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SUBMARINE APPROACH AND ATTACK TACTICS - SIMULATION AND ANALYSIS

by

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March 1995

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13. ABSTRACT

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The submarine approach problem addressed in this thesis was solved using Monte Carlo simulation. Each simulation run includes 1,000 replications for each combination of submarine speed, target speed and tactic. Each replication starts by specifying initial conditions for the target and submarine. Then the submarine's approach phase is simulated, consisting of three legs (TMA maneuvers) during which the submarine computes the target speed, course and range. The simulation continues with the attack phase, where the submarine decides if a torpedo can reach the target. Finally the success or failure of the attack is determined. The number of successful attacks in each simulation is a measure of effectiveness of the particular tactic. The simulation shows that the tactic which maximizes the probability of successful attack is Point-Lead-Point, but possibly other considerations not captured in the simulation model would recommend a different tactic choice. Due to the variety of arbitrary tactical assumptions, the principal contribution of this thesis is a representative simulation analysis. Specific tactical conclusions are likely to be misleading and are not recommended for actual use.

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SUBMARINE APPROACH AND ATTACK TACTICS - SIMULATION AND ANALYSIS

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The purpose of this thesis is to assess the probability of a diesel submarine's successful attack when using bearings-only Target Motion Analysis (TMA) while approaching a surface target. Four different approach tactics are examined:

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Specific tactical conclusions are likely to be misleading and are not recommended for actual use.

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LIST OF ABBREVIATIONS AND ACRONYMS

Ab	Angle of the bow
B	True bearing
Co	Submarine course
Ct	Submarine speed
DA	Deflection Angle
DT	Distance of the track
G	Gyro angle
Kn	Knots
LLOA	Limiting Lines Of Approach
LOF	Line Of Fire
LOS	Line Of Sight
n.m	Nautical miles
Pd	Probability of detection
Po	Probability for the submarine to be outside the SAR
Ps	Probability of successful attack
R	Range
SDZ	Submarine Detection Zone
So	Target course
St	Target speed
TDZ	Torpedo Danger Zone
TMA	Target Motion Analysis
UF	Pseudo distance

EXECUTIVE SUMMARY

If force projection and counter-projection have been a major theme of postwar naval development East and West, to them must be added the older theme of undersea warfare. The submarine is generally counted as a manageable threat as long as it can be detected by ASW forces.

The purpose of this thesis is to examine with simulation the probability of:

- A diesel submarine performing a successful attack on a surface target, given its limited speed (So).
- A target performing a successful pass through a submarine patrol area.

The submarine is diesel (Type 209), patrolling in an area, and conducts the attack submerged, avoiding the use of periscope or any active sensor. A bearings-only TMA approach is used.

The target is a military ship with constant course and speed (Ct,St) that has been detected by the submarine using its hydrophone array.

The research is conducted using a Monte Carlo simulation. The main elements of the simulation program are:

- Submarine model, including motion characteristics, sensor and weapons performances.
- Target model, including motion characteristics.
- Implementation of TMA procedures.

- Implementation of submarine tactics:
  POINT - LEAD - POINT.
  POINT - LAG - POINT.
  POINT - LEAD - LAG.
  POINT - LAG - LEAD.

Pedro Coll's Monte Carlo simulation program [Ref.3] was modified to meet the requirements of this research. Each simulation run includes 1,000 replications for each combination of submarine speed, target speed and tactic. Each replication starts by specifying initial conditions for the target and submarine. Then the submarine's approach phase is simulated, consisting of three legs (TMA maneuvers) during which the submarine computes the target speed, course and range. The simulation continues with the attack phase, where the submarine decides if a torpedo can reach the target. Finally the success or failure of the attack is determined. The number of successful attacks in each simulation is a measure of effectiveness (MOE) of the particular tactic.

The simulation shows that a modern diesel submarine is capable of reaching a favorable attack position, closing the non-maneuvering surface target within torpedo range and generating a TMA solution accurate enough to place the torpedo within acquisition range.

I. INTRODUCTION

The submarine has been one of the most important strategic and tactical weapons systems of the 20th century. This importance will likely increase further in the 21st century as submarines become less detectable and more lethal.

Diesel submarines have a relatively short cruising range, so they tend to inhabit littoral waters rather than the mid-ocean areas. Indeed, most developing countries have a few vessels deployed defensively near their own coastlines, leading some analysts to deride them as mere intelligent minefields. During the Falklands/Malvinas war, the Argentine Type 209 submarine *San Luis (S 32)* managed to elude 15 British frigates and destroyers and the antisubmarine aircraft of two carriers. The *San Luis* maneuvered into torpedo range of the British fleet and launched three torpedoes, although all three shots were unsuccessful. [Ref.1]

To avoid ASW forces a submarine must exploit its natural stealth and invisibility. A submarine commander must take advantage of long-range passive detection and torpedo ranges and stay as "dead" as possible to avoid radar or sonar reflections. He must try to refine his estimate of target motion while approaching the target, avoiding the use of the periscope or any active sensor. This bearings-only Target Motion Analysis (TMA) requires complex maneuvers in order for the submarine to successfully reach the firing point.

The purpose of this thesis is to assess the probability of a diesel submarine's successful attack using bearings-only TMA and four different tactics of approach.

A. BACKGROUND

The TMA that a diesel submarine performs while approaching a surface target was the thesis subject of LCDR Pedro F. Coll (SPAIN) [Ref.3]. His research was conducted using a Monte Carlo simulation. The relative motion plot, geographic plot and Ekelund ranging were simulated in order to determine the best submarine tactics for a successful attack. This thesis continues Coll's work by further refining and exercising Coll's simulation.

B. PROBLEM DEFINITION

The submarine is assumed to be conducting a barrier patrol against surface targets. The target will be a military ship with constant course and speed that has been detected by the submarine using its hydrophone array. Assuming that hostile ASW units may be present in the area, the submarine will conduct the approach and attack submerged, avoiding the use of any active sensor.

For the purpose of this simulation the Commanding Officer must:

- Select the appropriate speed of approach.
- Remain undetected within the approach region, while maneuvering for bearings-only TMA.
- Reach the firing point at the end of approach phase.
- Choose one of the approach tactics:
  POINT - LEAD - POINT.

POINT - LAG - POINT.
POINT - LEAD - LAG.
POINT - LAG - LEAD.

Make his final attack decision based on:

- Tactical restrictions.
- Operational area restrictions.
- Weapons and sensors characteristics.
- The increased likelihood of counter detection as attack range decreases.
- The increased likelihood of a torpedo miss as attack range increases.

C. SIMULATION METHODOLOGY SUMMARY

The main objective to this thesis is to estimate with a Monte Carlo simulation the probability of a successful attack for different submarine approach speeds (So), target speeds (St) and approach tactics.

Pedro Coll's Monte Carlo simulation program was modified to meet the requirements of this research. Each replication simulates one submarine approach, attack and torpedo release, and determines the success or failure of this attack. Each replication starts by specifying initial conditions for the target and submarine. Then the submarine's approach phase consists of three legs (TMA maneuvers) during which the submarine computes the target speed, course and range. The simulation continues with the attack phase, where the submarine decides if a torpedo can reach the target. Finally the success or failure of the attack is determined. The number of successful attacks in each simulation is a measure of effectiveness (MOE) of the particular tactic.

Each simulation includes 1,000 replications for each combination of So, St, and one of the four approach tactics examined. Figure 1 shows the flowchart of one replication including time counter.

The simulation shows that a modern diesel submarine is capable of reaching a favorable attack position, closing a non-maneuvering surface target within torpedo range and generating a TMA solution accurate enough to place the torpedo within acquisition range.

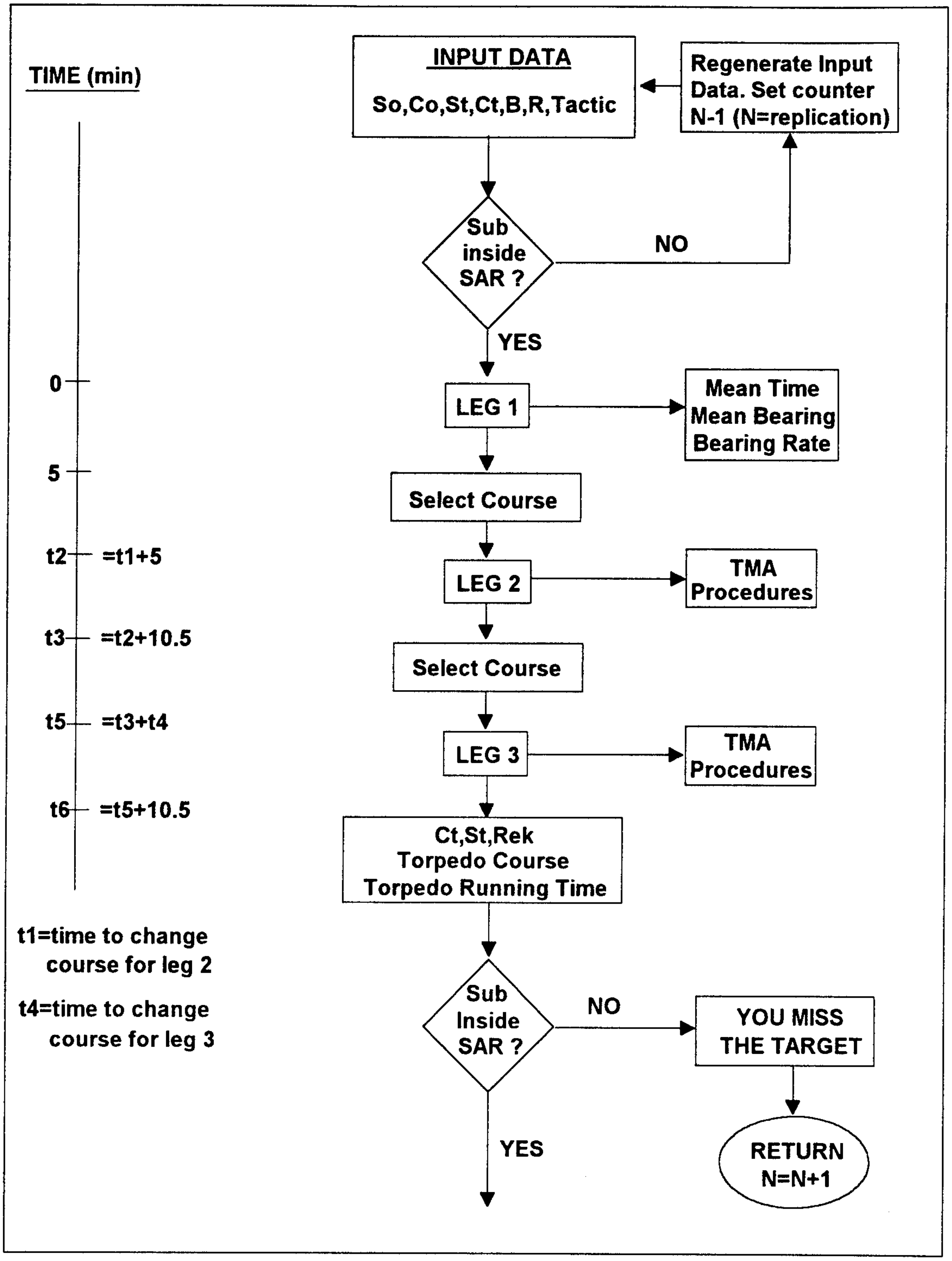

Figure 1. Flowchart of a Single Replication (Part 1)

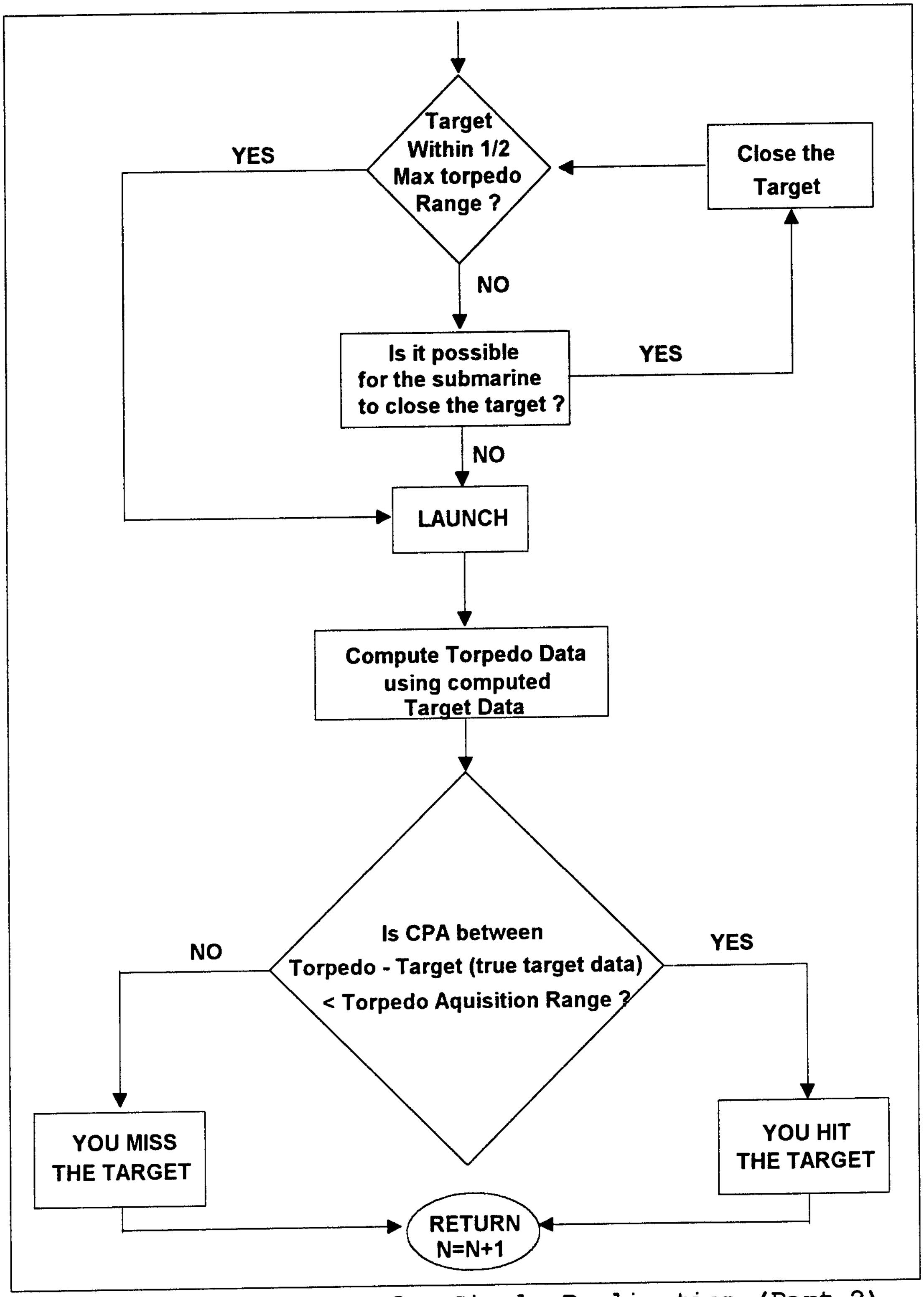

Figure 1. Flowchart of a Single Replication (Part 2)

II. APPROACH PHASE AND TARGET MOTION ANALYSIS

A. SUBMERGED APPROACH REGION

In designing antisubmarine screens, it is essential to determine the areas from which the submarine has a good chance of scoring a torpedo hit.

The Torpedo Danger Zone (TDZ) about an individual ship or group of ships is the region within which a torpedo must be fired, if it is to have a positive probability of scoring a hit (Ps). The shape and size of the zone will depend on the speed and type of the torpedo, as well as the speed and disposition of the ships. It is bounded by a closed curve containing the ship/ships and moving along with the ship/ships. For this work we will assume a single target.

In order for the submarine to reach a point inside the TDZ and remain undetected, it must make its approach to this curve submerged. Let its submerged speed be So. The speed of the surface target is St, and assume that So < St.

It is not necessarily possible for the submarine to always reach the curve. The area from which the submarine can reach the TDZ is called the Submerged Approach Region (SAR)(Figure 2).

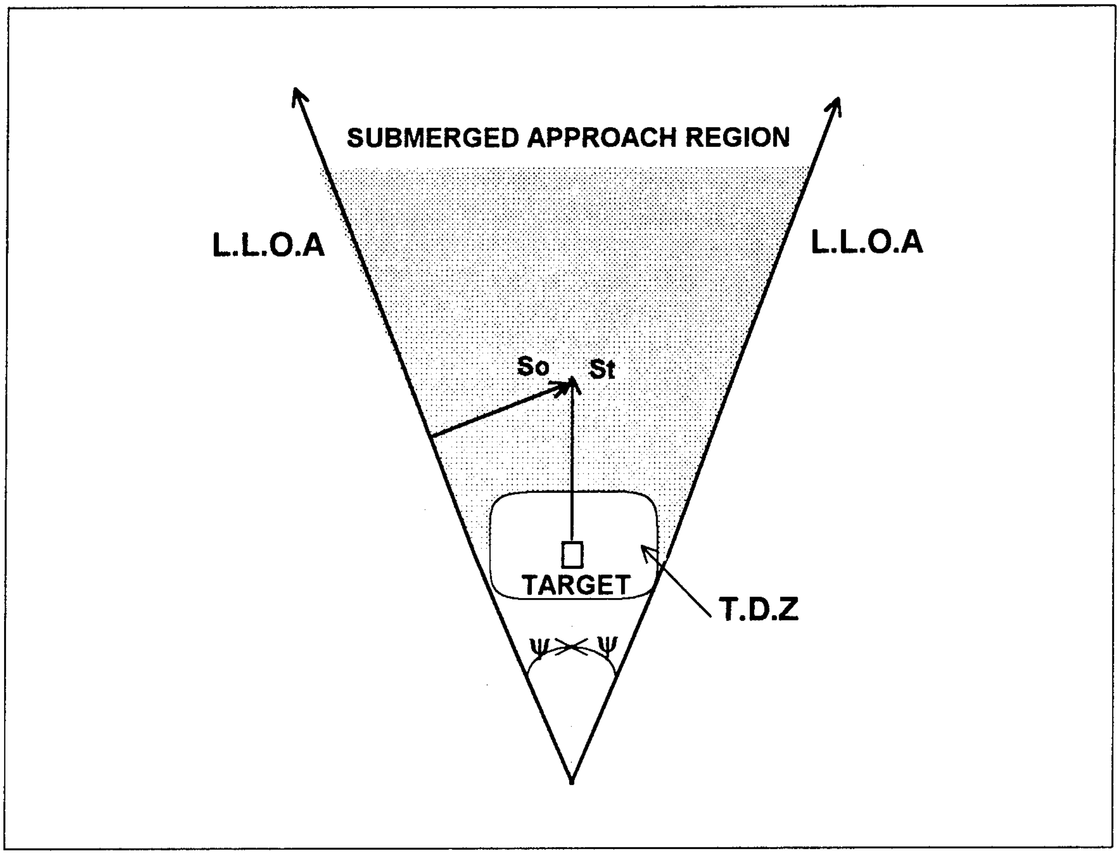

Figure 2. Submerged Approach Region

The tangents to the TDZ are called Limiting Lines Of Approach (LLOA), and the angle $\Psi = \sin^{-1}(So/St)$ in Figure 2 is the Limiting Approach Angle. The submarine has to be within the Limiting Lines Of Approach in order to reach an acceptable firing position. See [Ref.2] section 1.3 for more detail regarding the SAR.

During the approach phase, the submarine must always remain within the SAR. If during TMA maneuvers it moves outside the SAR, then it will never be able to reach the TDZ to launch a successful torpedo attack.

B. SUBMARINE - TARGET TRIANGLE

After the submarine detects the target, the available information is true bearing (B) (called line of sight (LOS)), bearing rate, and time. Using this information and TMA techniques, the submarine must solve the SUB - TARGET triangle, to compute Ct, St, Ekelund range (R), distance of the track (DT), and angle of the bow (Ab) (Figure 3).

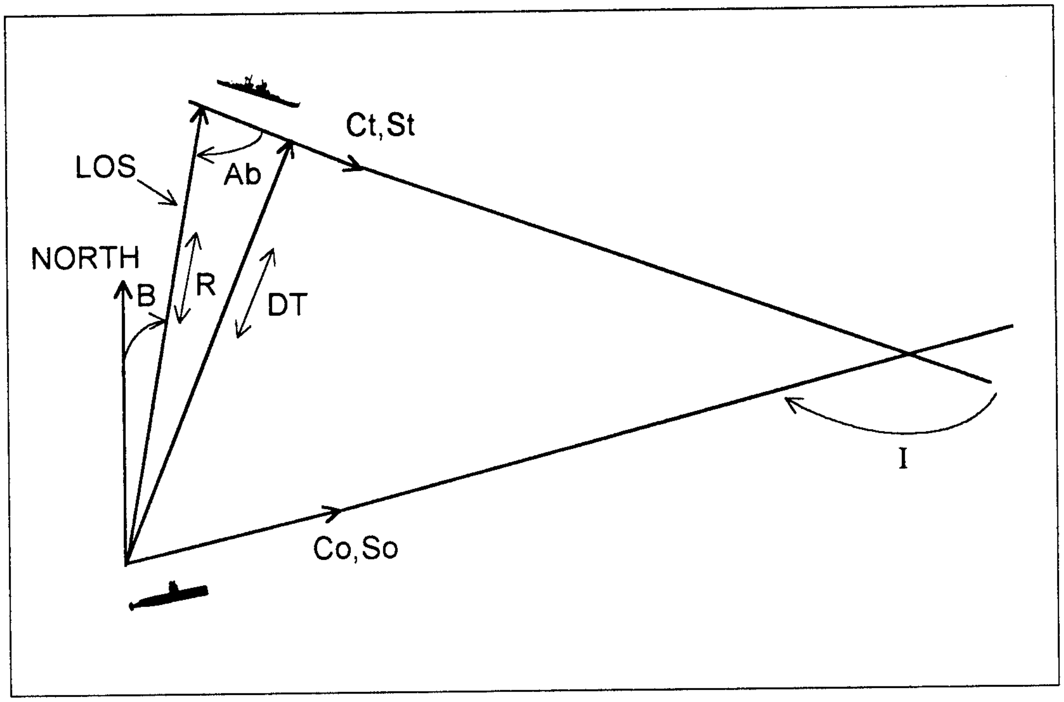

Figure 3. Submarine - Target Triangle

The Ekelund Ranging maneuver, a passive ranging method, consists of two steady submarine legs separated by a turn. Bearing-rates *(Brate1, Brate2)* and the components of submarine speed across the line of sight *(SSalos1, SSalos2)* are computed for each leg. Then equation (1) is used to compute Ekelund range [Ref.3].

$$Rek=\frac{SSalos2-SSalos1}{Brate1-Brate2} \qquad (1)$$

It is important to note that the sonar bearings received from the hydrophone array may contain errors. These errors are assumed in the simulation to be independent and normally distributed with mean zero and a specified standard deviation. Bearings are smoothed in the simulation to increase TMA accuracy and to mimic actual tracking procedures.

C. SIMULATED SUBMARINE APPROACH TACTICS

1. TMA Maneuver

The TMA maneuvers examined here are always composed of three legs:

a. First Leg

The first approach course is always a POINT leg, where submarine course and target true bearing are opposite vectors. An initial POINT leg is necessary to estimate target bearing rate (left or right), while remaining inside the SAR.

b. Second Leg

Referring to Figures 4 and 5, the second leg can be either LEAD or LAG. If LEAD,

$Co=B-70^\circ$ (Bearing rate left on leg 1) (2)

$Co=B+70^\circ$ (Bearing rate right on leg 1) (3)

And if LAG,

$Co=B-50^\circ$ (Bearing rate right on leg 1) (4)

$Co = B + 50^\circ$ (Bearing rate left on leg 1) (5)

c. Third Leg

The third leg depends on the second leg. The four possible complete TMA maneuvers are:

1. Point - Lead - Point.
2. Point - Lag - Point.
3. Point - Lead - Lag.
4. Point - Lag - Lead.

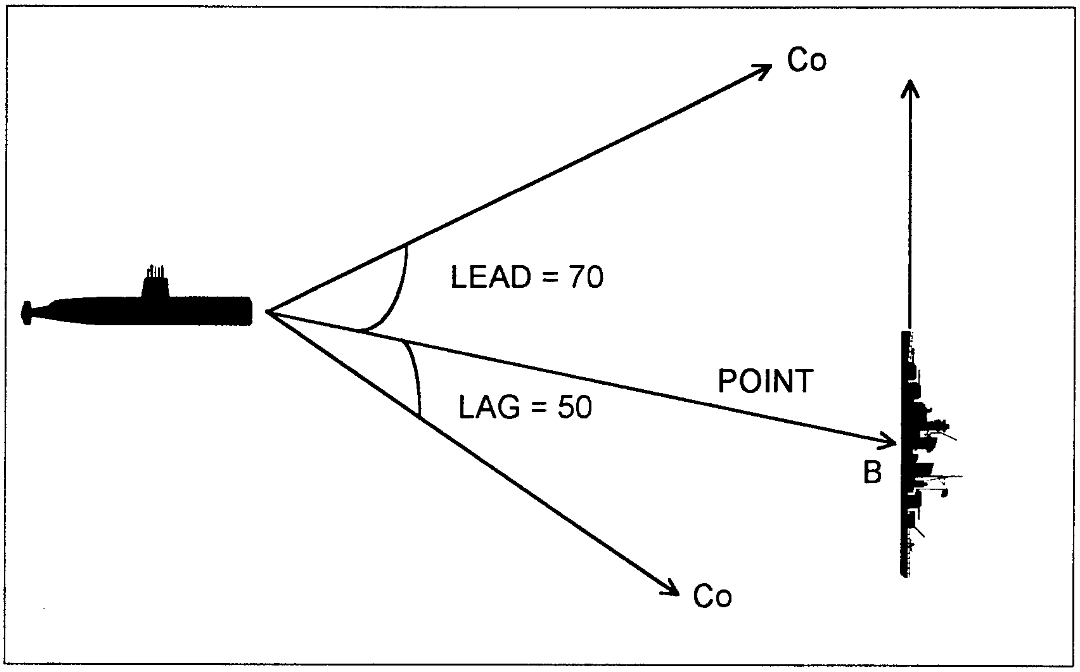

Figure 4. Possible Leg Situations (Bearing Rate Left)

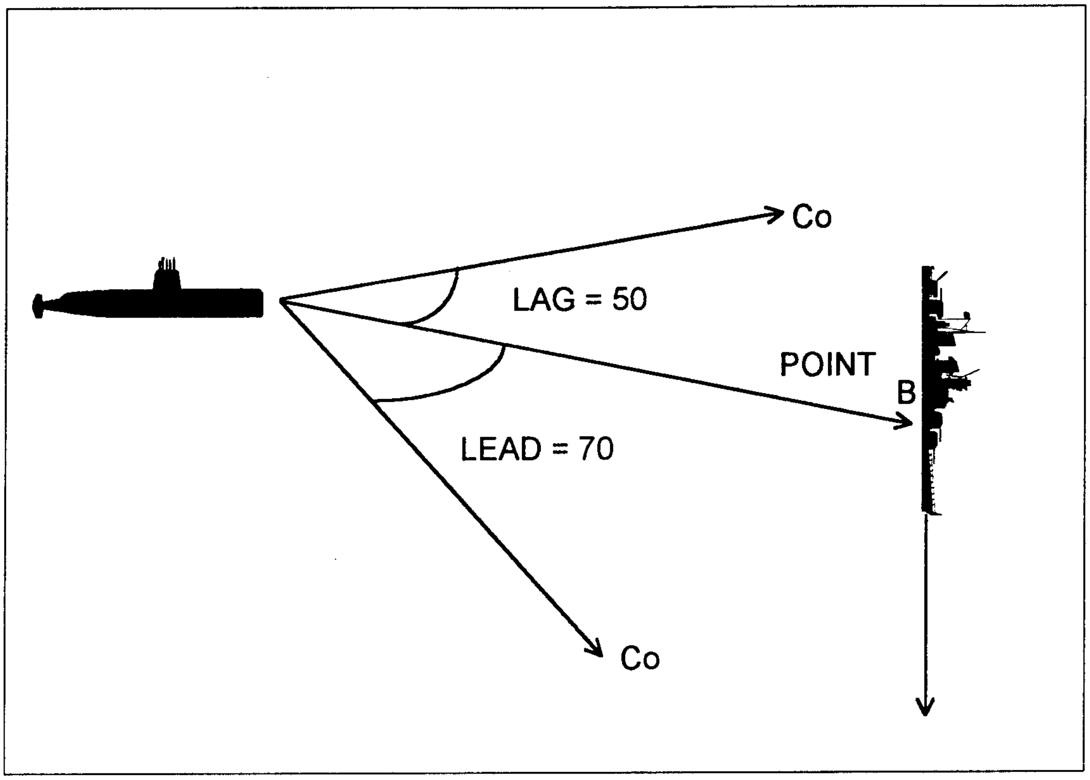

Figure 5. Possible Leg Situations (Bearing Rate Right)

2. Course Selection for Each Leg

Depending on the tactic situation, So, Co, estimated St and Ct, torpedo characteristics, and position in the submerged approach region, the second and third legs can be radically different.

The initial point leg is a short leg of 5 minutes, where only target bearing rate is computed. The other two legs last 10 minutes each.

Experience has shown that the change in course angle between two legs must be at least 50° for best accuracy in Ekelund range computation.

III. ATTACK PHASE

A. SUBMARINE - TARGET - TORPEDO TRIANGLE

At the end of the approach phase, having solved the TMA problem, the submarine tries to obtain the best possible firing position (Figure 6).

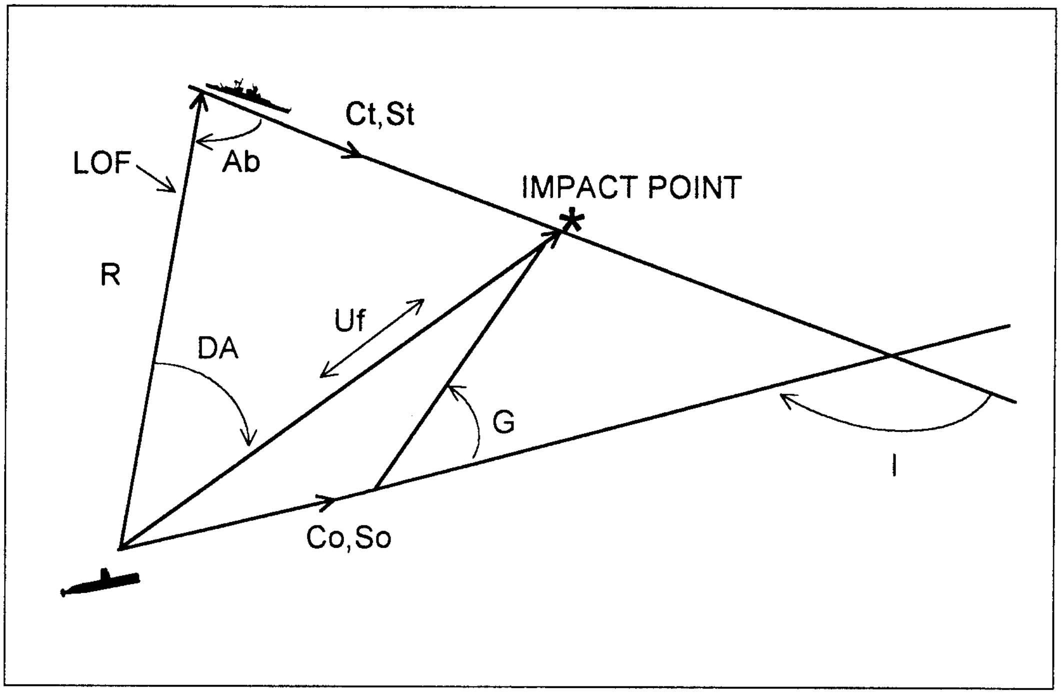

Figure 6. Submarine - Target - Torpedo Triangle

From this position, with the true bearing now called line of fire (LOF), the submarine must turn by an angle called the deflection angle (DA). From this course it will launch the torpedo with a gyro angle (G). The torpedo will hit the target at the impact point after running a distance of Uf.

B. SONAR DETECTION ZONE-TORPEDO DANGER ZONE

When a task force is passing through a submarine patrol area, an ASW screen is used in order to detect the submarine. The area in which detection is possible is called the Sonar Detection Zone (SDZ) (Figure 7).

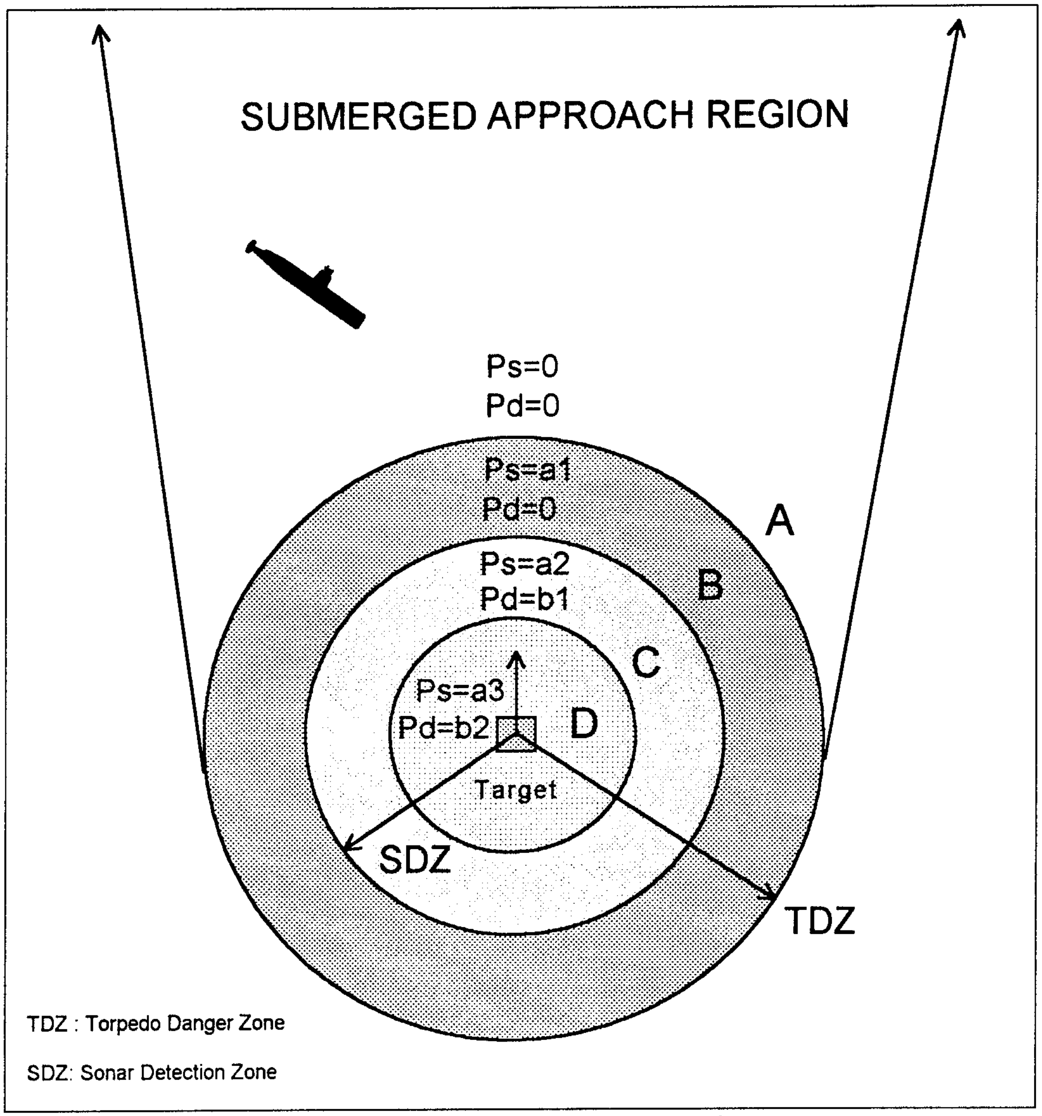

Figure 7. TDZ and SDZ Regions

In most situations where a submarine opposes a single transiting surface warship (as it modeled here), the TDZ strictly contains the SDZ.

As the submarine approaches from the SAR, both the probability of its detection (Pd) and the probability for a successful torpedo attack (Ps) increase. Pd depends on sonar characteristics, propagation conditions, submarine aspect, and self noise. Ps depends on torpedo characteristics and the computed firing data.

1. Area A (Figure 7)

The submarine is outside the maximum torpedo range and SDZ:

$$Pd = Ps = 0 \tag{6}$$

2. Area B (Figure 7)

The submarine is inside torpedo maximum range and outside SDZ:

$$Pd = 0 \tag{7}$$

$$Ps = a_1 \tag{8}$$

3. Area C (Figure 7)

The submarine is inside torpedo maximum range and SDZ:

$$Pd = b_1 \tag{9}$$

$$Ps = a_2 \tag{10}$$

$$a_1 < a_2 \tag{11}$$

4. Area D (Figure 7)

The submarine is inside torpedo maximum range and SDZ:

$$Pd = b_2 \tag{12}$$

$$Ps = a_3 \tag{13}$$

$$b_1 < b_2 \tag{14}$$

$$a_1 < a_2 < a_3 \tag{15}$$

C. FINAL ATTACK DECISION

Depending on his position at the end of the approach phase, the submarine Commanding Officer must decide upon one of the following actions, considering that the next step is the escape phase where the submarine must avoid detection and "escape" far from the dangerous zone.

1. Launch Immediately

The submarine will launch immediately if it is within areas B, C, or D, and is unable to reach a closer firing position. It will also launch if it decides not to increase Pd by closing the target.

2. Close the Target and Launch

The submarine will close the target if it is within area A. It will also close if it is within areas B or C and decides to obtain a better firing position to increase Ps and Pd.

3. Abandon the Attack

The submarine will abandon the attack if it is outside the submerged approach region and is thus unable to close the target to reach a position inside areas B, C , or D.

IV. SIMULATION MODEL

A. DIESEL SUBMARINE MODEL

The submarine of interest is a modern diesel type 209 [Ref.1]. The simulation model of [Ref.3] has been modified to test four TMA tactics.

1. Speed and Battery

The submarine is assumed to be conducting a barrier patrol in a predetermined patrol area, and tries to keep average battery charge level between 80%-90%. The approach speed range is between 2-8 knots, in order to manage longer sonar detection ranges and save energy for the escape phase.

2. Course Changes

Submarine initial course for each replication is generated randomly with a uniform distribution between 060° and 120°, and changes immediately after the initial detection, depending on the TMA tactic being investigated.

3. Passive Sonar Equipment

The submarine's passive sonar is a hull mounted circular hydrophone array, with a detection range that is a function of target's speed, in accordance with Table 1.

Target	Range
10 Kn	7 n.m
12 Kn	8 n.m
14 Kn	9.8 n.m
16 Kn	12.8 n.m
18 Kn	16.2 n.m
20 Kn	20 n.m
22 Kn	24.2 n.m
24 Kn	28.8 n.m

Table 1. Passive Detection Range of Target by Submarine

The measurement error from the received bearings is considered normally distributed with mean 0.0 and standard deviation of 0.5 degrees.

4. Weapons

The submarine is armed with passive acoustic torpedoes, with a maximum range of 7.5 nautical miles and 45.0 knots of speed, which gives a maximum running time of 6.0 minutes.

The acquisition range of the torpedo's acoustic detector is:

$$Acquisition\ Range\ (n.m.) = 0.001 * St^2 \tag{16}$$

The simulation scores a hit if the CPA between torpedo and target is less than the torpedo acquisition range.

B. TARGET MODEL

The target is a military ship which passes through the submarine patrol area.

1. Course - Speed

Target speed is constant for each simulation experiment, but it is varied parametrically from 10 Kn to 24 Kn to examine how the best submarine approach tactic varies with different target speeds. Target course is always 000^0.

2. Initial Target Position

The initial ordinate value Y for target location is given by "Detection Range" in Table 1. The initial abscissa value X is uniformly distributed between -24 n.m. and 24 n.m.

C. SIMULATION ASSUMPTIONS

The assumptions of the simulation program are:

- One non-maneuvering surface target, with constant speed 10-24 knots and constant course 000^c.
- No loss of sonar contact.
- Submarine initial leg is always a POINT leg.
- Submarine battery charge level at the beginning of the approach phase is between 80-90%.
- Sonar bearing errors have the Normal distribution with mean $\mu=0^\circ$ and standard deviation $\sigma=5^\circ$.
- Surface ship can not detect the submarine.

V. SIMULATION RESULTS

Four different approach tactics are simulated for each combination of eight target and four submarine speeds. A total of 128 (4*8*4) different combinations of tactical and speed variations were tested, with 1,000 replications used in each simulation test.

A. CONFIDENCE INTERVAL

Each simulation replication (x_i) is an independent identically distributed (iid) Bernoulli trial, with probability of success Ps, and probability of failure (1-Ps). The number of successes in a combination run consisting of n=1,000 trials, is a Binomial random variable. Using the Normal approximation to Binomial (good when $np>5$, $0.1<p<0.9$), the equations for the 95% confidence interval for the population mean (p) are:

$$P\left(\hat{p}-1.96\sqrt{\frac{\hat{p}(1-\hat{p})}{n-1}}<p<\hat{p}+1.96\sqrt{\frac{\hat{p}(1-\hat{p})}{n-1}}\right)=0.95 \quad (17)$$

$$95\%\ CI=\hat{p}\pm 1.96\sqrt{\frac{\hat{p}(1-\hat{p})}{n-1}} \quad (18)$$

$$\hat{p}=\frac{\sum_{i=1}^{n} x_i}{n} \quad (19)$$

$$x_i = 0\ or\ 1\ (unsuccessful\ or\ successful\ attack) \quad (20)$$

B. TACTIC 1 (POINT - LEAD - POINT)

In tactic 1, the initial leg is a POINT leg, the second leg is a LEAD 70° leg where the submarine closes the target, and the third is a POINT leg (Figure 8).

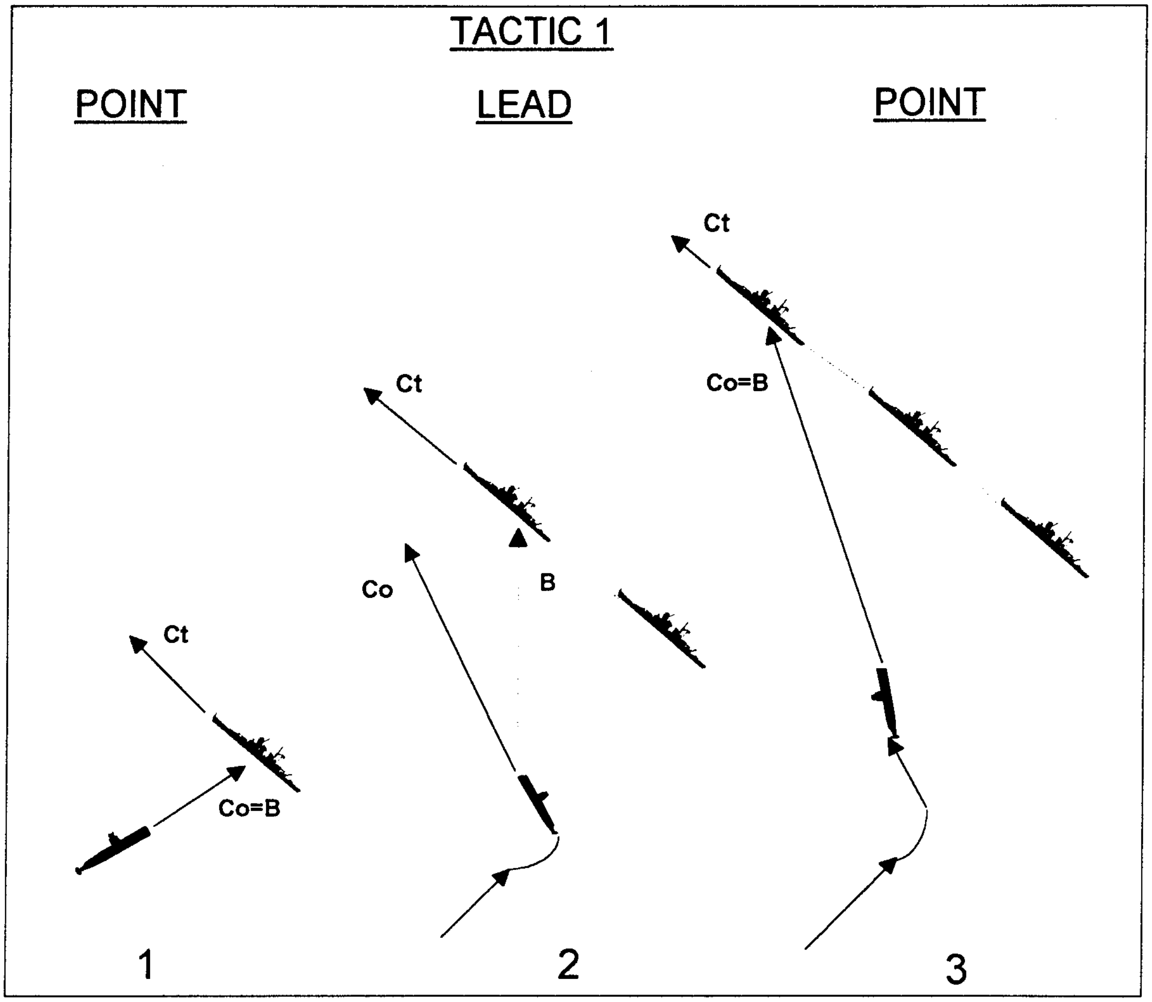

Figure 8. Geoplot (P-LEAD-P)

The advantage of this tactic is that the submarine closes the target during the LEAD leg. Thus it is difficult for the submarine to find itself outside the SAR, or outside maximum torpedo range.

The disadvantage of this tactic is that after the LEAD leg (in short range situations), it is possible for the submarine to be under the target and unable to continue to the next leg.

Figure 9 shows the probability of a successful attack for each speed combination, when using tactic POINT-LEAD-POINT. With St fixed, Ps generally increases as So increases. The high Ps of 80% appears when submarine speed (So) is 8 Kn and target speed (St) is 10 Kn.

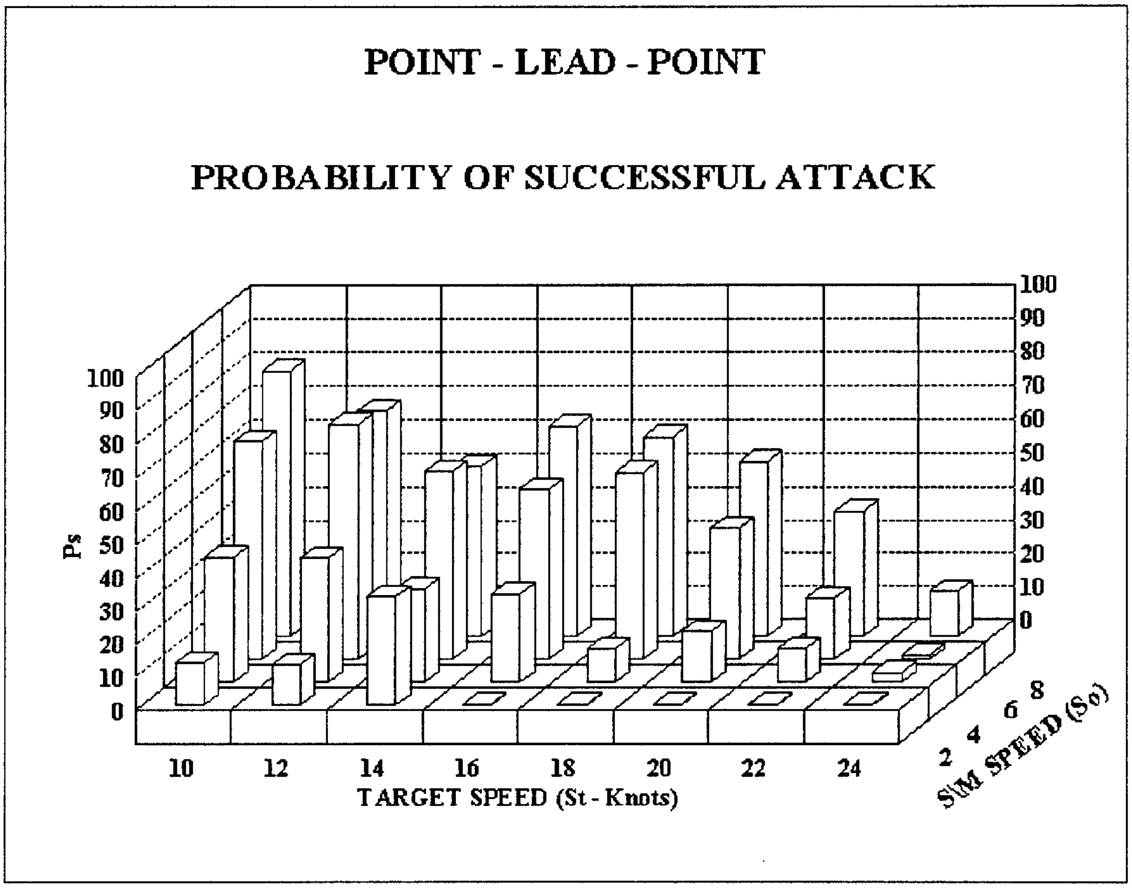

Figure 9. Ps vs St and So (P-LEAD-P)-(Bar Plot)

For target speed of 24 Kn, Ps is extremely low. This results because after the third leg, the submarine is out of maximum torpedo range and unable to obtain a better firing position.

Figure 10 shows the same data as Figure 9, presented to emphasize changes in Ps with target speed.

Figure 10 shows that as St increases, Ps generally decreases. An interesting point occurs at St=14 Kn and So=2 Kn where Ps increases and then starts decreasing again (to near zero). This results because for So=2 Kn and St≤12 Kn there is insufficient relative motion between the two platforms to allow an accurate TMA solution. And for St≥16 Kn, the target moves too fast for a good solution. At St=14 Kn, these two effects have a minimum combined effect and Ps is maximized.

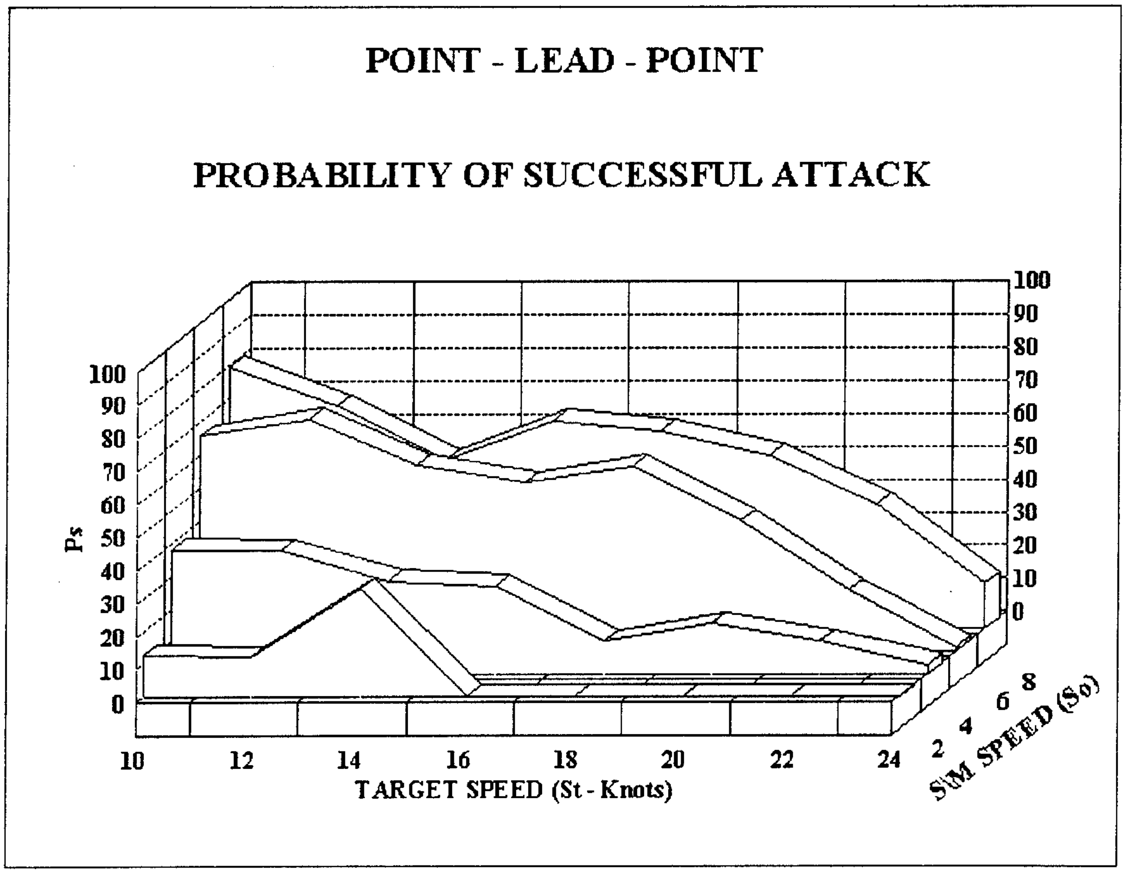

Figure 10. Ps vs St and So (P-LEAD-P)-(Area Plot)

Table 2 shows the 95% confidence intervals for Ps, computed as in equations 17-18-19-20. The lower and upper limits of the 95% confidence intervals for Ps increase as submarine speed increases, with the highest values of the limits at So=8 kn and St=10 kn (shaded in Table 2).

So	2		4		6		8	
St	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
10	0.11	0.14	0.36	0.39	0.64	0.67	0.78	0.81
12	0.111	0.131	0.36	0.39	0.692	0.72	0.662	0.691
14	0.313	0.343	0.267	0.295	0.551	0.581	0.497	0.528
16	0	0.002	0.253	0.281	0.498	0.529	0.615	0.645
18	0	0.002	0.09	0.108	0.548	0.578	0.585	0.615
20	0	0.002	0.142	0.164	0.382	0.412	0.511	0.542
22	0	0.002	0.09	0.108	0.171	0.195	0.362	0.392
24	0.001	0.005	0.023	0.033	0.009	0.015	0.125	0.147

Table 2. 95% CI for Ps (P-LEAD-P)

C. TACTIC 2 (POINT - LAG - LEAD)

In tactic 2, the initial leg is a POINT leg, the second leg is LAG 50° leg where the submarine opens the target range, and the third leg is a LEAD 70° (Figure 11).

The advantage of this tactic is that if the target starts at a short range, the submarine opens the range with the LAG leg and thus finds itself under the target (and unable to fire) less frequently.

The disadvantage of this tactic is that during the LAG leg (especially in high submarine speed and high target speed situations), it is possible for the submarine to find itself either outside the SAR or outside maximum torpedo range and thus unable to continue for the next leg.

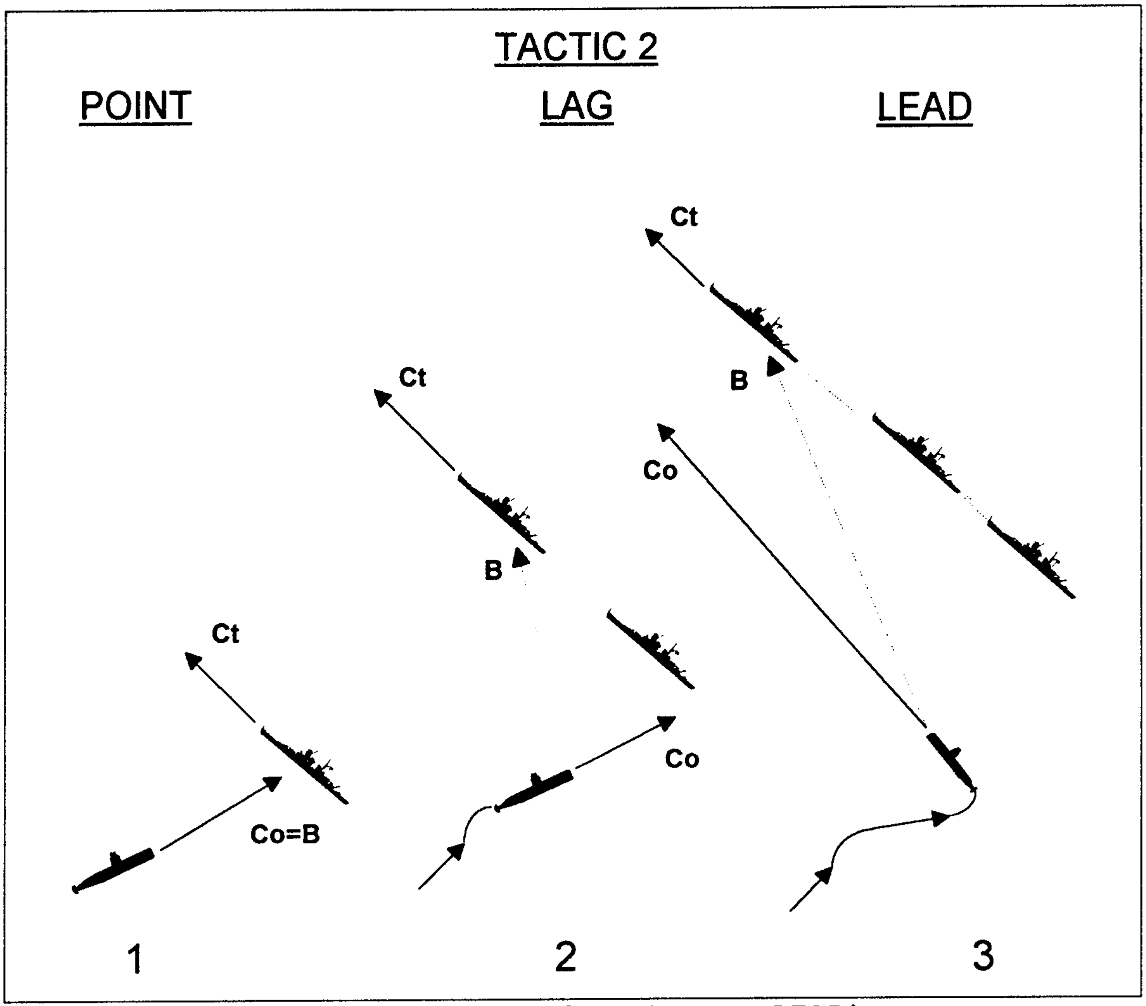

Figure 11. Geoplot (P-LAG-LEAD)

Figure 12 shows the probability of a successful attack for each speed combination, when the tactic used is POINT-LAG-LEAD. With St fixed, Ps generally increases as So increases. The high Ps of 66% appears when submarine speed So=8 Kn and target speed St=16 or 18 Kn.

For target speed 24 Kn, Ps is extremely low. This is because after the LAG leg, the submarine is out of maximum torpedo range and unable to obtain a better firing position.

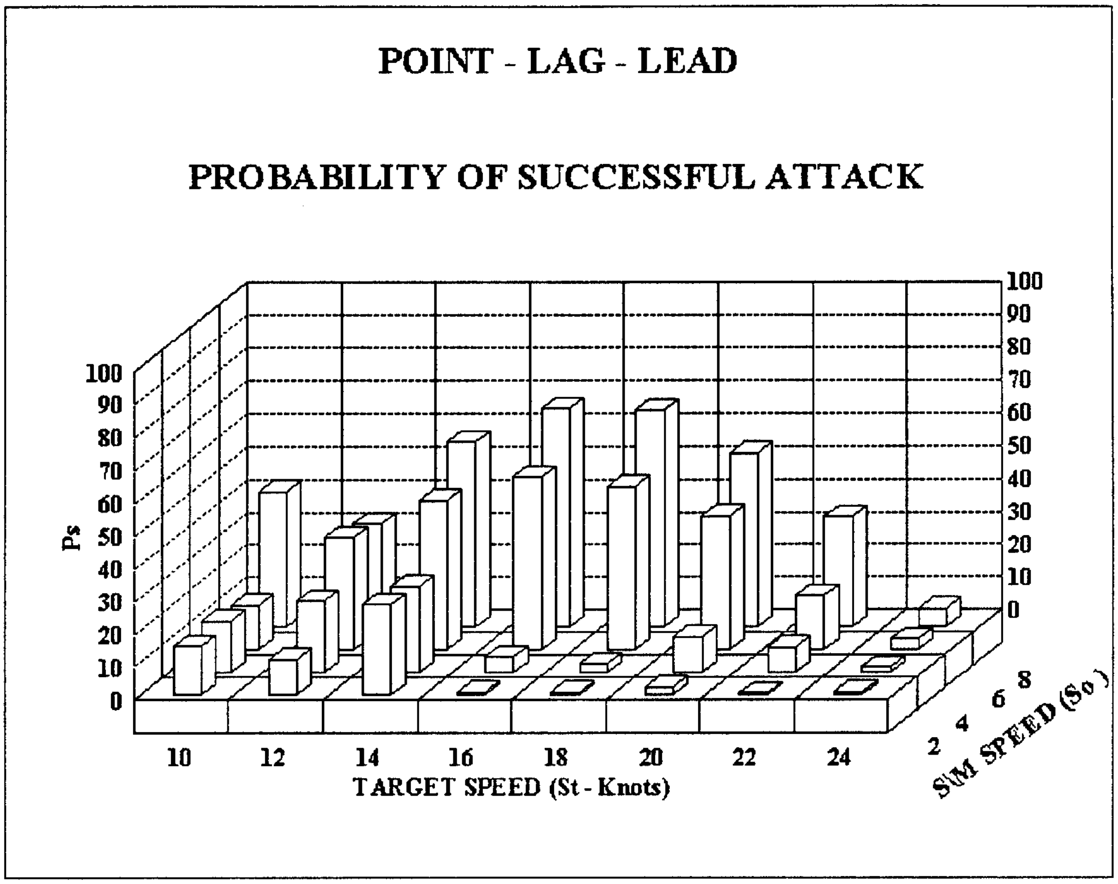

Figure 12. Ps vs St and So (P-LAG-LEAD)-(Bar Plot)

Figure 13 shows the same data as Figure 12, presented to emphasize changes in Ps with target speed. Figure 13 shows that as St increases, Ps increases and then starts decreasing again. Interesting points occur at St=14 Kn and So≤4 Kn and again at St=18 Kn and So=6-8 Kn, where Ps as a function of St peaks. This results because at slow submarine or target speeds there is insufficient relative motion for an accurate TMA solution. And for high target speeds, the submarine often finds itself outside either the SAR or maximum torpedo range.

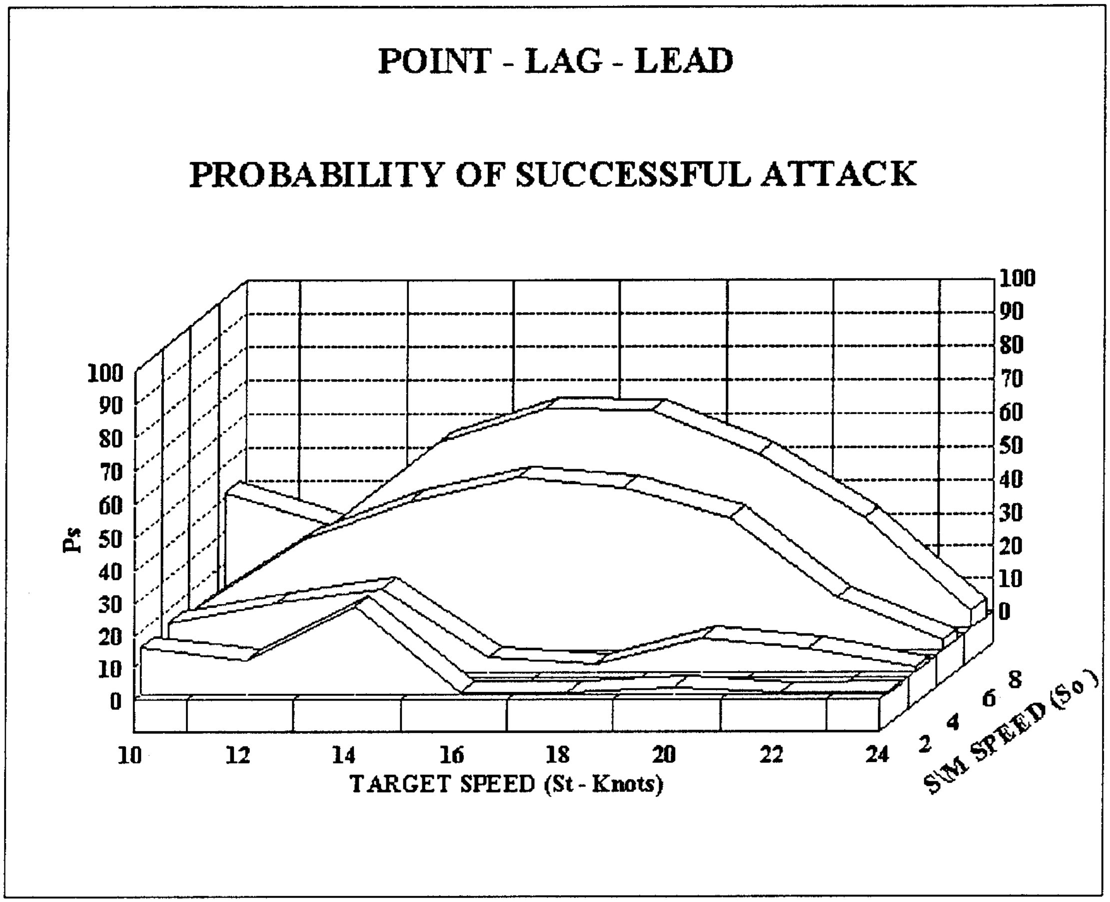

Figure 13. Ps vs St and So (P-LAG-LEAD)-(Area Plot)

Table 3 shows the 95% confidence intervals for Ps, computed as in equations 17-18-19-20. The lower and upper limits of the 95% confidence intervals for Ps, increase as submarine speed increases, with the highest values of the limits at So=8 Kn and St=16 - 18 Kn (shaded in Table 3).

So St	2		4		6		8	
	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
10	0.136	0.158	0.145	0.167	0.124	0.146	0.399	0.429
12	0.098	0.118	0.202	0.228	0.327	0.357	0.301	0.329
14	0.259	0.287	0.248	0.276	0.442	0.472	0.551	0.581
16	0.005	0.011	0.04	0.054	0.514	0.545	0.651	0.681
18	0.036	0.084	0.021	0.031	0.483	0.514	0.646	0.676
20	0.018	0.027	0.099	0.119	0.394	0.424	0.515	0.546
22	0.002	0.006	0.069	0.085	0.151	0.173	0.322	0.351
24	0.004	0.008	0.012	0.02	0.027	0.038	0.049	0.063

Table 3. 95% CI for Ps (P-LAG-LEAD)

D. TACTIC 3 (POINT - LEAD - LAG)

In tactic 3, the initial leg is a POINT leg, the second leg is LEAD 70° leg where the submarine closes the target, and the third leg is a LAG 50° leg (Figure 14).

The advantage of this tactic is that the submarine closes the target during the LEAD leg. Thus it is difficult for the submarine to find itself outside the SAR or outside maximum torpedo range.

The disadvantages of this tactic is that after the LEAD leg (in short range situations), it is possible for the submarine to be under the target and unable to continue to the next leg. And after the LAG leg (in high submarine speed and high target speed situations) the submarine can be outside the SAR or outside maximum torpedo range and unable to continue to the attack phase.

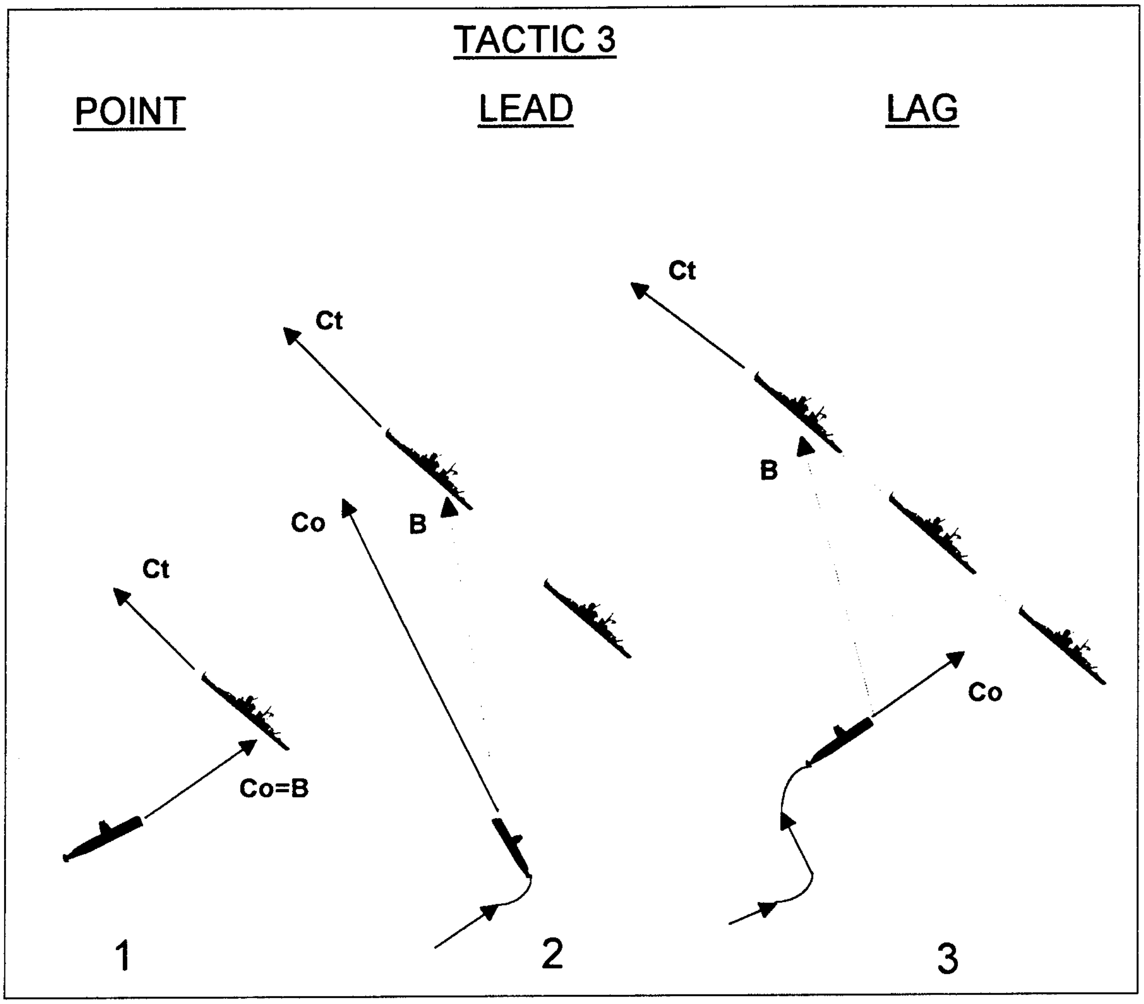

Figure 14. Geoplot (P-LEAD-LAG)

Figure 15 shows the probability of a successful attack for each speed combination, when the tactic used is POINT-LEAD-LAG. With St fixed, Ps generally increases as So increases. The high Ps of 62% appears when submarine speed So=8 Kn and target speed St=14 Kn.

For target speed 24 Kn, Ps is extremely low. This results because after the third leg, the submarine is out of maximum torpedo range and unable to obtain a better firing position.

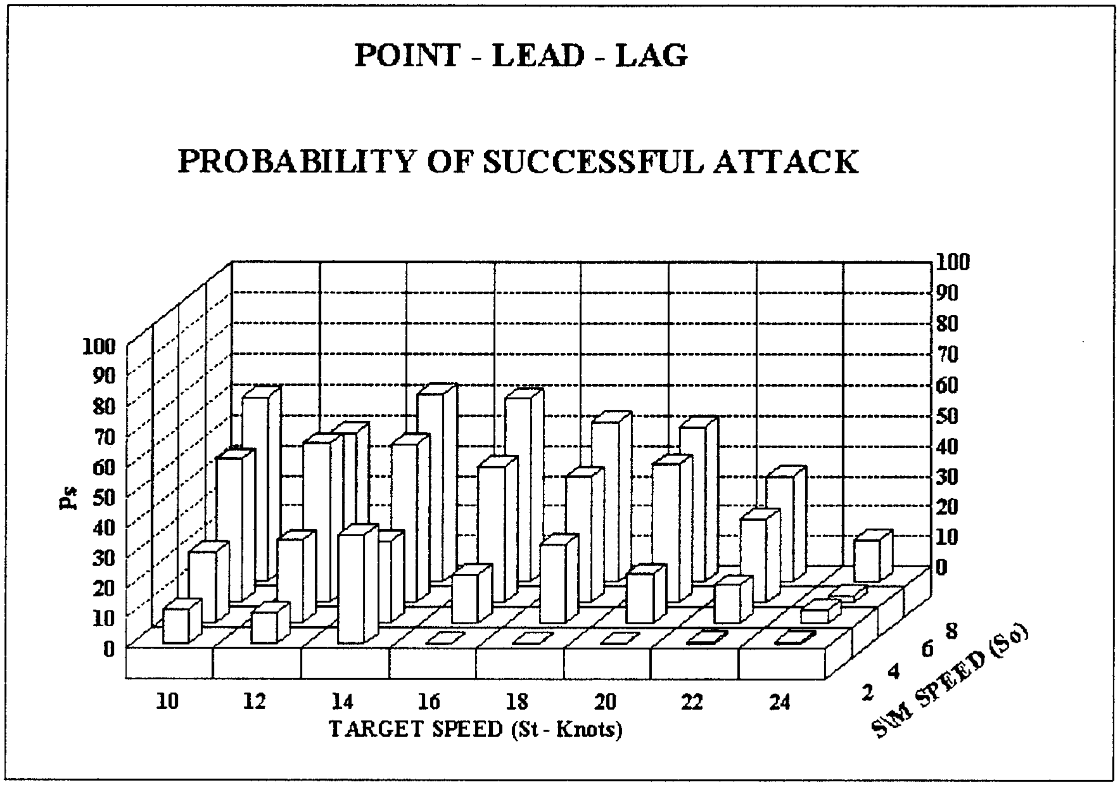

Figure 15. Ps vs St and So (P-LEAD-LAG)-(Bar Plot)

Figure 16 shows the same data as Figure 15, presented to emphasize changes in Ps with target speed. Figure 16 shows that as St increases, Ps increases and then starts decreasing again. An interesting point occurs at St=14 Kn and So=2 Kn where Ps peaks. This results, as before, because for slow submarine and target speeds the relative motion between the platforms is too small for an accurate TMA solution. And when target speeds are large (e.g., greater than 20 Kn), the target can more easily run past the submarine. For moderate target speeds (approximately 14 Kn), neither of these two effects dominates and Ps peaks.

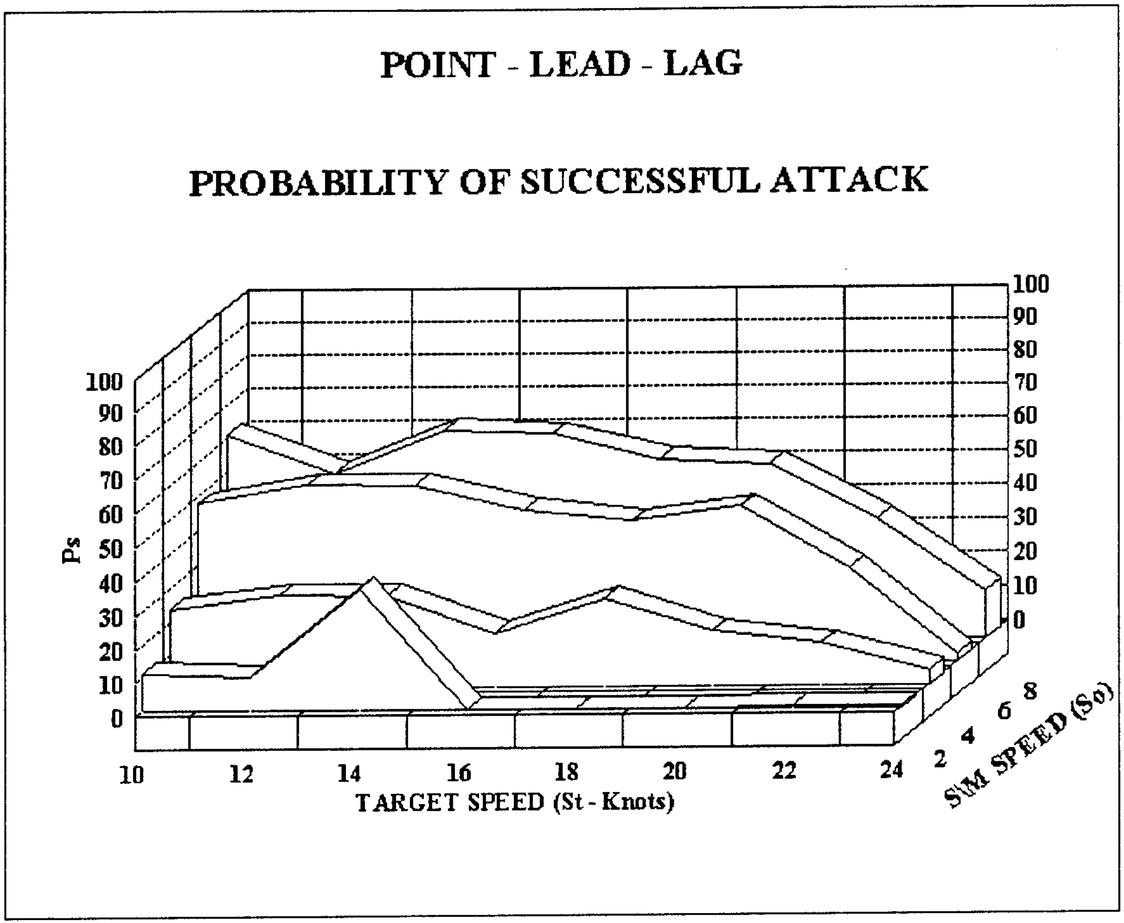

Figure 16. Ps vs St and So (P-LEAD-LAG)-(Area Plot)

Table 4 shows the 95% confidence intervals for Ps, computed as in equations 17-18-19-20. The lower and upper limits of the 95% confidence intervals for Ps, increase as submarine speed increases, with the highest values of the limits at So=8 Kn and St=14 Kn (shaded in Table 4).

So St	2		4		6		8	
	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
10	0.103	0.123	0.222	0.248	0.459	0.49	0.596	0.626
12	0.094	0.112	0.26	0.288	0.512	0.543	0.478	0.509
14	0.346	0.376	0.257	0.285	0.509	0.54	0.605	0.635
16	0	0.002	0.15	0.172	0.437	0.467	0.593	0.623
18	0	0.002	0.246	0.274	0.403	0.433	0.516	0.547
20	0	0.002	0.153	0.176	0.445	0.475	0.5	0.532
22	0.005	0.011	0.117	0.137	0.263	0.291	0.337	0.367
24	0.004	0.008	0.037	0.049	0.018	0.027	0.128	0.15

Table 4. 95% CI for Ps (P-LEAD-LAG)

E. TACTIC 4 (POINT - LAG - POINT)

In tactic 4, the initial leg is a POINT leg; the second leg is LAG 50° leg where the submarine opens the target range; and the third leg is a POINT leg (Figure 17).

The advantage of this tactic is that if the target is at a short range, the submarine opens the range, and is unlikely to find itself under the target.

The disadvantage of this tactic is, that after the LAG leg (for high submarine speed and high target speed situations), it is possible for the submarine to find itself outside the SAR, or outside the maximum torpedo range, and thus unable to continue for the next leg.

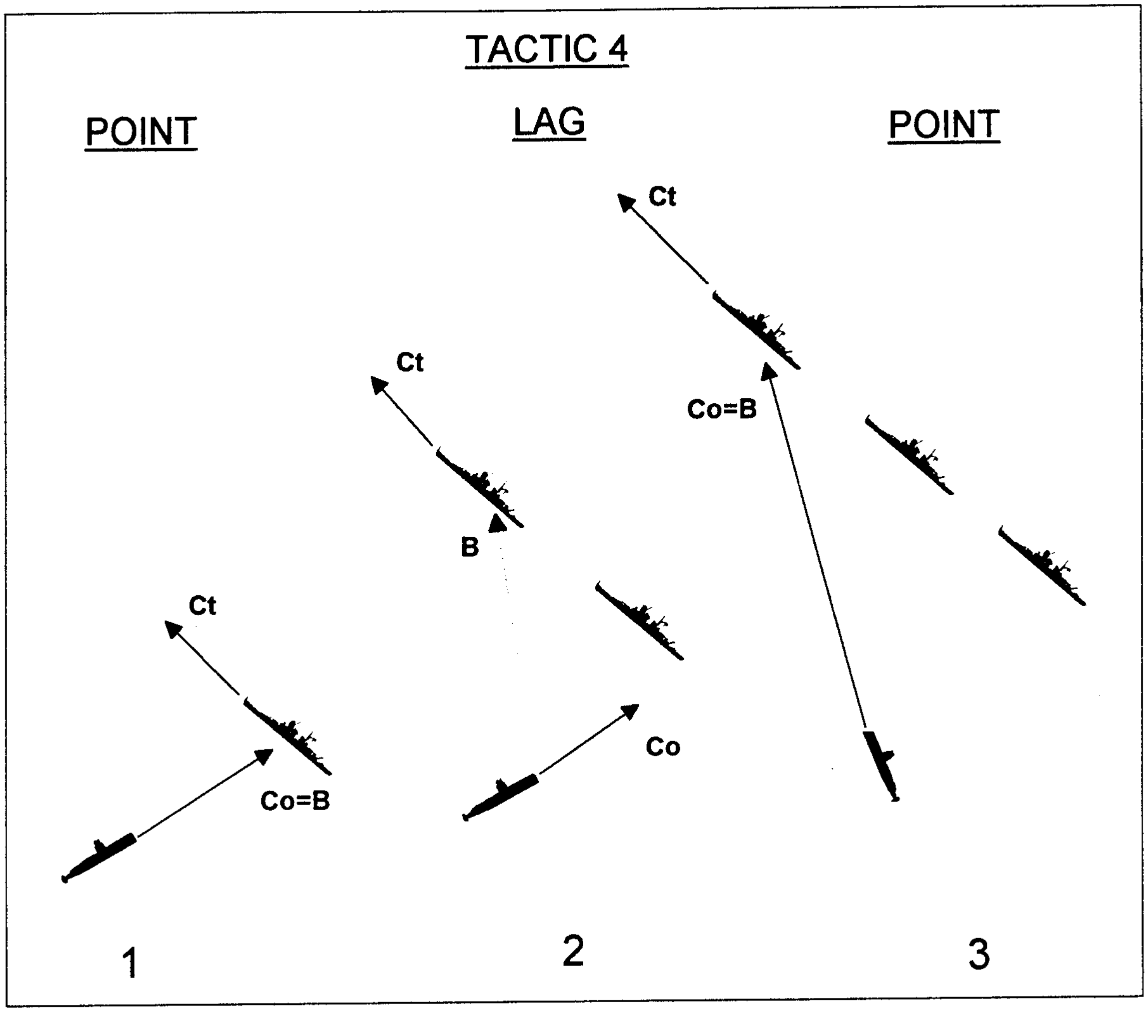

Figure 17. Geoplot (P-LAG-P)

Figure 18 shows the probability of a successful attack for each speed combination, when the tactic used is POINT-LAG-POINT. With St fixed, Ps generally increases as So increases. The high Ps of .30 appears when submarine speed So=6 Kn and target speed St=12 Kn.

For target speeds of 16-24 Kn, Ps is extremely low. This results because after the LAG leg the submarine is out of maximum torpedo range and unable to obtain a better firing position.

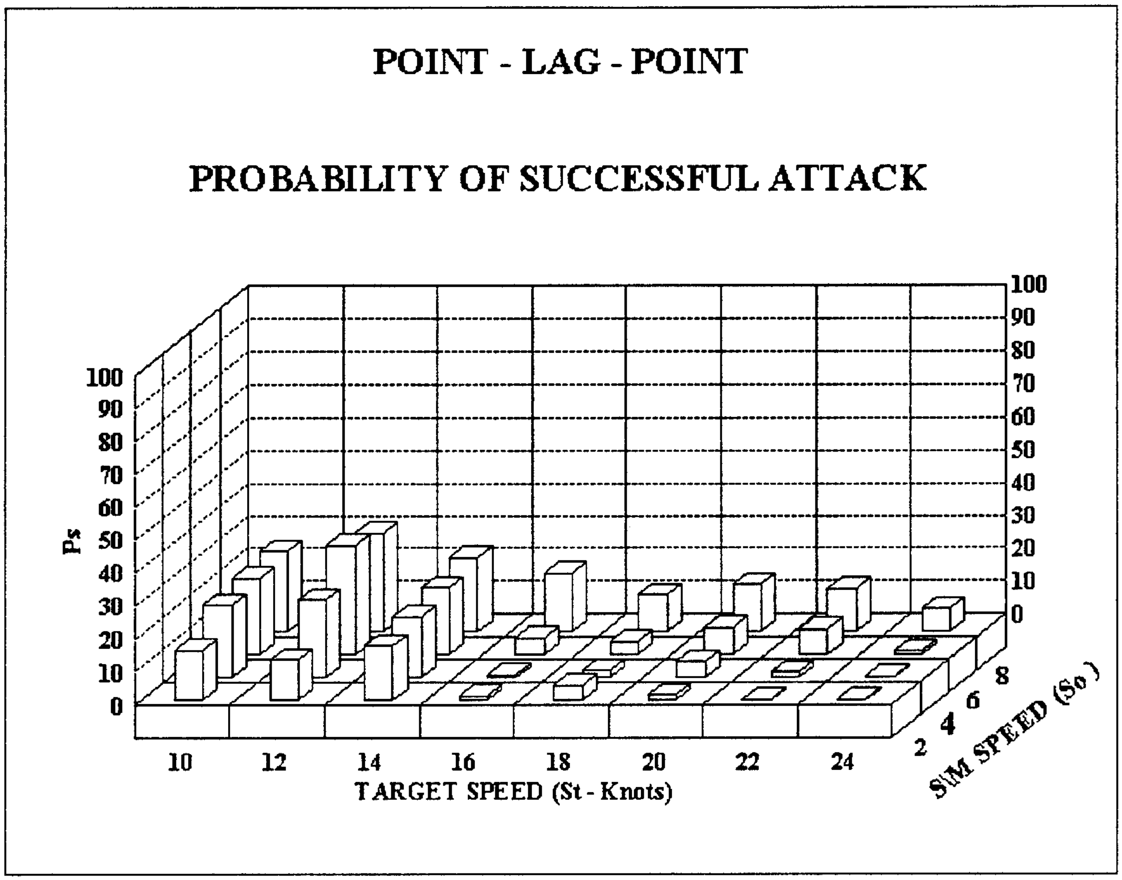

Figure 18. Ps vs St and So (P-LAG-P)-(Bar Plot)

Figure 19 shows the same data as Figure 18, presented to emphasize changes in Ps with target speed. As St increases, Ps initially increases and then decreases again. Interesting peaks occur at (St,So) equal to (14,2),(14,4),(12,6), and (12,8). The peaks occur because at slow target speeds the TMA solution is poor, and at high target speeds the submarine frequently finds itself outside either the SAR or maximum torpedo range.

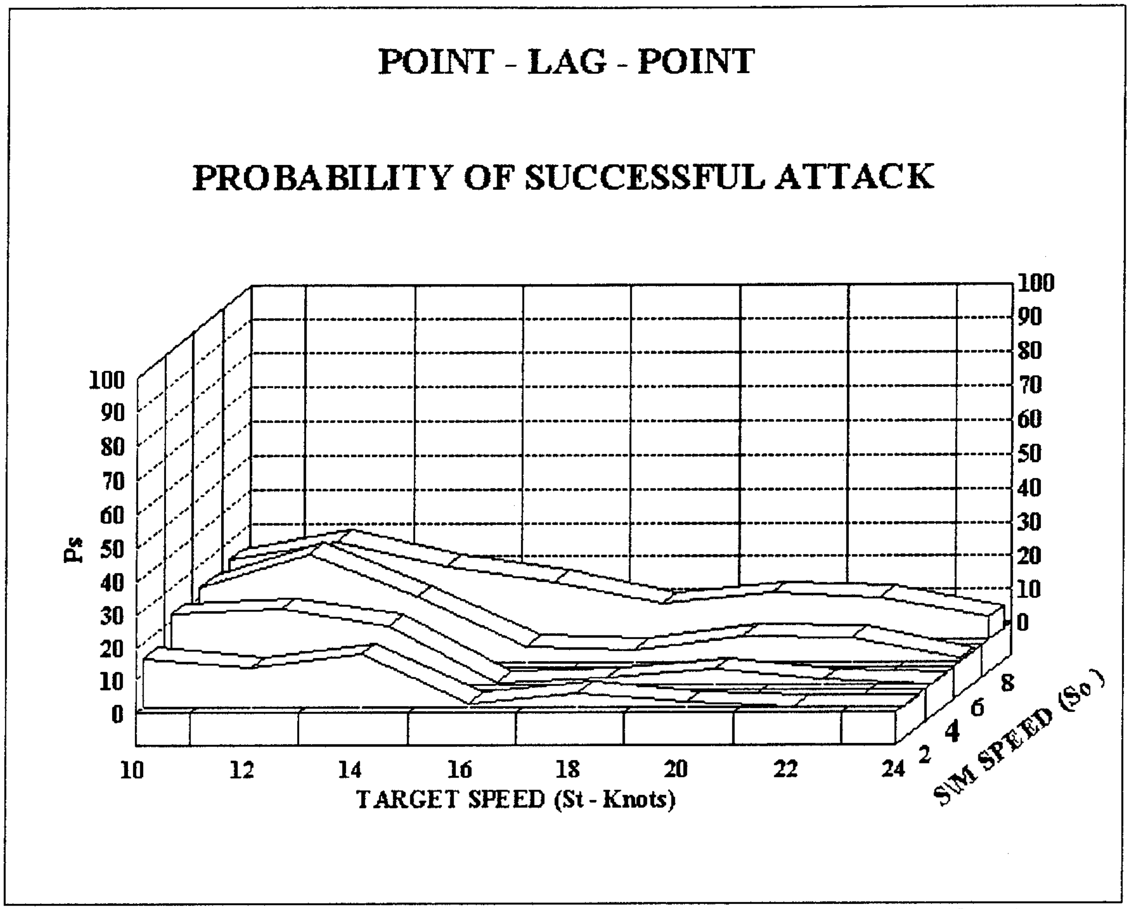

Figure 19. Ps vs St and So (P-LAG-P)-(Area Plot)

Table 5 shows the 95% confidence intervals for Ps, computed as in equations 17-18-19-20. The lower and upper limits of the 95% confidence intervals for Ps, increase as submarine speed increases, with the highest values of the limits at So=6 Kn and St=12 Kn (shaded in Table 5).

So St	2		4		6		8	
	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
10	0.139	0.161	0.202	0.228	0.215	0.241	0.229	0.255
12	0.112	0.132	0.218	0.244	0.315	0.347	0.283	0.311
14	0.151	0.173	0.169	0.193	0.188	0.212	0.212	0.238
16	0.01	0.017	0.005	0.011	0.043	0.057	0.163	0.187
18	0.038	0.05	0.016	0.024	0.032	0.044	0.1	0.12
20	0.012	0.02	0.04	0.053	0.073	0.09	0.13	0.152
22	0	0.002	0.012	0.02	0.068	0.084	0.119	0.139
24	0.001	0.003	0.001	0.003	0.007	0.013	0.061	0.077

Table 5. 95% CI for Ps (P-LAG-P)

F. RESULTS (SO,ST) UNIFORMLY DISTRIBUTED

We assume here that the submarine CO must decide which of four possible approach tactics to use, depending on the tactical situation, geographical restrictions, submarine battery charge level, estimated target speed, and initial range to the target.

The submarine CO will generally not know the target speed before starting the TMA maneuver, so one reasonable MOE to examine for each tactic is the probability of a successful attack given a specified probability distribution on target speed.

1. Ps for Uniformly Distributed St

Figure 20 shows Ps for each tactic and own ship speed assuming a target speed uniformly distributed between 10 and 24 Kn.

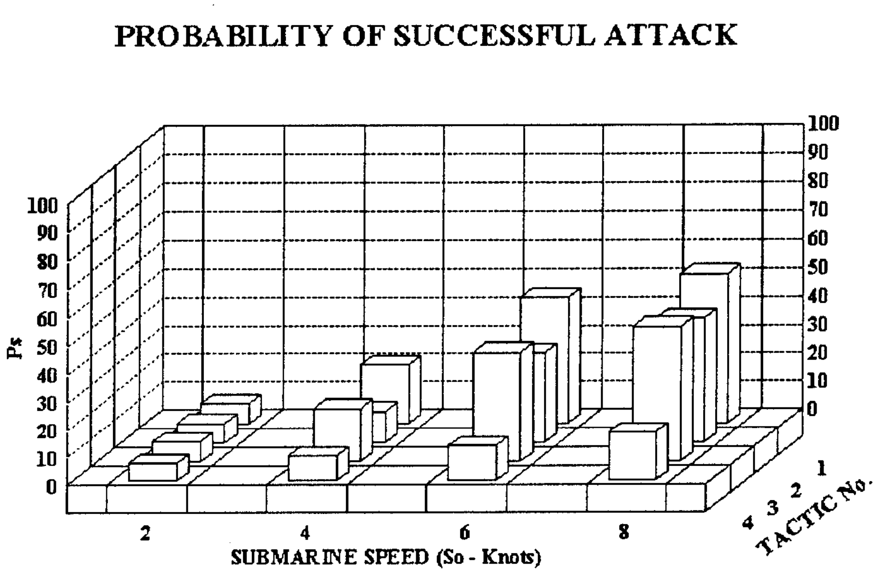

Figure 20. Ps vs So and Tactic (St~U[10,24])

Figure 21 shows the probability for the submarine to find itself outside the SAR (Po), for each tactic and own ship speed assuming a target speed uniformly distributed between 10 and 24 Kn.

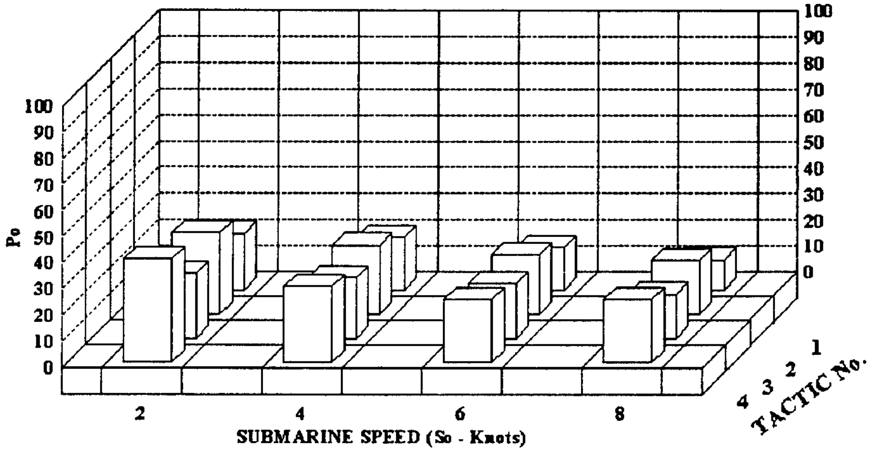

Figure 21. Po vs So and Tactic (St~U[10,24])

For So=2 Kn, Ps is extremely low for all tactics because it is very easy for the submarine to be outside the SAR. Figure 21 shows the highest Po at this speed. This results because as So decreases, the angle ψ decreases and the SAR becomes narrow (Chapter II). Also it is possible in this situation to have a poor TMA solution because of ineffective TMA legs at low submarine speeds.

As So increases, Po decreases and Ps increases with the highest Ps value at So=8 Kn. Tactic 4 has the worst Ps and the best Po values because after the lag leg, there is a point leg. This causes the submarine to have no chance to obtain a better firing position if it is outside maximum torpedo range. For tactics 1,2,3, however, Po decreases because of the lead leg.

For tactics 1,2,3 and So>2 Kn, Ps varies only slightly between tactics for the same So. Thus for the final decision, the submarine CO can almost equally choose between tactics 1,2 and 3.

2. Ps for Uniformly Distributed So

We can also look at the simulation results from the point of view of the surface ship CO, who must select a transit speed to maximize the probability of successfully passing through the SAR.

Figure 22 shows Ps vs surface ship speed (St) for each of the four submarine approach tactics and assuming a submarine speed (So) uniformly distributed between 2 and 8 Kn.

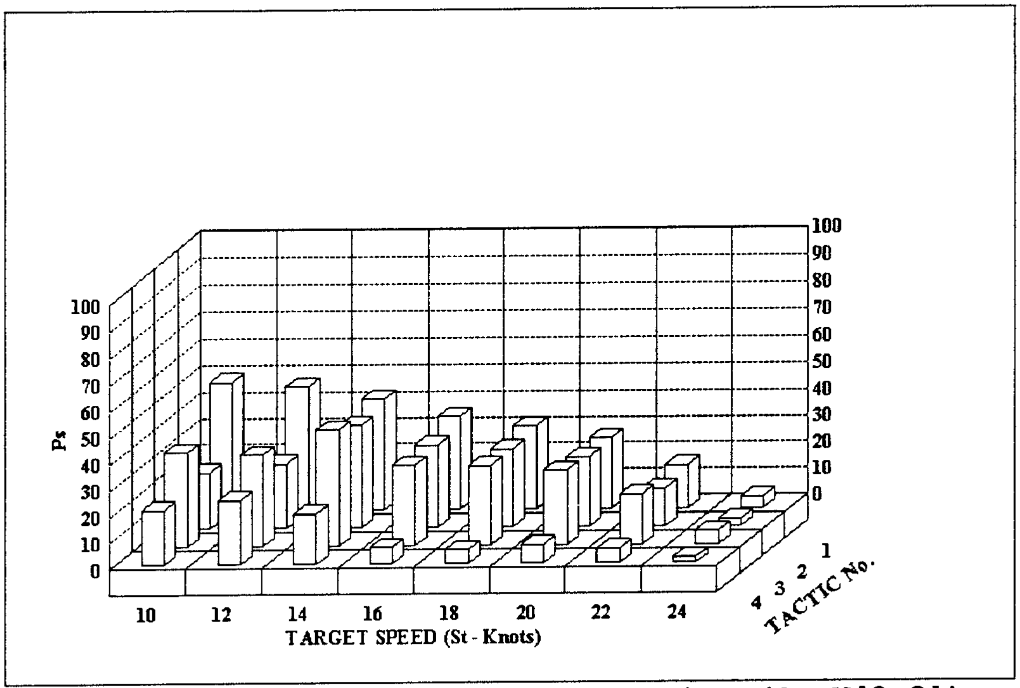

Figure 22. Ps vs St and Tactic (So~U[2,8])

Figure 23 shows the probability that the submarine finds itself outside the SAR (Po), for each tactic and surface ship speed (St) assuming a submarine speed (So) uniformly distributed between 2 and 8 Kn.

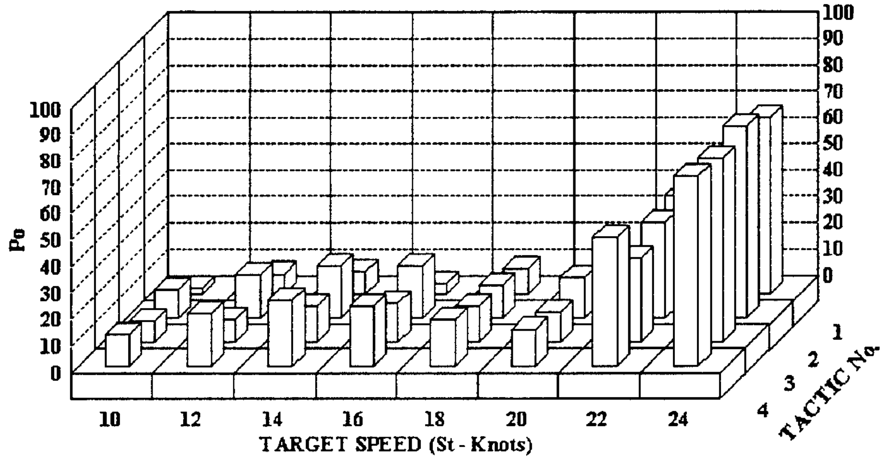

Figure 23. Po vs St and Tactic (So~U[2,8])

For St=24 Kn, 1-Ps (probability of successfuly passing through the SAR) is extremely high for all tactics, because at this target speed it is very easy for the submarine to be outside the SAR. Figure 23 shows the highest Po at this speed. This results because as St increases, angle ψ decreases and the SAR becomes narrow (Chapter II).

As St decreases, Po and 1-Ps values decrease with the highest 1-Ps value at St=24 Kn. Tactic 4 has the best 1-Ps and Po values because after the lag leg there is a point leg and there is no chance for the submarine to obtain a better firing position if it is outside maximum torpedo range.

Based on this analysis the surface ship CO should choose the highest possible transit speed, to maximize the probability of making a successful pass through the SAR.

VI. CONCLUSIONS

Submarine tactics are shaped by a combination of weapon characteristics, sensor characteristics, and the attempt to operate concealed from enemy sensors. The goal of the submarine is a successful attack and escape from ASW counter-attack.

The risk to the submarine of ASW counter-attack does not depend strongly on the TMA tactic selected by the submarine. However, the success of the submarine's attack does depend strongly on the tactic used. Each of the four tactics has advantages and disadvantages, and there are many reasons to either select or reject each tactic.

Tactic 1 gives the best results because the lead leg minimizes Po. Tactic 3 is better than tactic 2 because in tactic 2 the lag leg precedes the lead leg resulting in the submarine being often outside the SAR. Tactic 4, which has a lag leg and two point legs, has the worst results because the submarine is often outside the SAR or outside the maximum torpedo range.

Also Ps decreases as So decreases or St increases. This results because as angle ψ decreases the SAR becomes narrow, and it is easier for the submarine to be outside the SAR.

The following table summarizes the simulation results, but it is possible for other factors to change the final decision.

	So=2-4 kn	So=6-8 kn
St=10-12 kn	Tactic 1-3	Tactic 1-3
St=14-16 kn	Tactic 1-3-2	Tactic 1-3-2
St=18-20 kn	Tactic 1-2-3	Tactic 1-2-3
St=22-24 kn	Tactic 1-3-2	Tactic 1-3-2

Table 6. Tactic for St vs So

Table 6 ranks the tactics based on maximizing Ps and minimizing Po for a typical range of St and So. Tactic 1 is always preferred but there may be other considerations not captured in the simulation model which would recommend the second or third choice.

A possible continuation of this work might be a classified thesis using real data and a decision flowchart, where the final decision for the tactic used will depend on geographical or tactical constraints.

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3. Coll, Pedro F., *Target Motion Analysis from a Diesel Submarine Perspective*, Master's Thesis, Naval Postgraduate School, Monterey California, September 1994.

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