1986-12

A partial evaluation of the Integrated Tactical Decision Aid (ITDA) system

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NPS55-86-026

NAVAL POSTGRADUATE SCHOOL

Monterey, California

TECHNICAL

A PARTIAL EVALUATION OF THE INTEGRATED TACTICAL DECISION AID (ITDA) SYSTEM

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DECEMBER 1986

Prepared for:
Naval Air Development Center
Warminster, PA 18974-5000

NAVAL POSTGRADUATE SCHOOL
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The work reported herein was supported in part by the Naval Air Development Center.

This report was prepared by:

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b DECLASSIFICATION / DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) NPS55-86-026	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School 6b OFFICE SYMBOL (If applicable) Code 55	7a NAME OF MONITORING ORGANIZATION Naval Air Development Center
6c. ADDRESS (City, State, and ZIP Code) Monterey, CA 93943-5000	7b ADDRESS (City, State, and ZIP Code) Warminster, PA 18974-5000
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO · PROJECT NO · TASK NO · WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)

A PARTIAL EVALUATION OF THE INTEGRATED TACTICAL DECISION AID (ITDA) SYSTEM

12. PERSONAL AUTHOR(S)

Eagle, James N.

13a. TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Technical	FROM ______ TO ______	December 1986	20

16. SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	ASW, model, ITDA, search

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The mathematical accuracy and modelling reasonableness of the barrier and area search modules in the Integrated Tactical Decision Aid (ITDA) system were examined. Several problems were identified and solutions suggested. The use of ITDA was monitored during a 16-day sea period on the USS Carl Vinson (CVN70).

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL James N. Eagle	22b TELEPHONE (Include Area Code) (408)646-2654 · 22c OFFICE SYMBOL Code 55Er

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

☆ U.S. Government Printing Office: 1986—606 243

A Partial Evaluation of the Integrated Tactical Decision Aid (ITDA) System

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Introduction

The purpose of this technical report is twofold:

1. to critically examine the ITDA ASW barrier and area search models for mathematical accuracy and modelling reasonableness, and

2. to report on the use of ITDA programs on USS CARL VINSON (CVN 70) during a 16 day period of high intensity, exercise operations (RIMPAC 86).

Available for examination were ITDA Ver. 1 (including the BASIC language source code), the more recent ITDA Ver. 2 (without source code), and the JOTS II Technical Reference Manual (Ref. 1). Reference is made in this report to Version 1 source code to explain the functioning of the Version 2 program. This was required because the Version 2 source code was unavailable. Fortunately, the barrier and area search modules appear functionally very similar, if not identical, in both ITDA versions. So the lack of Version 2 source code is not judged to be especially critical to this examination.

ASW Barrier Search Model

Brief Description of Model. The ITDA ASW barrier search model is accurately described in Ref. 1. Its description here is primarily to establish notation.

The barrier search model estimates the probability of detection of a target submarine penetrating a back-and-forth ASW barrier (Figure 1.). The barrier penetration is considered in "target-stationary relative space". That is, the target is assumed to be stationary, and all relative speed for the encounter is provided by the searcher. The searcher's relative speed component across the barrier front is

$$V_S \cos(\alpha),$$

where V_S is searcher speed, and α is the barrier advancing angle (when $\alpha>0$) or retiring angle (when $\alpha<0$). The component of relative speed perpendicular to the barrier is

$$V_T + V_S \sin(\alpha),$$

where V_T is target speed.

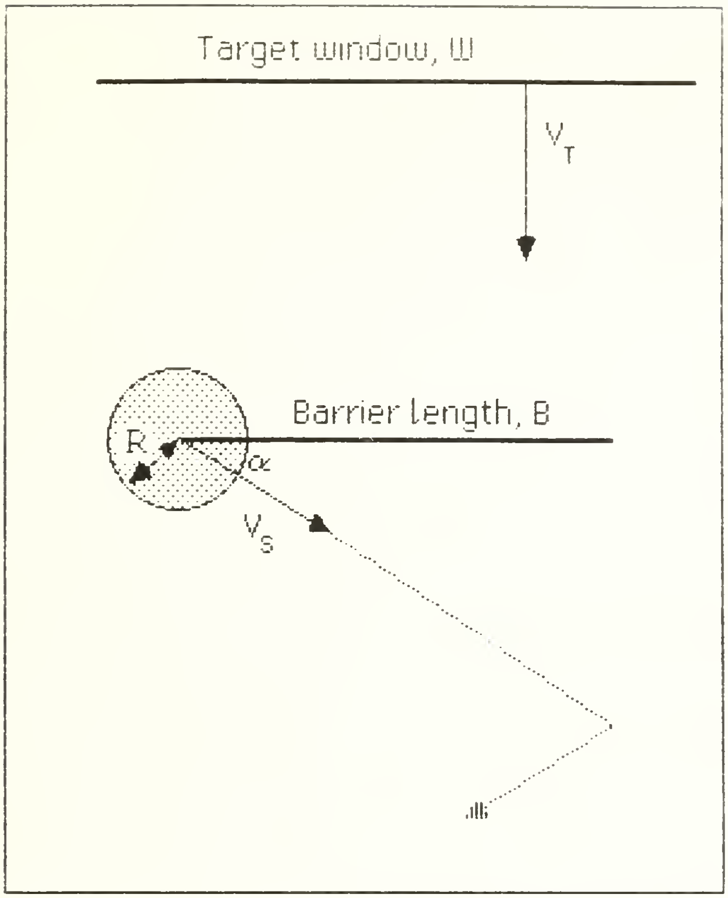

Figure 1. Barrier Geometry

For barrier penetration points uniformly distributed across a target window (W), the probability of the target coming within range R of the searcher (P_0) is the ratio of the area "covered" by the searcher in relative space to the total area that could be occupied by the target. In Figure 2. the covered area is shaded. In the ITDA barrier search model, this area is obtained by numerical integration. Allowance is made for sensors which sweep less than 360° by reducing the detection range R.

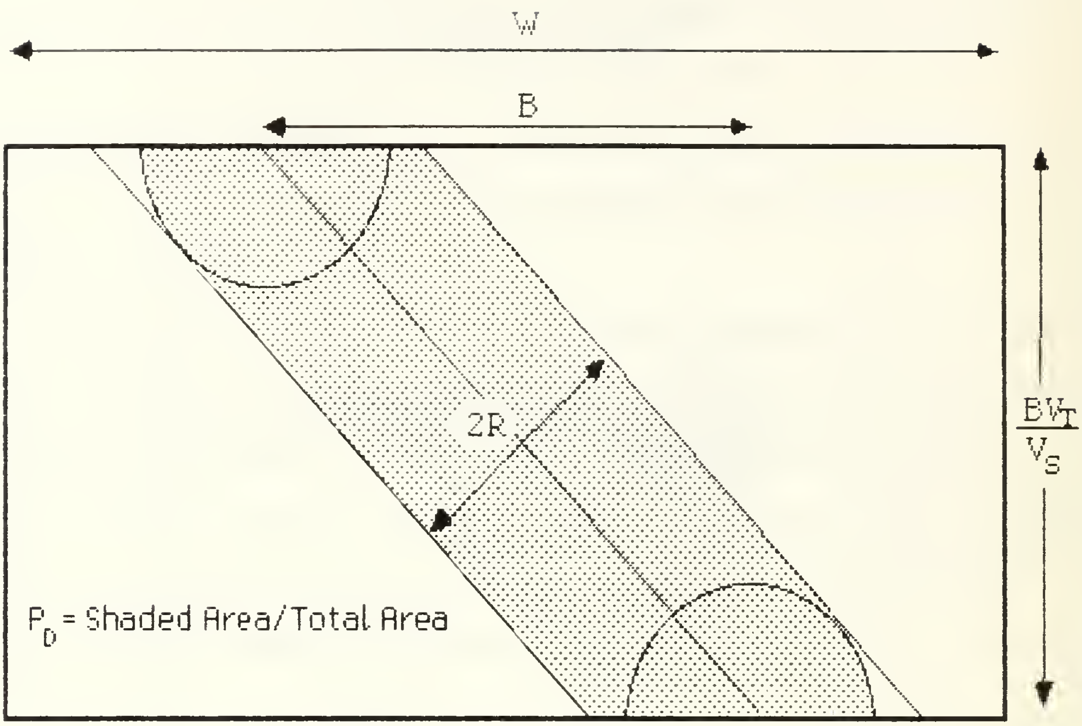

Figure 2. Calculation of P_D

Discussion. Although the modelling concepts used are good, there are some minor problems in the implementation.

1. The calculated P_D is too large for target window sizes (W) less than 2(B/2 - RK). This problem results because the limits of the numerical integration are, in some instances, improperly set. Specifically, in line 51070 of the ITDA Ver. 1 BASIC code, the upper limit of integration is B/2 - RK. It should be min (B/2 - RK, W/2). With the original limits, the integration can be performed outside the target window, W. This increases the calculated P_D above the proper value. To illustrate with an example, let

R = detection range = 10 nm

V_S = searcher speed = 10 knots

V_T = target speed = 10 knots

B = barrier width = 80 nm

W = target window = 10 nm

α = advancing/retiring angle = 0

K = kinematic enhancement factor = $(1 + (V_S/V_T)^2)^{1/2}$ = 1.414

The ITDA model gives a probability of detection of 1. However, for any $W \leq (B - 2RK)$, the correct answer is $2RK/B$ = .35.

2. P_D is improperly calculated when either $V_S \cos(\alpha)$ or $V_T - V_S \sin(\alpha)$ is negative. The cause of this problem is that the integrand in the numerical integration in line 51160 of the BASIC code is allowed to become negative whenever

$$Ksqr = V_S \cos(\alpha) / (V_T + V_S \sin(\alpha)) < 0.$$

Adding negative terms in the numerical integration results in the calculated P_D being too small. To illustrate, continue the previous example with W = 100 nm and α = -10°. Then P_D is correctly calculated as .31. Setting α = - 170° should give the same result, but yields .29.

The failure becomes particularly spectacular when the denominator of Ksqr is exactly 0. For example, setting

R = 10 nm

V_S = 20 knots

V_T = 10 knots

B = 80 nm

W = 100 nm

α = -30°

results in a P_D of 1.42×10^6.

A simple fix for this problem is only allow α such that

$$-90° < \alpha < 90° \text{ and } V_T + V_S \sin(\alpha) > 0.$$

The other cases are either redundant or result in the searcher moving "south" faster than the target.

3. Sweeping sensors are modelled in an unusual manner. The user is given the option of calculating P_D under the assumption that the detecting sensor sweeps $\pm\theta°$ either side of a center bearing. The effective detection range then becomes $R\sin(\min(\theta, 90°))$. The problem with this approach is that it assumes that the center bearing is along the relative track of the searcher. An more reasonable assumption is that the center bearing be along the searcher's absolute (i.e., geographic) track. See Figure 3.

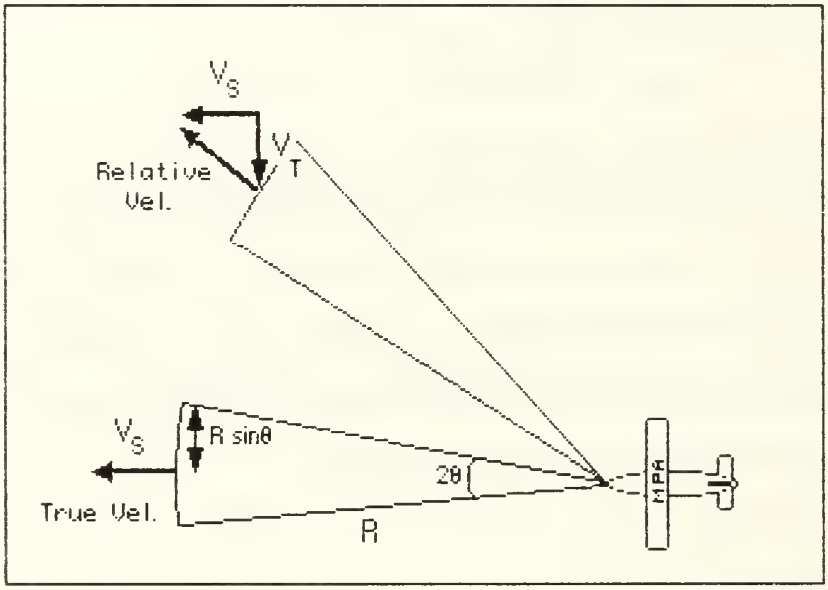

Figure 3. Orientation of Swept Area

These two assumptions lead to significantly different calculated probabilities of detection. For example, in the limit as θ and α decrease to 0, the ITDA model gives a probability of detection of 0. Whereas assuming that the sensor is looking directly ahead along a fixed line of bearing gives a probability of detection of min(1, R/W). Note that in this case, there is no increase in P_D as the searcher increases speed (i.e., no kinematic enhancement). The probability of detection is simply that fraction of the possible barrier penetration points that are covered by the finite detection "ray" of the sensor. For nonzero values of θ and α, similar closed form expressions can probably be derived, although the geometry becomes more complex and performing the numerical integration may be preferred.

4. This is a comment, not a problem. For α=0° and a 360° sensor, it is possible to approximate the ratio of the shaded area to the total area in Figure 2. without numerical integration. True, the HP9020 is not being computationally stressed by the integration, but there is something to be said for the simplicity of closed form solutions. Using the notation introduced, the probability of detection given a barrier penetration is approximately

$$P_D = \begin{cases} \min(2RK/B, 1) & \text{for } W \leq B - 2RK \\ 1 - (1/WB)(\max(.5(B+W) - RK, 0))^2 & \text{for } B-2RK \leq W \leq B+2R \\ ((B+2R)/W)\ (1 - (\max(B - R(K-1), 0))^2/(B^2+2RB)) & \text{for } W \geq B+2R \end{cases}$$

where $K = (1 + (V_S/V_T)^2)^{1/2}$ as before. To obtain this expression for P_D, the circular boundary of the shaded area in Figure 2. is replaced with a straight line. The resulting region has an area which is greater than or equal to the area of the original shaded region. So this calculation gives an upper bound for P_D. Figure 4. is a comparison plot of P_D calculated by the ITDA model and the approximation above. The ITDA model values greater than .35 are in error and result from improper limits of integration used when calculating P_D for small W.

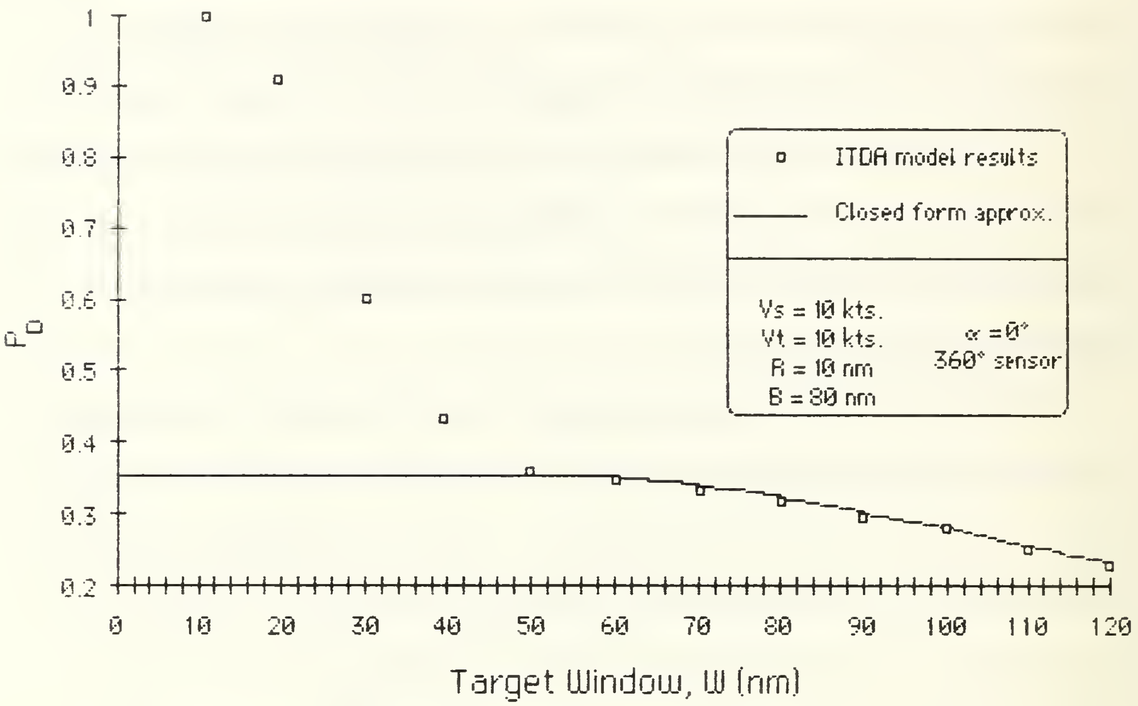

Figure 4. Comparison of ITDA Model Results and Approximation

5. This is a second comment. One advantage of using numerical integration for evaluating P_D is that it can accommodate a nonuniform distribution of target penetration points. This advantage is not exploited in the current barrier search program. For example, if the target knows that the barrier is in place, then an attempt might be made to penetrate near the one of the ends of the barrier to minimize P_D. If numerical integration is used to evaluate P_D, then it is a simple matter to weight the possible barrier penetration points according to any specified probability distribution. Specifically, if the barrier penetration point x has a probability density function g(x) and $P_D(x)$ is the probability of detection given a barrier penetration at x, then

$$P_D = \int_{\substack{\text{All } x \\ \text{s.t. } g(x)>0}} P_D(x)\, g(x)\, dx$$

6. A third comment. A possible problem with this advancing/retiring barrier methodology is that the detection probabilities are conditional on the target's penetration of the barrier. Changing the angle of searcher's advance or retreat will affect both the probability of detection given barrier penetration and the probability of barrier penetration. The second effect is not accounted for in this model. For example, a retreating barrier can dramatically increase the probability of detection given a barrier penetration, but it also reduces the probability of such a penetration during any specified time interval. In the limit as the searcher speed perpendicular to the barrier increases to the target speed, the predicted P_D increases to 1. However, the target can not now overtake the retreating barrier, so the probability of a barrier penetration occurring at all becomes zero. This line of argument suggests that the calculated probabilities of detection may be too large for retiring barriers and too small for advancing barriers.

ASW Area Search Model

Brief Description of Model. As described in Ref. 1, probability of detection for an area search is given by

$$P_D = 1 - \exp(-2R\,V_R\,t/A), \qquad (1)$$

where

R = detection range

A = search area size

t = time allowed for search

V_S = searcher speed

V_T = target speed, and

V_R = mean relative speed

$$= (1/2\pi)\int_0^{2\pi} (V_S^2 + V_T^2 + 2V_SV_T\cos\phi)^{1/2}\, d\phi \qquad (2)$$

Discussion

1. The mean relative speed calculation can be made more efficient. In the original BASIC code and in Ref. 1, the calculation of V_R is as shown in Equation (2). A preferred expression for numerical evaluation is

$$(1/\pi)\int_0^{\pi} (V_S^2 + V_T^2 - 2V_SV_T\cos\phi)^{1/2}\, d\phi\ . \qquad (3)$$

Equation (3) makes use of the symmetry of the cosine function to reduce the extent of the numerical integration, and has the correct sign for the $2V_SV_T\cos\phi$ term in the Law of Cosines. These problems are to some extent cosmetic, as cosine symmetry causes both (2) and (3) to give the same numerical results.

It is noted that V_R can be approximated with the following closed form expression:

$$V_R/V_S \approx .36\max(V_T/V_S\, ,\, 1) + .64\,(1+(V_T/V_S)^2)^{1/2} \qquad (4)$$

Figure 5 contains plots of the estimated V_R/V_S versus V_T/V_S and a multiplicative correction factor to convert the estimated values to true values. The estimate is always within 1.1% of the true value.

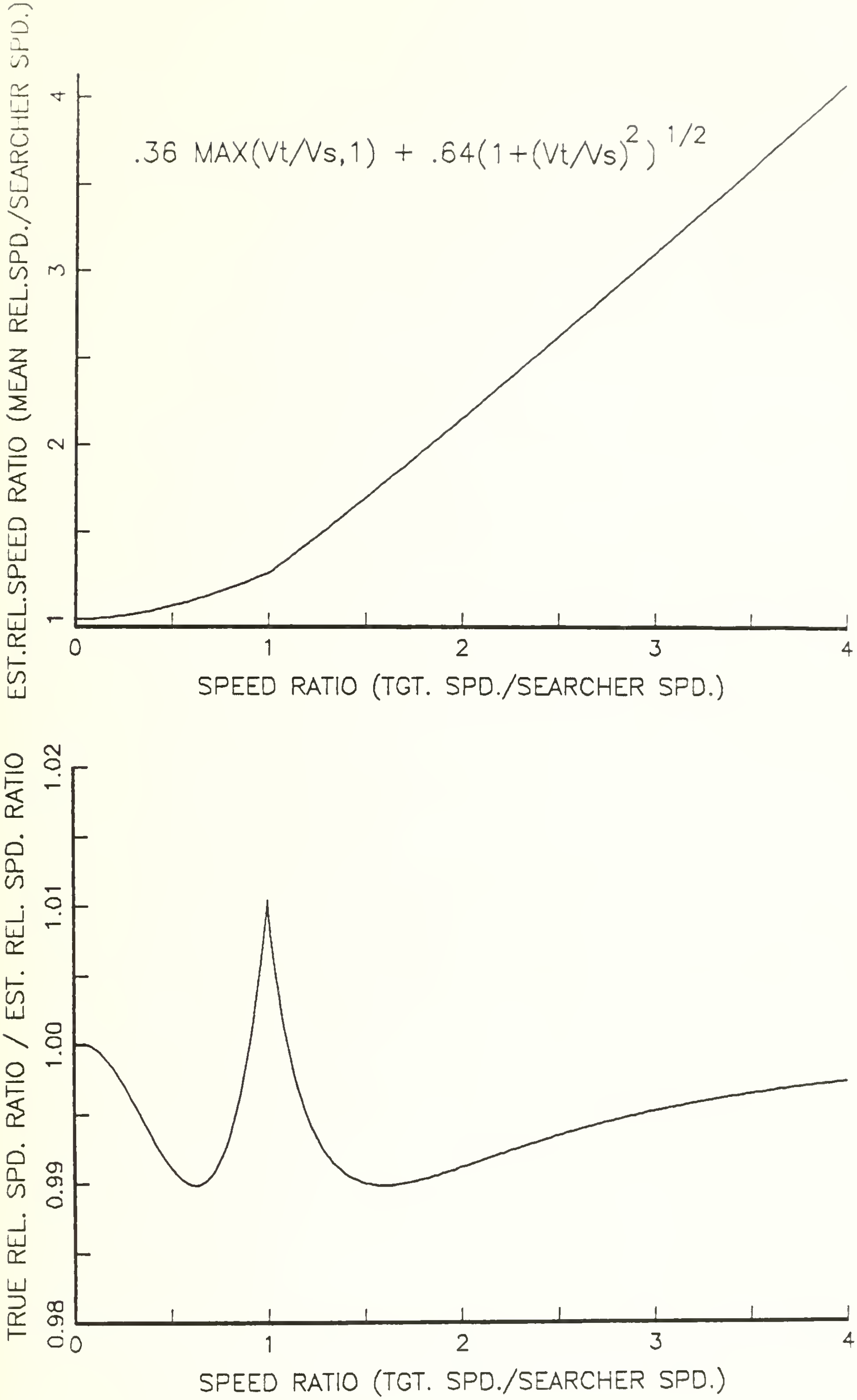

Figure 5. Estimated Relative Speed Ratio vs. Speed Ratio

2. A Monte Carlo area search simulation was conducted to test the accuracy of Equation (1). The search geometry is shown in Figure 6. The searcher starts in the lower left corner of a 100 nm x 100 nm search area and conducts a systematic search at speed V_S with a cookie-cutter sensor having a range of 10 nm. The target's starting position is uniformly distributed over the search area. The target conducts a random tour at speed V_T with a mean time between course changes of 1 hour. That is, the target track consists of connected line segments, each of which has a course selected from an independent, uniform distribution between 0° and 360°. And the time on each leg is selected from an independent, exponential distribution with mean 1 hour. When the target encounters a search area boundary a perfect reflection is performed.

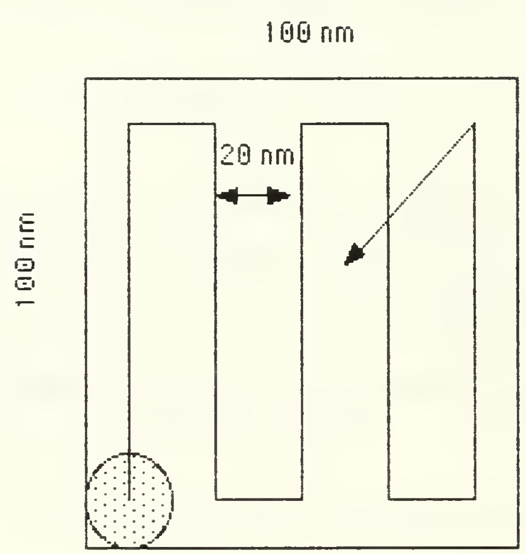

Figure 6. Simulation Geometry

Seven simulations were conducted, each with V_S and V_T selected so that the mean relative speed, as calcuated from Equation (3), was 15 knots. The results are plotted in Figure 7, together with P_D calculated from Equation (1). The fit between (1) and the simulation was reasonable when V_S and V_T were nearly equal. Otherwise the fit was not especially impressive.

The simulation results were sensitive to the mean time between target course changes and the searcher track used (neither of which are represented in Equation (1)). In particular, the simulation showed that a search track starting near the center of the search area gives better search performance, especially for small values of V_S.

3. The need for an area search simulation. For this area search example, Equation (1) does not model a systematic search for a randomly moving target very accurately. And unfortunately the search literature has little else to offer in the way of closed form expressions for P_D when the target track is random and the searcher conducts a systematic search (e.g., parallel sweeps, spiral in, or spiral out). This suggests that some sort of numerical solution, probably a Monte Carlo simulation, may be required to assess the effectiveness of such an area search. This simulation could be very general. It could allow, for example:

1. different areas for the target and searcher,
2. a customized target motion model (e.g., patrol or transit)
3. any desired search track,
4. multiple searchers and targets,
5. counterdetection by the target.

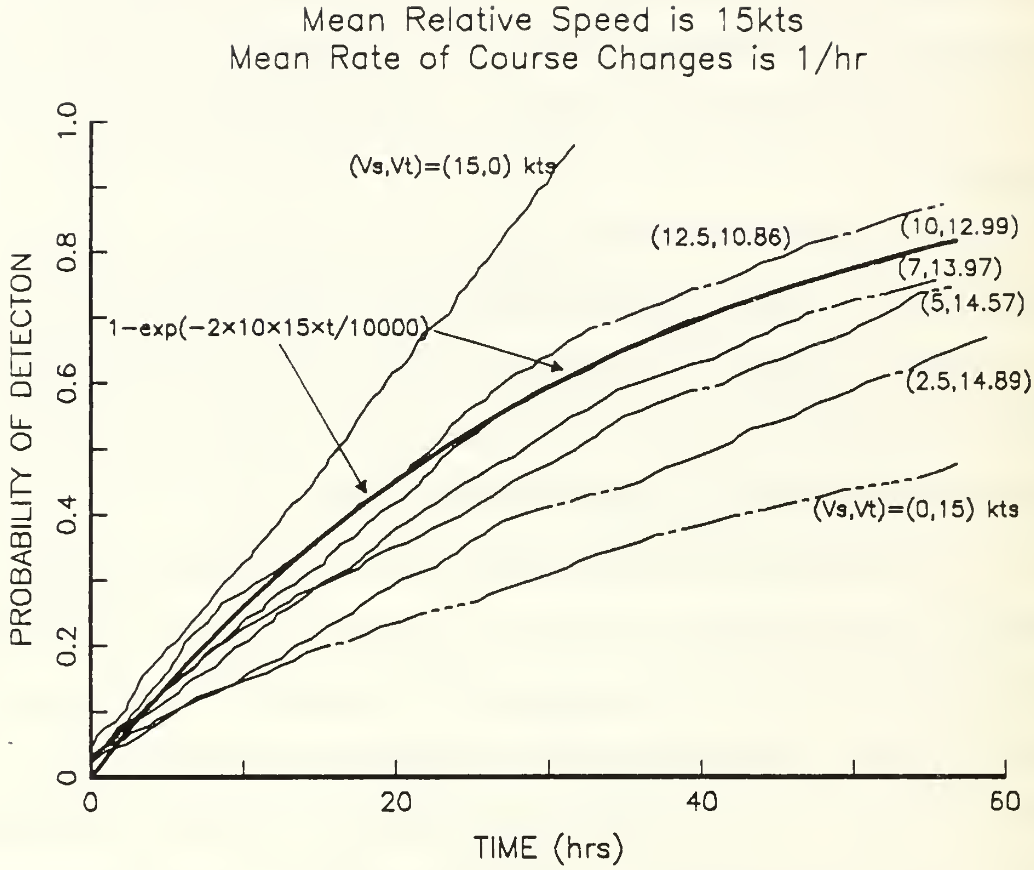

Figure 7. Probability of Detection by Simulation

Output could include the searcher track(s) and graph of probability of detection by time t. With a cursor or lightpen input of area boundaries and track points, problem setup time would be reduced. This simulation might be of particular use for battle group ASW planning, since frequently several ASW platforms search for the same target submarine.

At Sea Observations

Background. During the period 2-18 June 1986, the author, as a commander in the Naval Reserve, was attached to the staff of Commander Carrier Group Three. At that time, the staff was embarked on USS CARL VINSON (CVN 70) and operating in support of the exercise RIMPAC 86.

RIMPAC 86 was a two-carrier battle group, multinational exercise involving approximately 60 ships and 30,000 at-sea personnel. The purpose was to demonstrate the fleet's ability to operate effectively against a realistic air, surface, and subsurface threat. During this exercise, use of the ITDA system by the carrier group staff and CARL VINSON ship's company was observed.

Exercise Scenario. The general scenario was that a coup had toppled the pro-West government of White Country (represented for purposes of the exercise by the Hawaiian Islands). The US naval response was to send two carrier battle groups (Ranger and Carl Vinson) to White Country as a show of force. These battle groups were opposed by some 60 ships simulating Soviet platforms. As the exercise progressed, the battle groups approached White Country close enough to launch air strikes. Opposing surface action groups and submarines engaged as the battle groups came into range.

JOTS and DOTS. The ITDA system on CARL VINSON is called VINSON DOTS, which appears to be a one-of-a-kind installation, funded by DARPA, through NOSC, San Diego. There was no formal documentation for this system aboard CARL VINSON, but the overall program structure and functional modules seem very similar to the older JOTS. In fact, much of the BASIC code has been carried over directly from JOTS (as indicated by documentation comments in the BASIC code). The principle DOTS enhancements included the organization of the contact database and the implementation of automated input of LINK 11 data.

The controlling terminal for VINSON DOTS is an Hewlett-Packard 9020 located in the War Room of the Flag Spaces. Feeding this station is another HP 9020 in the Carrier Intelligence Center (CVIC). This unit processes and correlates intelligence information generated off the ship. The correlator-tracker used is POST (Prototype Ocean Surveillance Terminal). Also feeding into the Flag HP 9020 is real-time NTDS (Link 11) data. The Flag terminal displays and operates on available contact data and also sends this data to HP 9020 machines in the ASW Module (ASWMOD) and Combat Direction Center (CDC). Another HP 9020 is located in the Tactical Operations Plot (TOP) which runs JOTS III and is currently not in the VINSON DOTS network (and so does not have access to real-time NTDS information).

The VINSON DOTS network accepts data only from the Flag terminal and these data currently come from three sources: 1) manual input, 2) NTDS input, and 3) POST input.

The NTDS input is automated and requires no human filtering. Automated input is also available from POST, but due to the classification of some POST data, this feature is not presently implemented. To remove the more sensitive data, POST contact information must be manually sanitized and then entered into the VINSON DOTS database from the Flag terminal. Automatic sanitization and entry of POST data is a planned enhancement.

Even though contact data to be shared over the network must be entered from the Flag 9020, any other terminal may be used to enter or modify contact information to be used exclusively on that terminal. This allows users to customize their databases.

Use of DOTS Aboard CVN 70. Of the many tactical decision aids that DOTS provides, the principle observed uses during RIMPAC 86 were:

1. Maintaining an contact history database for the exercise, containing all surface, air, and subsurface contacts.

For each detection recorded, some or all the following data were saved: time, location, target course and speed, detecting sensor and detection parameters (dimensions and orientation of elliptical spas or bearing spread and inclusive ranges for bearing boxes). In addition, JOTS III (but not DOTS) provides a comment field which was used extensively by the TOP watchstanders (responsible for maintaining the surface plot).

2. Plotting current or past contact positions.

There were two principle ways this capability was used:

a. Displaying the current position of some group of contacts (e.g., Blue surface ships), or

b. Displaying the contact history (i.e., track) of a few contacts.

Color and NTDS symbology were effectively used to identify the platform type and threat status (hostile, friendly, or unknown).

The processing and display of Link 11 data transfer was fast enough to follow the air war. This was demonstrated during several air raids on the battle group where actual aircraft were used. (A-3's simulated bombers with A-4's and A-7's flying as air-launched cruise missiles.)

3. Performing time/distance navigational calculations.

- e.g., if BATES was underway from San Diego 0800 on 2 June, could she be in the Hawaiian Operation area by 0800 on 10 June with a 15 knot speed of advance?

- with a 18 knot speed of advance going through specified points, where will the contact be in 24 hours?

4. Plotting spas, patrol areas, 4-Whiskey grid (i.e., screen) assignments

5. Preparing "executive summaries" of the contact situation.

No direct use of the AAW, ASW or EW decision aids was observed, although several of the Carrier Group Three staff members were very knowledgeable in their use.

Observed Problems.

1. Resolution on the HP 9020 screen was insufficient to display many contacts. (The POST display, using an HP 9020C machine, was much better.)

2. TOP watchstanders used JOTS III rather than DOTS because JOTS III is more complete.

3. The HP Think Jet printer generally only provided marginally acceptable hard copy. The installed thermal printer on some of the HP 9020 machines provided a finer resolution output.

References

(1) JOTS II Technical Reference Manual, Commander Naval Air Force, U.S. Atlantic Fleet, May 1984, CONFIDENTIAL.

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