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Revisiting Measures of Effectiveness in Support of Low-Frequency, Multistatic Sonar Search in the Littoral Battlespaces

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14. ABSTRACT

In Support of the Multistatic ASW Capability Enhancement (MACE) Program, a new operations research tool has been developed that takes into account the complex, range-dependent, littoral battlespace and the need for new measures of performance (MOPs) to reflect current and evolving war-fighting concepts. This paper argues that (1) the prevalent legacy ASW MOP is often inappropriate to use, (2) the prevalent legacy MOP is often improperly calculated, and (3) there is a better operations research framework for considering range-dependent multistatic systems.

15. SUBJECT TERMS

Multistatic ASW Capability Enhancement; MACE; littoral battlespace; measures of performance; MOPS; Multistatic Interaction Calculator; MUSICAL

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Outline

I. Introduction

Since the end of the Cold War, the Anti-Submarine Warfare (ASW) threat of interest has continued to evolve. One current threat of interest is the modern diesel submarine. With advanced propulsion and energy storage technologies, the projected threat will be able to remain quiet for tactically long periods of time. Additionally, the challenge of detecting and classifying diesel submarines in future conflicts will likely be made more difficult by the requirement to operate in acoustically complex and often harsh littoral battlespaces. The combination of quieter, longer-endurance threats and complex/harsh acoustic environments has given rise to projected passive sonar performance shortfalls and has motivated the Navy to explore new sensing (searching) technologies. One of the new sensing technologies being explored is low-frequency, active multistatics. The Office of Naval Research, through the Multistatic ASW Capability Enhancement (MACE) Program, is developing a low-frequency, long-endurance, off-board source to support multistatic signal processing capability.[1] The MACE system provides the technology framework in which the below-described operations research analysis is cast.

Because modern diesel submarines can be so difficult to detect, legacy war-fighting concepts based on the rapid detection, localization, and eradication of the submarine threat are often no longer feasible. New concepts of localized battlespace dominance are evolving. These new operational concepts require new measures of performance (MOPs). Even when legacy MOPs continue to be applicable, the complex environment of the littoral battlespace and different threat operating habits will often require new calculation techniques.

In support of the MACE Program, a new operations research tool has been developed that takes into account the complex, range-dependent, littoral battle-space and the need for new MOPs to reflect current and evolving war-fighting concepts. This paper argues that (1) the prevalent legacy ASW MOP is often inappropriate to use, (2) the prevalent legacy MOP is often improperly calculated, and (3) there is a better operations research framework for considering range-dependent multistatic systems.

II. Nature of Littoral, Low-Frequency, Multistatic ASW

Prior to selecting MOPs and methods for calculating them, it is important to understand the nature of the operations research problem and the data to be considered. Five characteristics of low-frequency, multistatic ASW within littoral battlespaces have been selected for this discussion. These five characteristics are at odds with assumptions made by legacy ASW MOPs and/or the methods for calculating them. Other characteristics could have been added to the discussion, but are not deemed necessary to make the arguments of this paper.

1. **Azimuthally Signatured Sensor Performance.** Low-frequency, multi-static performance in the littoral battlespace can be highly variable in range and azimuth. Figure 1 is a plot of signal excess for a single MACE source and a towed array receiver. Performance is highly broken in range and azimuth. This brokeness is caused by range-dependent acoustic phenomena, as well as inherent multistatic phenomena. While these two separate effects can be isolated, it is not necessary to do so here.

2. **Sensor Performance Varies Within the Battlespace.** Even when the azimuthal variability of sensor performance is modeled (or measured) for particular source and receiver locations, it is not a predictor of performance when the source or receiver are moved within the battlespace. Figure 2 shows how total and directional system performance varies as a function of location within the battlespace. The area coverage is for a co-located source and receiver at the center of each box (i.e., monostatic systems). Depending on where within the area the monostatic system is placed, expected area coverage of positive signal excess varies from greater than 2,500 square kiloyards to less 500 square kiloyards.

3. **Threat Detectability is Aspect Dependent.** When solving the active sonar equation, equation (1), the reflectivity of the threat hull (called target strength) is an extremely important parameter. As can be seen from figure 3, the values of target strength can vary by more than 20 dB, depending on values of the bistatic angle and bistatic aspect angle (see figure 4).

$$SE=SL - TL_{s\text{-}t}-TL_{t\text{-}r} + TS - RL - DT_{R}, \qquad (1)$$

where SE = signal excess (dB),
SL = signal level of the source (dB),
$TL_{s\text{-}t}$ = transmission loss (source to target) (dB),
$TL_{t\text{-}r}$ = transmission loss (target to receiver (dB),
TS = target strength (dB),
RL = reverberation level (dB),
DT_R = detection threshold (reverberation-limited) (dB).

4. **Threat Behavior is Intentional (Not Random).** Threat diesel submarines of Third World nations will tend to operate in shallow national waters. Unless motivated by a specific mission to go farther from their national coastline, threat submarines will often favor operating within a particular shallow bathymetry contour line. Likely threat motion cannot be assumed to be random within a large operating area.

5. **Friendly ASW Assets Operate With Intentionality.** The employment of ASW assets may be undertaken with ASW being the most important military function or as a collateral function along with some higher priority military mission (e.g., anti-air warfare). Whether ASW is conducted as a top priority mission or as an ancillary support mission, it will not be random and it will seldom yield the same results as if it had been random.

III. Legacy Measure of Performance (MOP) Assumptions and Limitations

Traditional search equations (for example, the random area search equation) tend to be designed for conditions encountered in open-ocean scenarios. Their extension to the littoral battlespaces cannot be taken for granted. As discussed in section II, low-frequency, multistatic search system performance will have many characteristics that are at odds with the assumptions behind these closed-form expressions. Additionally, traditional search equations express themselves in terms of cumulative probability of detection (CPD). When the operational ASW objective was to attrit the threat submarine, CPD proved to be a relevant and robust MOP. However, the evolution of the threat and the tactics to deal with it have created a need to add a new MOP. In many operational settings, attriting the threat is no longer a feasible objective. The operational response has often been to redefine the ASW mission as a support role where the objective is to keep the high-value unit safe from attack by the threat submarine, rather than to aggressively search out and attrit the threat. In other words, if the threat submarine chooses to remain distant and hidden, ASW can be said to be successful. The CPD metric can be inadequate for this scenario even though its continued application to the problem has largely gone unquestioned. In fact, when deploying ASW resources, maximizing CPD can actually increase the risk exposure of the high-value unit, because CPD is maximized when searchers minimize redundant efforts, spreading out the formation. But when the desire is to achieve and maintain a high level of confidence that a threat is not within a particular region of the battlespace, redundant efforts are often necessary. In these circumstances, another MOP is necessary.

IV. An Alternative Approach for Assessing Littoral, Multistatic ASW Performance

Multistatic Interaction Calculator (MUSICAL). To address the issues identified above, a new operations research tool was developed, the Multistatic Interaction Calculator (MUSICAL). Inputs to MUSICAL include range-dependent and area-varying sensor performance predictions. An aspect-dependent, multistatic, target strength model is included. Kinematic models account for threat and Blue Force motion. Outputs from MUSICAL include the familiar cumulative probability of detection MOP, but also include threat density probability maps, based on so-called *negative search* information. Figure 5 is a simplified block diagram of MUSICAL.

MUSICAL Inputs. In addition to the inputs identified above, MUSICAL allows the operations research analyst a high fidelity of control over critical modeling parameters. One critical parameter is sensor performance variability. Currently, tactical decision aids tend to use a single value for *sigma* in converting signal excess to a probability of detection. This one value is used whether the active sonar system is low or high frequency, narrowband or broadband, coherent or incoherent, or used in deep or shallow water. These parameters can have an enormous impact on sonar performance variability. In the reverberation-limited condition (often encountered in the littoral battlespace), analysis of *in-situ* reverberation may be used to derive a more accurate value for *sigma*. Figure 6 indicates the motivation for using an *in-situ*-measured sigma to convert an *in-situ* signal excess assessment into an *in-situ* probability of detection assessment. Both 6 dB and 12 dB can be reasonable values for sigma, yet there are enormous differences in the area over which a detection of a target might be anticipated. Another critical operations research parameter is the correlation/dependence between "look events." MUSICAL allows the analyst to set this parameter. Thirdly, MUSICAL allows the analyst to set the *M* of *N* logic (e.g., *three* threshold crossings are required out of *five* pings for a detection to be modeled). This allows some signal processing system logic to be incorporated in the performance calculation.

MUSICAL MOPs. MUSICAL supports the calculation of multiple MOPs. For the evolving ASW mission, MUSICAL introduces the metric of area clearance. Area clearance is an old operational concept, but it has languished as a concept only. The tools for quantifying, visualizing, and exploiting the effects of area clearance have not been available to operational decision-makers. Within MUSICAL, area clearance is portrayed two ways. One portrayal is in the form of threat density probability maps. This shows how an *a priori* threat distribution is perturbed by the ASW search history (see figure 7). The threat tracks near the center of the operating area have been re-weighted/ re-colored based on the negative search history. A second way that MUSICAL portrays area clearance is by quantifying the probability that the threat could have remained undetected within an analyst-selected box given the search history (see figure 8). The red box is a 50 x 50 nautical mile (nm) box centered on the middle of the searcher formation. The computer identified the most cleared 50 x 50 nm box as the blue box. That the best cleared box is not centered on the formation is not surprising in a range-dependent environment. As figure 9 indicates, the traditional CPD metric is unaffected by selection of the high-value unit operating box location (blue or red found in figure 8). CPD is thus not well suited to supporting this type of operational decision. MUSICAL does calculate the traditional CPD, because CPD continues to be a valuable metric for selected scenarios (e.g., barrier search operations), where gaining contact on the threat is essential to the military objective.

In addition to the above mentioned MOPs (CPD and area clearance), MUSICAL predicts multiple encounter parameters of military interest. All the modeled detection data are stored and available for analysis. This quantifies the relative contribution of each source-receiver combination against each postulated threat behavior. Thus, MUSICAL can be used to identify the risk of the threat submarine getting close to the high-value unit or any other combatant. Additionally, the value of Doppler-sensitive sonar waveforms could be assessed. It is essential to model all these parameters if MUSICAL (or any other operations research framework) is to support the evaluation of new system design and employment concepts.

Bayesian Integration Methods. Central to MUSICAL is the selection of Bayes Theorem as the basis for data fusion. A common formulation of Bayes Theorem is given in Equation (2):[2]

$$P[A_k \mid B] = \frac{P[B \mid A_k] * P[A_k]}{\sum_{x=1}^{n} P[B \mid A_x] * P[A_x]}, \tag{2}$$

where $P[A_k|B]$ = the probability that the target is in A_k given search event B failed to detect it;

$P[B|A_k]$ = the probability of the target remaining undetected in area A_k given search event B (i.e., the probability of surviving a search event undetected);

$P[A_k]$ = the probability that the target is in area A_k prior to search event B.

Note: The denominator provides for normalization of the search results.

The use of Bayes Theorem provides for an analytical framework that is distinct from most ASW simulation engines. Traditional ASW simulation systems are designed to model search, detection, classification, and engagement from the perspective of an attrition scenario. Thus, they have implemented what can be called a "track kill" integration method, so that whenever a threshold crossing is modeled to have occurred, the threat Monte Carlo track is said to be "detected" and this often "kills" the simulated track. Conversely, if no threshold crossing occurs, the simulation continues. "Track kill" systems are not designed to accrete *knowledge* in the non-contact scenario. This is exactly the strength of the Bayesian framework; it allows knowledge to be gained from *negative search* information. It is an ideal framework for analyzing the degree to which an area is effectively cleared (some would say *sanitized*). Because Bayesian methods do not "kill" tracks but simply re-weight them based on search history, when there is a positive contact report, it too can be integrated within a Bayesian framework. The positive contact report will often have the form of a bivariate normal distribution. Within a Bayesian framework, this can be crossed with the target distribution that existed just prior to the detection report. The fused data will often be non-Gaussian. In a "track kill" framework, there may not be enough Monte Carlo tracks remaining in the region of the contact report to construct a reliable fusion between the prior distribution and the contact report.

MUSICAL Example. The below example has been worked out to demonstrate how MUSICAL and its MOPs might support ASW decision-making. The scenario is set in a littoral battlespace of operational interest. The considered threat is a modern diesel submarine. A battlegroup with an aircraft carrier will take station somewhere near the center of a 100 x 100 nm box. The ASW Commander requires a 50 x 50 nm box for carrier operations. Four surface combatants with towed array sensors are available to the battlegroup. The use of five off-board sources is considered. The ASW mission is to keep the aircraft carrier safe from diesel submarine intrusion and attack.

Plots of performance variation across the operational area can be used by analysts to develop candidate strategies for system employment. To this end, plots such as that in figure 2 have been very useful. Candidate employment strategies can then be evaluated by MUSICAL, generating values for the CPD and area clearance metrics. The question of which MOP to use must be guided by the military objective (e.g., CPD works well for barrier searches while area clearance works well for keeping the high-value unit safe).

In addition to the area clearance scenario discussed earlier in this paper, MUSICAL allows consideration of alternative threat motion objectives (see figure 8). For example, with its Monte Carlo engine, MUSICAL can support modeling the probability of a threat penetrating the formation and making an attack on the high-value unit prior to being detected. Figure 10 shows the scenario of a would-be penetrator starting from the northwest. For this scenario, the CPD metric was deemed appropriate. MUSICAL provides a framework for considering both of these scenarios (area clearance and defense against a penetrator) and devising a strategy for keeping the high-value unit safe in both of them.

V. Summary

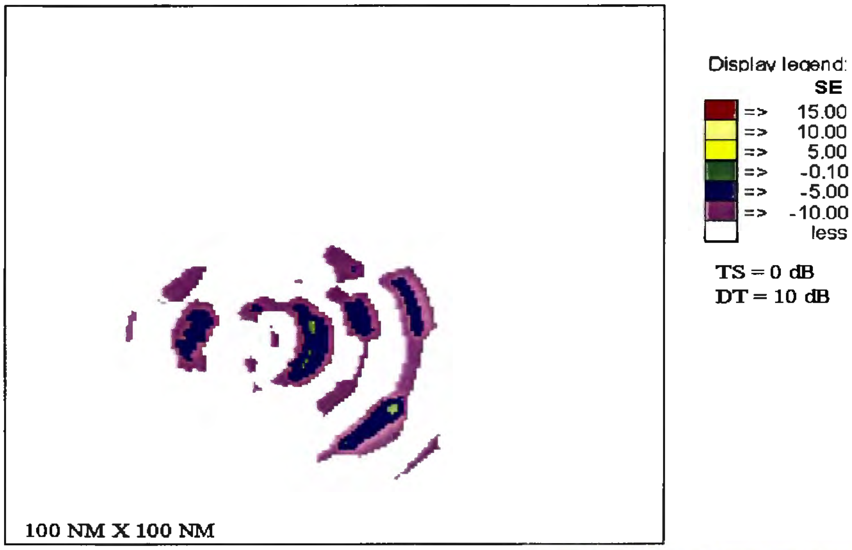
The modern diesel submarine operating in acoustically complex littoral battlespaces has necessitated a shift from traditional attrition-based ASW. The emerging tactical response to the modern diesel submarine has been one of battlespace dominance. The objective of battlespace dominance is to protect the high-value unit by securing a certain portion of the battlespace against successful threat penetration. While the cumulative probability of detection (CPD) is a suitable measure of performance (MOP) when attrition is the objective, battlespace dominance requires a new MOP—area clearance. MUSICAL provides a means of calculating area clearance and quantifying the residual risk to the high-value unit. It also presents this information in an intuitive format.

Whether the proper MOP is area clearance (e.g., for battlespace dominance) or CPD (e.g., for barrier searches), the manner in which these MOPs are calculated is very important. The acoustic and operational conditions encountered in the littoral battlespaces, especially for low-frequency multistatic systems, will often violate the assumptions going into traditional closed-form expressions of these MOPs. To address this shortfall, MUSICAL uses (1) range-dependent, multistatic performance predictions; (2) aspect-dependent, multistatic target strength modeling; and (3) Monte Carlo simulation of threat motion.

End Notes

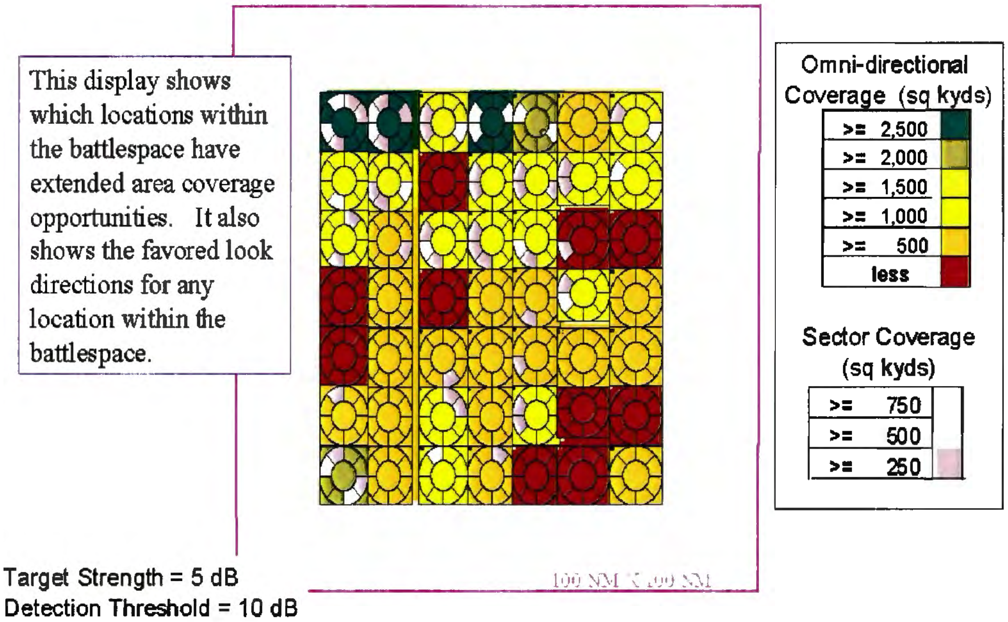
[1] The Multistatic ASW Capability Enhancement (MACE) Program is managed by Tommy Goldsberry, Office of Naval Research, Code 32M.

[2] *Naval Operations Analysis*, 2nd ed., Naval Institute Press, Annapolis, MD, 1977, p. 134.



Modeled data of non-operational system

Figure 1. Representative Plot of Modeled Signal Excess for a Single Source-Receiver Geometry



This display shows which locations within the battlespace have extended area coverage opportunities. It also shows the favored look directions for any location within the battlespace.

Target Strength = 5 dB
Detection Threshold = 10 dB

Modeled data of non-operational system

Figure 2. Variability of Sonar Performance Within the Littoral Battlespace

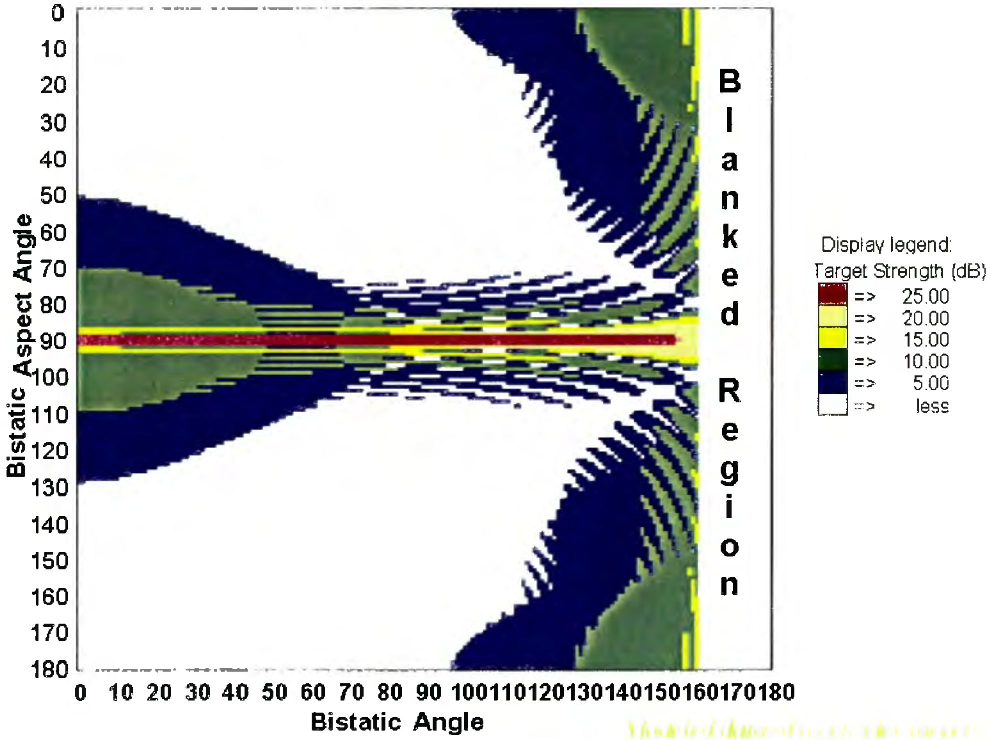


Figure 3 Multistatic Target Strength Dependence on Geometry

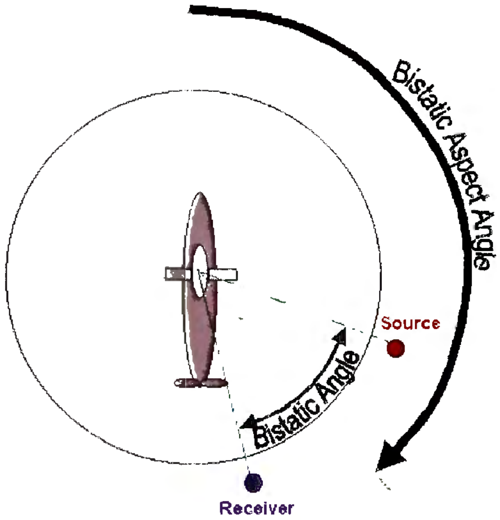


Figure 4. Plot of Angles Relating to Multistatic Target Strength.

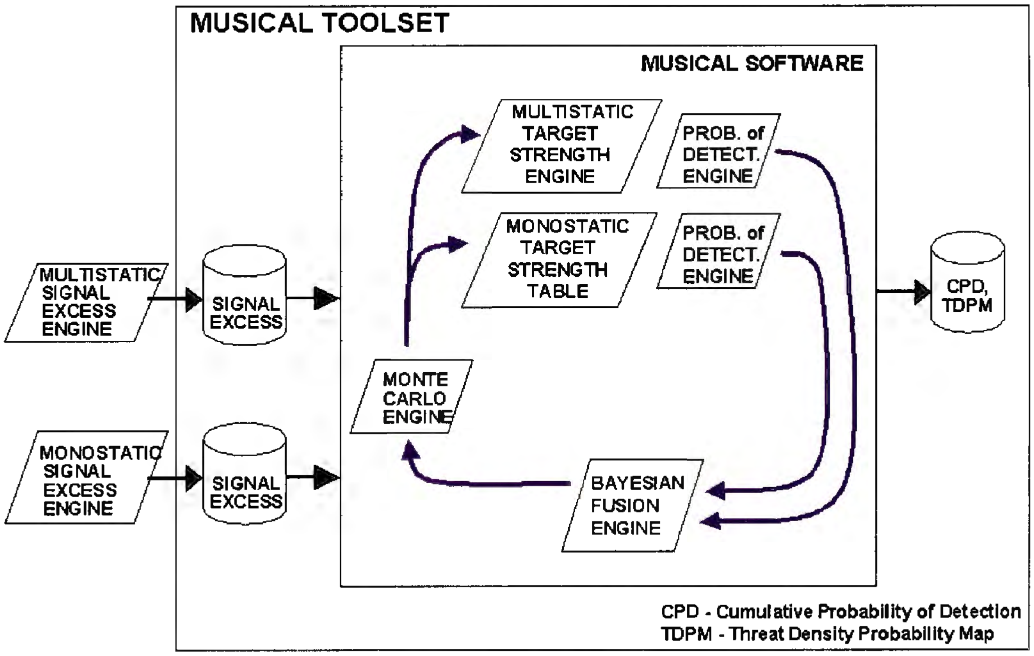
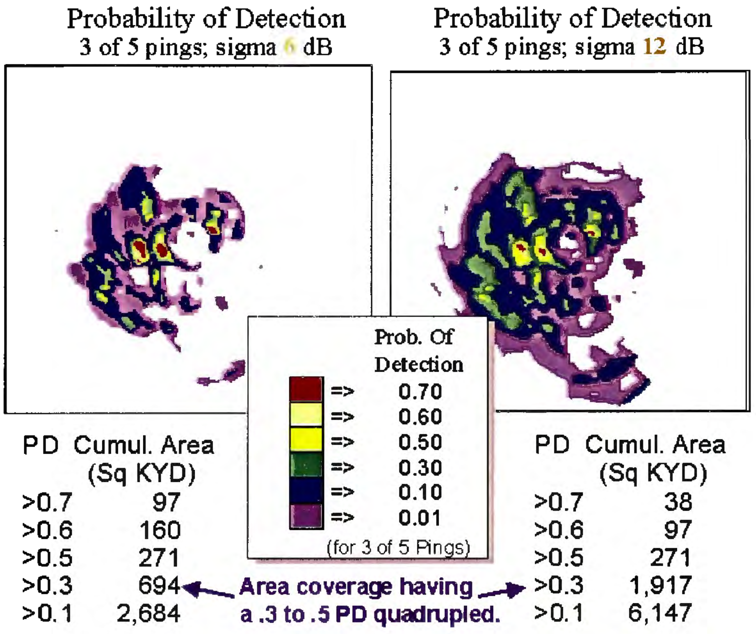


Figure 5. Simplified Block Diagram of MUSICAL

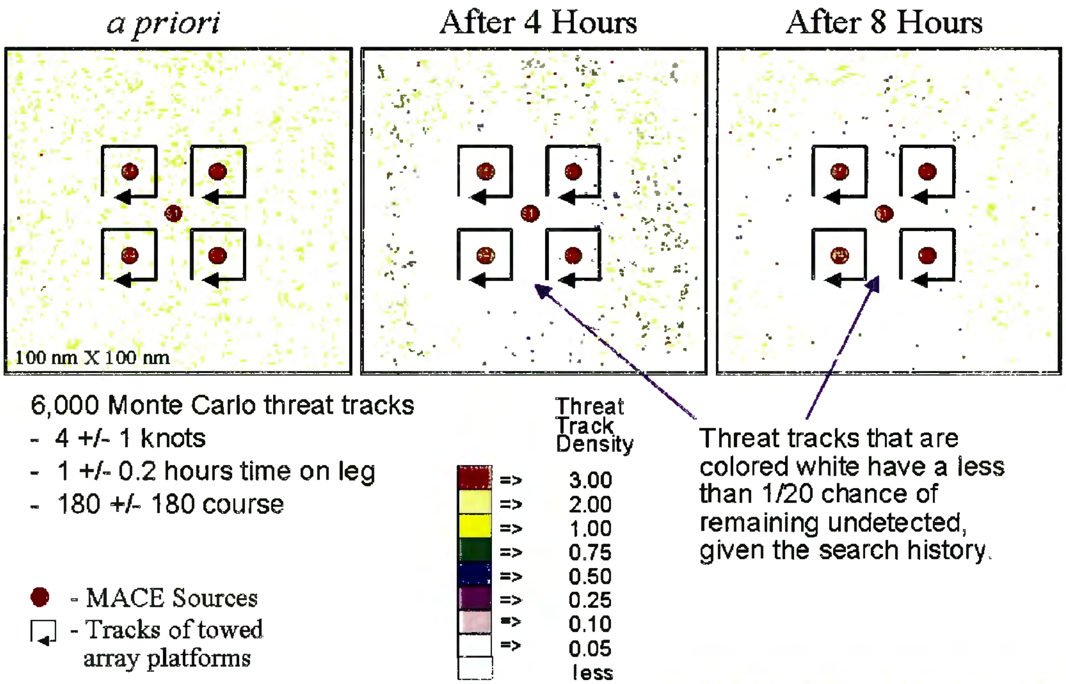


PD	Cumul. Area (Sq KYD)
>0.7	97
>0.6	160
>0.5	271
>0.3	694
>0.1	2,684

PD	Cumul. Area (Sq KYD)
>0.7	38
>0.6	97
>0.5	271
>0.3	1,917
>0.1	6,147

Modeled data of non-operational system

Figure 6. Significance of *Sigma* in Converting Signal Excess to a Probability of Detection



6,000 Monte Carlo threat tracks
- 4 +/- 1 knots
- 1 +/- 0.2 hours time on leg
- 180 +/- 180 course

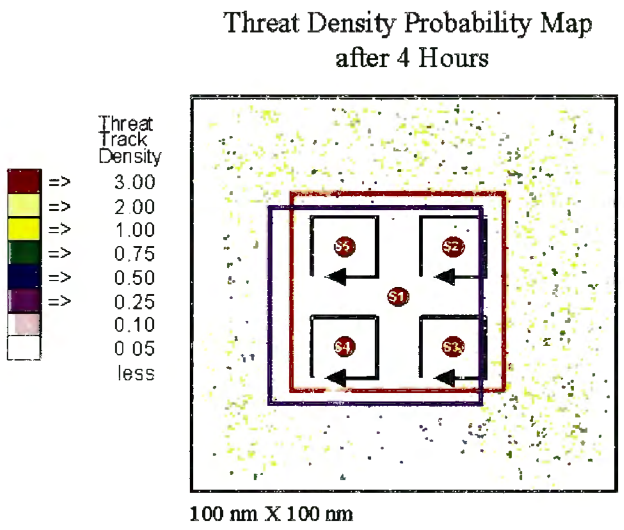
● - MACE Sources

- Tracks of towed array platforms

Threat tracks that are colored white have a less than 1/20 chance of remaining undetected, given the search history.

Performance of non-operational system

Figure 7 *A Priori* Threat Distribution Perturbed by Threat Motion and Search History

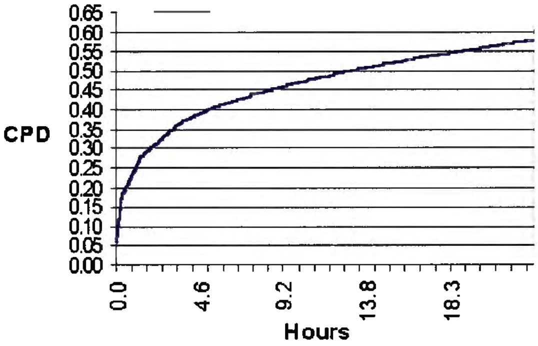


🟥 - Centrally located box - 7% probability threat remains in box in undetected (50nm X 50nm).

🟪 - Computer selected box - 2% probability threat remains in box in undetected (50nm X 50nm).

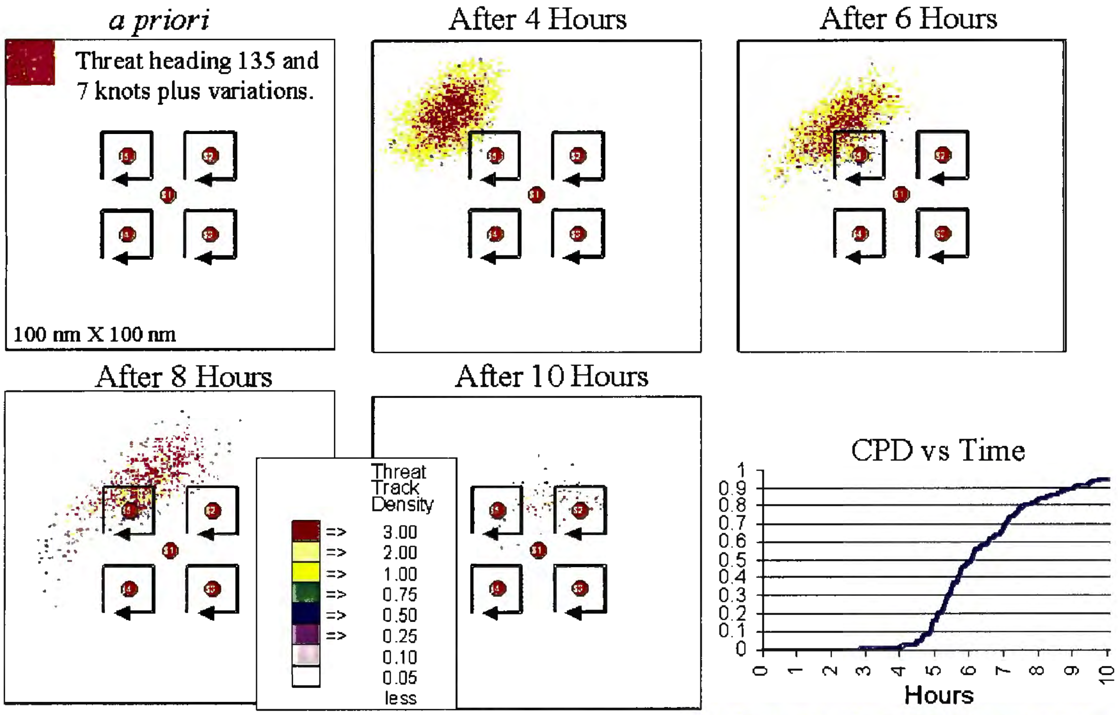
Performance of non-operational system

Figure 8 *A Priori* Threat Distribution Perturbed by Threat Motion and Search History



Performance of non-operational system

Figure 9. CPD Accretion History For Area Search Scenario



Performance of non-operational system

Figure 10. Sequence of Threat Density Probability Maps for the Penetrator Scenario

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