerprinting** is where fingerprint information is taken from the digital scan
- **Facial recognition** analyzes the characteristics of a person's face where the overall facial structure, including distances between eyes, nose, mouth, and jaw edges are measured.
- **Iris Scanning** analyzes the features that exist in the colored tissue surrounding the pupil of an eye – the iris.
- **Retinal Scanning** analyzes the layer of blood vessels at the back of the eye. This is one of the most accurate physical biometric available today since there is no known way to replicate a retina. Similar to iris scanning,
- **Speaker Recognition** where the tone, pitch and speed of speech and voice are used as a means of authentication. Users have to repeat certain access phases in order to be recognized.
- **Signature Recognition** measures an individual's signature

Biometric techniques offers higher security authentication and they are typically used as part of a 2-token authentication where the physical existence of the person is needed to gain access or identification. Some of the common usage includes access control to premises, secure transactions, zone control and operation of appliances.

Content Checking

Many forms of digital information can contain malicious software such as virus, Trojan horse and worms. These programs can be transmitted across network in various ways in email attachment and FTP downloads. Content checking, such as Norton, McAfee virus detection tools, is an excellent mechanism to protect network by proactively keeping viruses, spam, erroneous web surfing, and inappropriate file attachments to a minimum. This can be done as part of firewall and end-user workstation.

Data Backups

Regular backup is a vital defense in securing important information against unplanned disruption like natural disaster, virus or hacking. Data backup is achieved by maintaining a redundant secondary system that can be activated without loss of data or disruption to the operation. Backup should be stored in a secure environment or secure remote location to avoid unnecessary theft or sabotage. Critical software such as operating system and application software are required to be backed up. In the remote backup site, it should have the following security features:

- Redundant power supply with backup generators.
- Redundant Bandwidth with multiple service providers.
- Guards, Locks or Biometrics mechanism in place to control personnel access.
- Firewall security.
- Data storage mechanism/servers.
- 24x7 emergence response team

De-Militarized Zone (DMZ)

A DMZ is a network segment that sits between an organization's internal network and an external network. It allows contained hosts to provide services to the external network while protecting the internal network from possible intrusions into the internal host. Typically DMZ is created just outside the organization's firewall and it protected by another set of routers and firewalls. The servers placed in the DMZ will be fortified with harden operating system and tight down services. The services offered in DMZ are accessed by the external network and have limited, controlled access back to the organization's systems in the internal network.

Encryption

Encryption is a process where mathematical algorithms are used to transform data such that only the intended parties are able to decipher the message. The purpose of encryption is to protect the confidentiality of the data. Currently there are 3 classes of encryption

- Symmetric encryption where the same key is used to encrypt and decrypt the data, like Data Encryption Standard (DES)
- Asymmetric encryption where different keys are used to encrypt and decrypt data, e.g. Public Key Infrastructure.
- Hash or message digest is specific signature message created using encryption algorithms to provide identification of the message to ensure integrity. An example is the Secure Hash Algorithm 1 (SHA-1)

Proper use of encryption technology can provide cryptographic separation of information at different levels of classification, permitting such information to be communicated via a common infrastructure, and even tunneled across a non-secure public internet.

Through various permutation of usage of encryption, encryption techniques provide not only information confidentiality but also integrity and mutual authentication of the communicating parties (e.g. in VPN tunneling). Encryption techniques are commonly used in secure communications, data storage protection, digital signatures and protection of access tokens, etc.

Firewalls

A firewall is a mechanism (hardware or software) for controlling the flow of data traffic into a network. It is policy driven and has a set of rules specifying the types of traffic that can be allowed across or be blocked. Such rules can be set based on the Internet Protocol address, designated network ports and services requested by the requesting systems.

Firewall control the network traffic using a variety of techniques:

Packet filtering firewall examines the source or destination addresses of the incoming packet to either blocks or allows the packet to pass.

Stateful Inspection firewalls not only examine the contents of each packet but also remind the communication session so as to derive pattern of usage and intelligently filter or block malevolent network traffic.

Proxy firewalls are more advanced stateful firewalls which block any non-established, non-permitted connections. It examines the entire packet to ensure compliance with the protocol that is indicated by the destination port number.

Application Layer Filtering applies the rules of traffic inspection to the application-level data where the data stream for specific application is analyzed before they are passed to the application. Application Layer Firewall analysis are application-aware and it inspects, screens or blocks

incoming traffic, and redirect or modifying this data based on application specific characteristic as it passes through the firewall.

Due to the more advanced features and filtering capabilities of the firewalls, firewalls are placed behind the router to block all undesired traffic into the internal network. This is an effective means ensure network availability and guarding against denial of service attacks.

Host Hardening

Host hardening is the process of tightening the configuration of the system's operating system and applications with the purpose of securing any unnecessary openings on the system. This typically involves applying relevant software patches, fixes, setting file system permissions, disabling unnecessary services, and enforcing password restrictions. Host hardening is a critical part of host defense and it provides the last layer of protection for any individual system.

Internet Protocol Security (IPsec)

IPsec is a set of protocols developed to support secure exchange of messages at the Internet Protocol layer. It has been deployed widely to implement Virtual Private Network (VPN). IPsec support two modes of encryption:

- Transport: encrypts only the data portion (payload) of each packet, but leaves the header untouched.
- Tunnel: encrypts both the header and payload.

In the way the protocol is implemented, IPsec authenticates both terminals and creates a secure virtual extension of the private network between the both terminals. This prevents unauthorized users from penetrating the virtual private network and prevents eavesdroppers from tapping on the on the external network to read private messages.

IPsec and VPNs are encryption tools used for secure end-to-end communications and they are often deployed for remote access to the internal networks.

Intrusion Detection Systems (IDS)

IDS are used to detect and raise alerts in the event of any malicious attacks. It monitors the network traffic for predefined signature for signs of malicious anomaly such as network attacks and misuses. Should such events occurs, IDS captures the states of these anomaly and raises alerts to the system administrators. The information captured in the IDS can be analyzed and used for tuning the network defenses against future attacks.

IDS are monitoring mechanism that can be used to protect against repeated attacks. They are placed at junctions of incoming traffic to monitor the network activities at these junctions. IDS are also installed in network suspected of suspicious activities.

Intrusion Prevention Systems (IPS)

A more proactive IDS is the IPS. IPS automatically detects and thwarts computer attacks against protected resources. It has a database containing the signature or behavior of known attacks and through referencing this database; IPS can identify a potential attack and effectively block such malicious traffic before any harm is done to the system.

Similar to IDS, IPS is placed behind the router interface to block off malevolent network traffic.

Network Address Translation:

An evolution of the firewall is the network address translation which hides the private network addresses and as a result protects the internal network from the external connections. Such translators contain the internal network traffic within the enclave and provide segregated interface to the external networks. Without details of the internal network, external hosts can only corresponds with this Network Address Translator and this provides additional protection layer of protection to the protected systems.

Network address translations are applied at the interface of the internal networks which they are protecting. They are normally integrated with the firewalls to provide both translation and filtering capabilities.

Open Secure Shell (OpenSSH)

OpenSSH is an open standard version of SSH (Secure Shell) that allows users to remote login to the servers. It provides strong authentication and secure communication over insecure channels. Thus OpenSSH is a means for averting hijacking, eavesdropping and other possible network attacks.

OpenSSH protocols can be used for remote secure logins. Besides OpenSSH, Transport Layer Security (TLS) also provide encryption to enforce privacy in communication between clients and servers systems.

Remote Alternate Site

It is possible that natural or man-made disasters might wipes out operation center, therefore an alternate site is essential to ensure continual operations of services which are critical to mission completion. The setting up of an alternate site will have to be done as part of the contingency plan. Critical systems,

information and equipment will have to be provided in this alternate site. Means to transfer control and information to this alternate site will have to be established. A set group of operators may have to be arranged to operate the alternate during the transition period.

Routers

Routers are network traffic-managing devices that sit in between sub-networks and determine the next network point an information packet should be sent. They are the first layer of out-facing devices which all incoming network will encounter. Routers play their roles in defense in depth by filtering traffic before it enters or exits the network. Routers are usually placed at the enclave boundary to regulate traffic into and out of the enclave and at network intersections to inter-connect different networks.

Virtual Private Network (VPN) Devices

VPN uses encryption to create a virtual tunnel between two terminal so as to form a protect network session over unprotected networks to create a private communication channel. In doing so, VPN offers data confidentiality and integrity and with built in two-way authentication, non-repudiation of data exchange.

VPNs are communication used to extend network across distributed sites and to provide secure remote login into protected network. Normally VPN devices are placed behind the firewall into the private network. However software VPNS can be extended into the server system to provide end-to-end encryption.

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