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OPTIMAL DEPLOYMENT ANGLES FOR THE AIR-DROPPED UNDERSEA WARFARE CABLE IN SHALLOW WATER

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March, 1994

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OPTIMAL DEPLOYMENT ANGLES FOR THE AIR-DROPPED UNDERSEA WARFARE CABLE IN SHALLOW WATER

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

The Advanced Air Deployable Array (AdDA) is an air-dropped undersea warfare device for detection of an enemy submarine in the shallow waters region. Previous studies have introduced six tactical deployment methods by C-130 aircraft. This thesis addresses one of the methods, called " Bound the Expanding Farthest-On Circle". Changes in deployment rules are suggested, and feasibility conditions identified. A model is developed showing how the isolation area where the submarine is to be contained, and the number of needed array segments, can be reduced. Also, as the main work of this study, the effective deployment angles for successive AdDA cable are determined for C-130 pilots. Today these cables, because of their advantages and great utility, can give unique solutions in shallow water tactical operations.

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I would like to dedicate this thesis to my wife Penelope and my daughter Maria for their support and understanding during all this period. To conclude with, I would like to thank the Hellenic Navy for giving me this unique opportunity to be a student at the Naval Postgraduate School.

EXECUTIVE SUMMARY

Much of the water surrounding Crete and other Greek islands is shallow, and defense against submarines in these shallow waters is important. The Advanced Air Deployable Array (AdDA), which is an air-dropped undersea warfare device for detection of an enemy submarine in the shallow waters region, can be used in this area.

Previous studies proposed six different tactical deployment options for the AdDA and explored the effects of the depth in the AdDA deployment area. These studies assumed that the aircraft's transit time, to the point where the deployment of the first array segment begins, depended on the fixed distance between the airbase and the last known location of the submarine (datum point). This limited study of the performance of the AdDA deployment methods. Important results, such as the deployment starting point, the area in which the target is bounded by the deployed cables, and the number of needed AdDA segments, depend on transit time, and the set of the feasible solutions was restricted.

The current study modifies one of these tactics, called the "Bound the Expanding Farthest-On Circle" tactic. In this method array segments are deployed successively so as to bound the current progress of the target with activated detection devices. The resulting barrier has approximately the shape

of a portion of a spiral, and the deployment method may be described as providing rapid containment of the target. It is shown that relaxation of the previous requirement for positioning the first-laid cable segment can reduce the area of containment and the number of segments required. A model is developed determining the distance between the airbase and the point where the deployment of the first array segment begins. This is expanded so that the aircraft's transit time to the target, target speed, the aircraft's cruising speed, the deployment and sinking times for an array segment, and the distance between the airbase and the last known location of the target, can be varied.

In the "Bound the Expanding Farthest-On Circle" tactic, successive cables are deployed at an angle from each other at increasing distances from the datum point, forming a polygon. These angles represent course changes for the deploying aircraft, and were not considered during the previous work. The current study shows how these angles may be computed for use by deploying aircraft. These angles also provide a basis to determine the area in which the target is bounded by the cables, and the number of the needed array segments. Here the feasibility of the tactic depends on the aircraft course changes, and the analysis of this tactical deployment method shows how feasible aircraft flying patterns may be specified.

Today, the AdDA cable offers unique solutions in solving some of the problems in the shallow water area of Greece or other nations.

I. INTRODUCTION

In this chapter: a small briefing about the geographical position of Greece will be given; we will give the definition of the shallow-water defense-zone border line, as it was defined by the Air Defense Initiative Architecture for military applications; a general discussion of the nature of the shallow-water sensor deployment problem will be provided; and finally we will describe the purpose of this thesis.

A. THE STRATEGIC SIGNIFICANCE OF GREECE

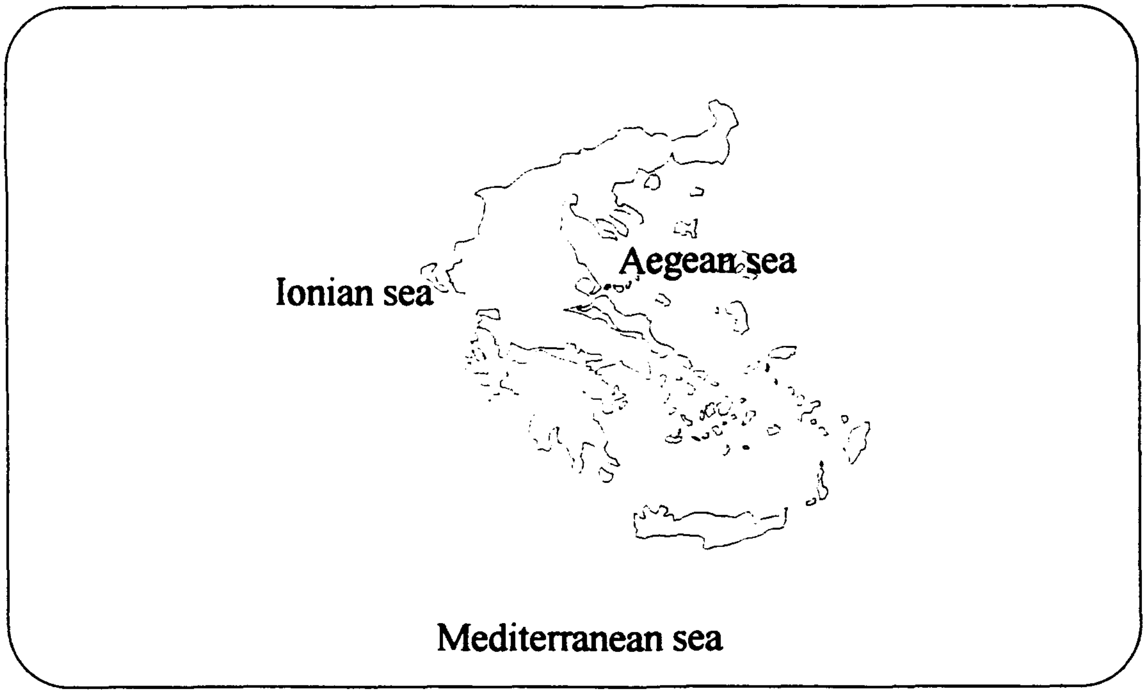

Figure 1. Greece and the shallow waters around it.

Located in southern Europe, on the southern tip of the Balkans Peninsula, Greece is bounded on the north by Albania, Yugoslavia and Bulgaria, on the east by Turkey and the Aegean Sea, and on the south and west by the Sea of Crete and the Ionian Sea. More than 2000 Greek islands lie scattered in the surrounding seas, ranging from small, barren rocks to Crete, the fifth largest island in the Mediterranean Sea. A fact worth noting is that the shallow waters around Crete are among the USN Mediterranean fleet's most useful and long-standing anchorages.

By virtue of the geographical position, Greece is the geostrategic link between Europe and the Middle East, two highly sensitive areas in terms of international security. International peace has often been endangered by events in this region, which is important in major Middle East crises. Greece had a particularly significant strategic value throughout the WW II period, even though its nature may gradually have changed. The shift of the center of gravity of the East-West confrontation from the land frontier in southeast Europe to the Mediterranean has had a marked effect on the strategic value of Greece, and the Aegean Sea has emerged as a strategic zone of particular significance.

Another fact worth noting is that developments of the 1960s in the field of naval strategy raised once more the significance of Greece and the surrounding area. The continued deployment of submarines in the Mediterranean make this area highly important in the confrontation between

East and West, because it is considered a safe patrol area for these submarines.

B. THE SHALLOW WATER DEFENSE ZONE (SWDZ)

Undersea warfare operations and tactics vary according to ocean depth, and in the Mediterranean, shallow water operations are of particular importance. The "shallow water defense zone border line " was initially defined as a boundary for water of 100 fathoms (600 feet) or less in depth. Later, due to the new Air Defense Initiative Architecture, the definition changed. Today " shallow water, " for military application, is the water of 200 fathoms (1200 feet) or less in depth [Ref.1:p.4]. With this definition, much of the water of Aegean Sea and Ionian Sea is shallow. Also, the water of many areas of the Sea of Crete is shallow. Undersea warfare operations in such shallow water form the subject of this thesis.

C. NATURE OF THE PROBLEM

Submarines are of major importance in any country's defense policy, in both their torpedo and cruise missile attack role, and in their strategic nuclear deterrence role. Many specific undersea warfare problems can be narrowed to a series of consecutive events designed to counter a submarine's wartime threat. These events are

1. the initial detection,

2. the localization of an ocean area sufficiently small as to permit effective action and,

3. the submarine's destruction.

It is obvious that a very high probability of success in the detection and localization is necessary in order to handle the problem effectively. Certainty a low probability of success in any one area will seriously affect the overall undersea warfare capability.

Once we know the general area in which a submarine is operating, a variety of techniques are available to localize the submarine contact so that it can be monitored or destroyed. For example, in deep water, a ship's sonar is an effective means of locating submarines, within a limited area, and in shallow water, fiber-optic cables offer considerable potential as a means of localizing an intruding submarine. A system receiving current attention is the Advanced Air Deployable Array (AdDA), which is an air-dropped fiber-optic undersea warfare device for detection of an enemy submarine in shallow waters.

Very little is known about effective methods to deploy AdDA cables. An initial investigation of alternative deployment methods has been undertaken at the Naval Postgraduate School [Ref.1,2]. These studies have found six tactical deployment options and have explored several environment factors, including the effects of deployment depth. It is the objective of this thesis to examine one of these tactics, which shows considerable promise, in detail, and extend the findings of these studies through a model that allows added realism and greater utility. We will develop a model which allows the specification of aircraft course changes during cable deployment, as well as pinpointing the first cable's location. As we will show, the latter should depend on the constraints of the pattern as well as target location. Some results in the performance of the deployment tactic will be given as a function of our mathematical model. A similar analysis should be performed for each of the other five tactics, but such an analysis is beyond the scope of this thesis.

D. THIS THESIS.

In the following chapter we will describe the Advanced Air Deployable Array and summarize previous work that has been done on methods for its deployment. In order to aid the reader, some terms will be introduced.

Of the six tactical deployment methods which have been introduced, a single-aircraft method called "Bound the Expanding Farthest-On Circle" shows a great deal of promise in terms of minimizing the area in which a previously detected target is bounded by the cables. We will study this approach in depth in Chapter IV, showing how specific aircraft flying patterns may be determined. This will provide guidance for pilots.

In the last chapter we will discuss the basic conclusions and new findings that have resulted from this work. We will also give recommendations for further analysis which will expand our knowledge of cable deployment tactics.

II. OPTICAL FIBER SENSORS AND THEIR DEPLOYMENT

Over the last decade, a significant non-communication application for optical fibers has emerged. This new application involves the use of optical fibers as sensors, and the potential use of optical fibers as acoustic, magnetic, temperature, strain, and acceleration sensors has recently led to research with significant potential payoff.

In this chapter we will give a general description of optical fiber cables and their advantages, with emphasis on the Advanced Air Deployable Array (AdDA).

To help the reader become more familiar with the way the AdDA segments are deployed, we will introduce a general deployment technique with the Hercules C-130. Then, we will summarize some work of previous studies pertinent to the six tactical deployment options for the AdDA.

A. OPTICAL FIBER SENSORS - ADVANTAGES.

Optical fiber cables are being developed for tactical field use because of the advantages they offer. They can support a greater variety of users than a conventional copper wire cable. Their advantages include

1. easy deployment due to a small diameter and light weight,
2. a long lifetime (30 -90 days continuous),
3. their immunity to electromagnetic interference and electromagnetic pulse,
4. transmission security, and

5. the capability for transmitting wide-band signals over many miles without repeaters [Ref.4].

For many applications, these advantages result in lower acquisition and operational costs of fiber optic cables, as well as enhanced operational capabilities.

The Advanced Air Deployable Array, which was designed for submarine detection in shallow water, has all the above advantages, and additionally, the probability of detection for each element of the array is high [Ref.2:p.9].

B. DEPLOYMENT TECHNIQUE

For this study, it is assumed that the cables are deployed from the rear cargo door of a Hercules C-130, which is open during the deployment of the cables.

The maximum aircraft's speed, while deploying AdDA segments, is about 125 kts (deployment speed), and the maximum number of AdDA segments it can carry is taken as twelve. After deployment of an AdDA segment it takes a bit of time for the segment to sink to the sea floor, where it becomes an active sensor. For an array, the sinking rate has been estimated as 0.024 fathoms / second [Ref.1:p.23]. As the cable is being deployed, it is assumed it forms a straight line from the aircraft to the sea surface, and another from the sea surface to the sea floor. In the air the angle that the cable makes with the horizontal depends on the ratio of the cable sink rate to the aircraft lay speed. Studies have indicated that cross winds create no increase in cable tension. However, when the system is laid on the sea floor, the cable's specific gravity must be sufficient to ensure that it remains stationary on the bottom in undersea currents. [Ref.3]

C. PREVIOUS WORK

The last two studies examined the effects of various deployment tactics of the AdDA segments on the localization an enemy submarine in shallow water.

The thesis by Aktan...

"...explores the effects of the deployment depth, and the effect of using longer or shorter AdDA segments, on the performance of the six proposed AdDA deployments tactics which employ single or dual aircraft" [Ref.1:p.iii].

The thesis by Ferguson...

"...explores the effects of deploying this ASW sensor, together with complementary sensors, on the probability of detecting a submarine in the shallow water area". [Ref.2:p.iii].

In both studies two different deployment platforms were compared (the fixed-wing C-130 and the CH-53 helicopter), using three measures of effectiveness that are listed below [Ref.2:p.11-12].

1. <u>THE AREA OF ISOLATION</u>
is a measure of performance, since it is desirable to isolate the enemy submarine in the shallow water defense zone in an area as small as possible.

2. <u>THE NUMBER OF ARRAYS REQUIRED</u>
is a measure of cost, and the number of array segments will differ due to the AdDA deployment tactic that is used.

3. <u>THE ISOLATION EFFICIENCY</u>
is a measure that was sought to combine the area of isolation and the number of arrays required to isolate the area. The isolation efficiency

coefficient displays a measure of increasing effectiveness as its value increases. This MOE will be addressed as Isolation Efficiency (IE) in this thesis and is given in equation form as:

$$IE = \left(\frac{1}{(Isolation\ Area) \times (Number\ of\ Arrays\ Required)}\right) \times 1000.$$

D. PROPOSED ADDA DEPLOYMENT TACTICS

In the last two studies, six deployment tactics for the AdDA were discussed using two different types of deployment platforms, the C-130 and the CH-53. Also, according to the number of deployment platforms, these tactics were classified as dual or single deployment tactics [Ref.2:p.13].

The six deployment tactics are:

- Arbitrary 50 nautical miles placement (for both single and dual aircraft),
- Box the Farthest - on Region (for both single and dual aircraft),
- Bound the Expanding Farthest - on Circle (for single aircraft),
- Rapid Enclosure of the Farthest - on Region (for dual aircraft),
- Deep Water Envelope Parallel Enclosure (for dual aircraft), and
- Triangular Cap (for dual aircraft).

These deployment tactics will be described in the following sections. In their graphical representations which follow, the last known location of the enemy submarine is called the datum. This point is assumed to be on a straight line which is parallel to the coast line and tangent to the 200 fathom curve. This is called the shallow water defense zone border line (SWDZBL). It is also assumed that the deep water undersea warfare assets did not lose contact with the enemy submarine until it is on the SWDZBL [Ref.1:p.11]. The point where the deployment of the first AdDA segment takes place is called the deployment starting point S and it can be on the shallow water defense zone border line or not, according to the tactic used.

1. The Arbitrary 50 n.m. Placement tactic.

In the previous theses, the "Arbitrary 50 n. m." tactic was proposed as either a single or dual aircraft deployment tactic. For a single plane, this tactic is summarized as follows [Ref.2:p.14]:

a. The plane flies from the base to the closest of the two starting points on the SWDZBL 50 nautical miles away from the datum.

b. The plane starts shallow water deployment of its first AdDA segment on a course perpendicular to the SWDZBL, and continues deploying array segments until the entire width of the shallow water defense zone border line is spanned.

c. After the last AdDA segment is deployed on this course, the plane flies to the second starting point. This is again on the shallow water defense zone and 50 n. m. away from the last known location of the submarine the opposite side from the initial starting point. The plane then deploys the AdDA segments in the same manner as it did the first set of cables.

Figure 2 is a graphical representation of this tactic for a single plane.

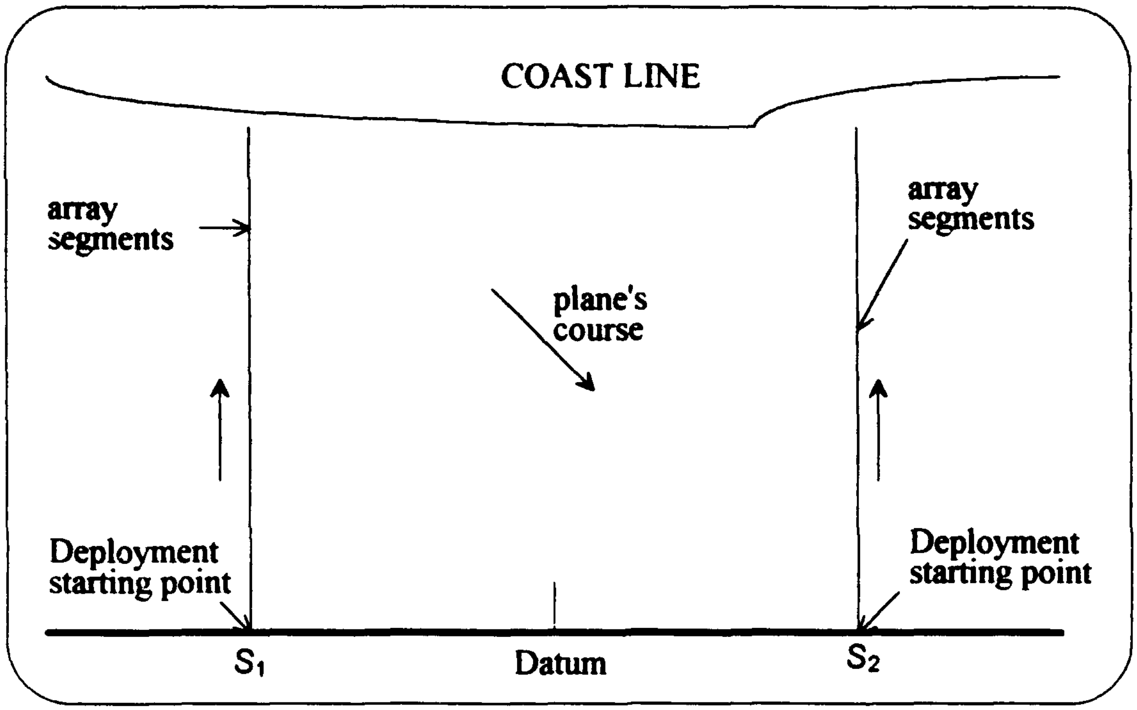

Figure 2. The " Arbitrary 50 n.m." tactic for a single plane.

For dual aircraft, the planes arrive at their starting points S, which are on the SWDZBL 50 n.m. away from datum in opposite directions. Then they deploy AdDA segments on a course perpendicular to the SWDZBL, until the width W of the SWDZ is spanned. [Ref.2:p.15]

A graphical representation of this tactic for dual aircraft is given in Figure 3.

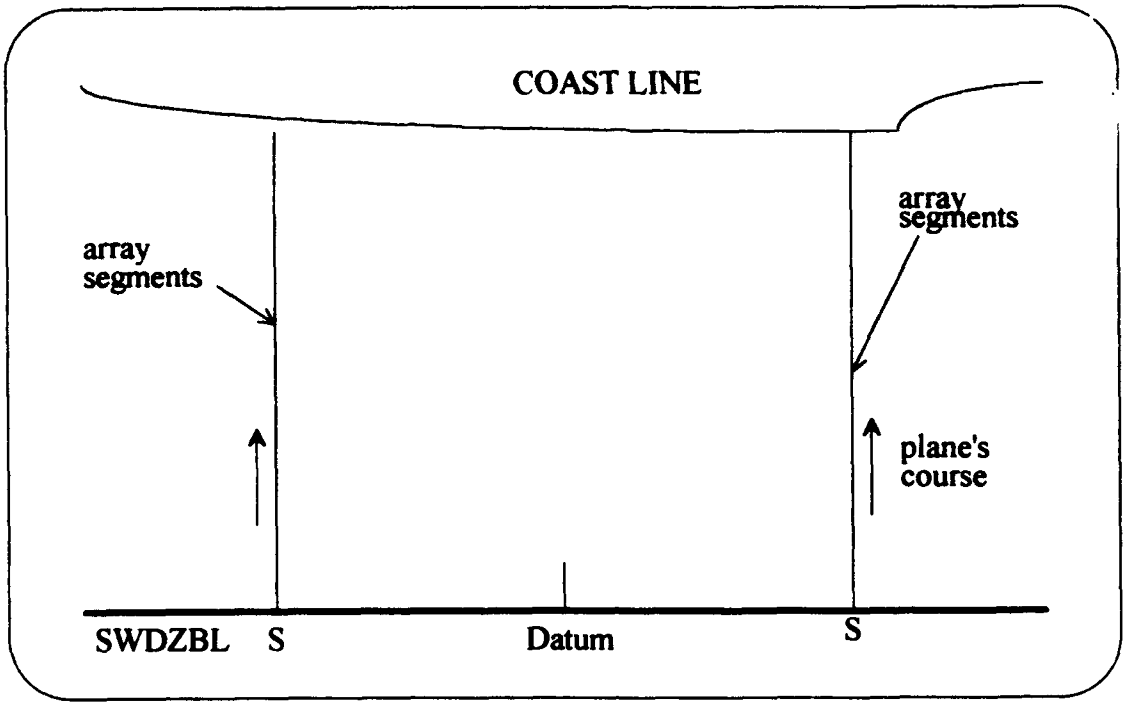

Figure 3. The "Arbitrary 50 n.m." tactic for dual aircraft.

2. Box the Farthest - on Region

The " Box the Farthest-on Region " tactic was also proposed for both single and dual aircraft and is similar to the previous deployment tactic. For a single aircraft, the distances D_0 and D_4 between the starting points S_1 and S_2 and the datum are not equal to each other, and each may be different than 50 n.m. The closest to the datum is starting point S_1, which is on the SWDZBL as far from datum as the maximum distance that could be traveled by the submarine before the deployment and activation of the first AdDA segment are completed. The plane flies from the base to starting point S_1 and begins deploying the first set of array segments on a course perpendicular to the SWDZBL. It then flies to the second starting point S_2, on the SWDZBL on the opposite side from the initial starting point, and deploys AdDA segments in the same manner as it did the first set of cables. Location of the second starting point S_2 must take into consideration the distance D_4 that the submarine could travel in this direction from the time it reaches the SWDZBL, until the first AdDA segment from this point is activated. A graphical representation of this deployment tactic is given in Figure 4 [Ref.1:p.13].

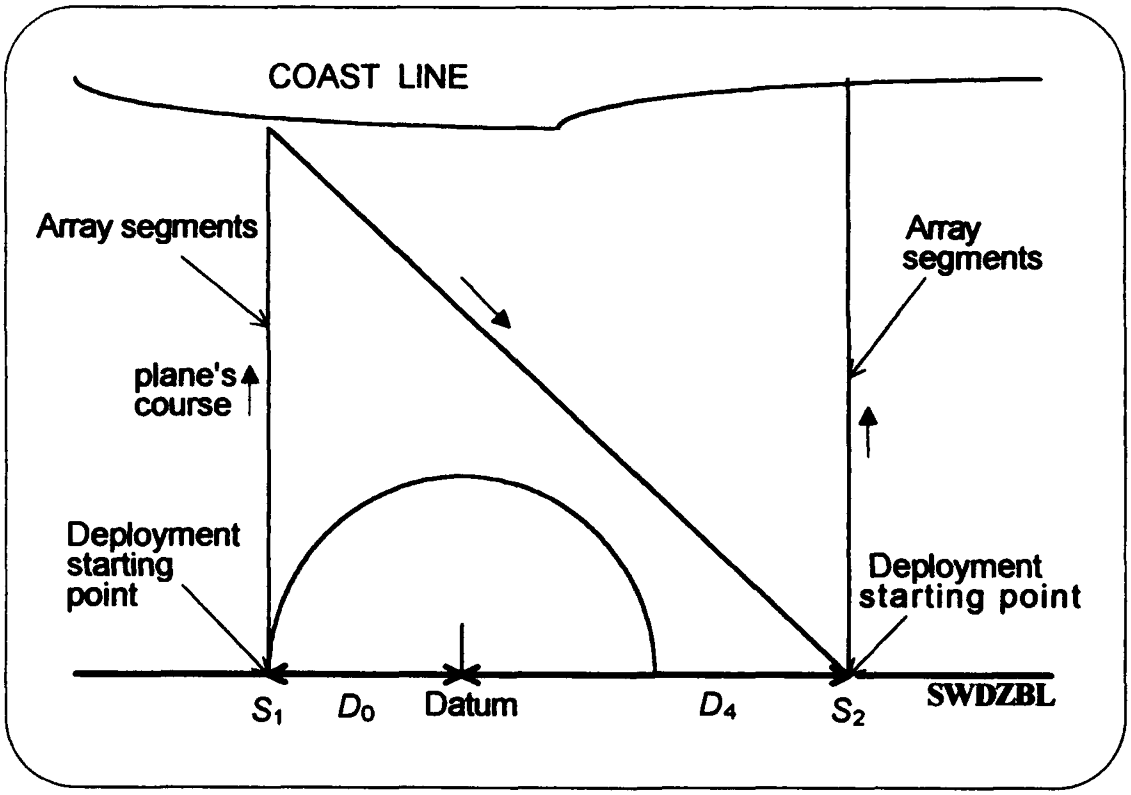

Figure 4. The "Box the Farthest -On Region" tactic for a single plane.

For dual aircraft, the planes arrive at their starting points S_1 and S_2 which are on the SWDZBL in equal distances D_1 and D_2 from the datum and in opposite directions. Then each plane deploys a set of AdDA segments on a course parallel to the SWDZBL, as shown in Figure 5 [Ref.2:p.16].

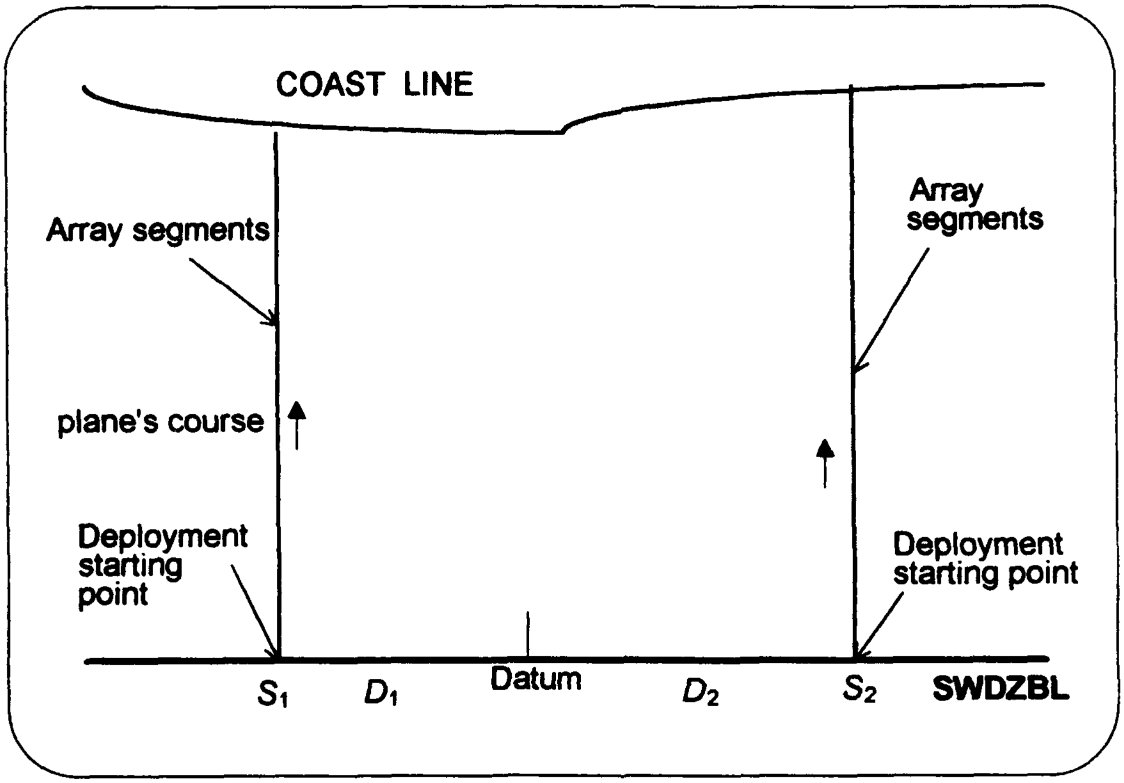

Figure 5. The " Box the Farthest - On Region " tactic for dual aircraft.

3. Bound the Expanding Farthest-On Circle.

The bound the Expanding Farthest on circle tactic was only proposed for a single aircraft and can be summarized as follows [Ref.1:p.32-33], [Ref.2:p.16-17].

a. The plane flies from the airbase to the array deployment starting point S. The distance D_0 between the starting point S and datum is the maximum distance the submarine could travel during the aircraft flight to its starting point S, and the time until the activation of the first array segment.

b. The n^{th} farthest-on circle represents the greatest possible distance from the datum that could be traveled by the submarine during the aircraft's flight to its starting point S and the activation (deploying and sinking) of (n+1) array segments. If we denote the AdDA cable length as L, the submarine speed as S_e, the flight time from the base to the starting point S as T_S, and the times for deploying and sinking to the sea floor of one AdDA segment as T_d and T_{SK}, respectively, then the radius D_n of the n^{th} farthest on circle of the submarine is given by,

$$D_n = S_e(T_S + T_d(n+1) + T_{SK}),\ n = 0,1,2,3,\ldots$$

c. The first array segment will be deployed perpendicular to the shallow water defense zone border line (SWDZBL).

d. After the deployment of the first array segment, the rest of the AdDA segments will be deployed so that the end of the n^{th} array will be a point on the $(n+2)^{nd}$ farthest-on circle.

A graphical representation of this deployment tactic is given in Figure 6.

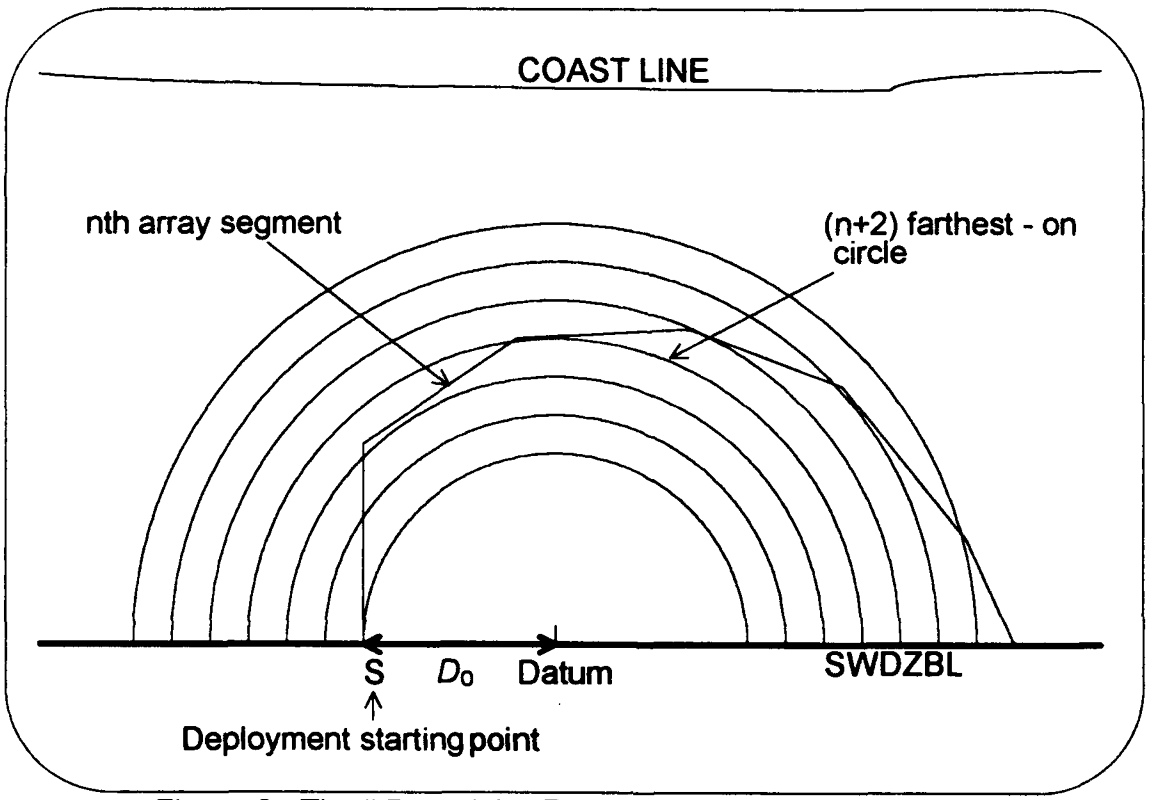

Figure 6. The " Bound the Expanding Farthest - On Circle " tactic.

4. Rapid Enclosure of the Farthest - On Region

The tactic " Rapid Enclosure of the Farthest - on Region " was only proposed for dual aircraft and is summarized as follows [Ref. 2 : p.18].

a. Both planes fly at the same time at their deployment starting points located on the SWDZBL at a distance D_0 from the last known location (datum) of the submarine.

b. The planes begin to deploy array segments perpendicular to the shallow water defense zone border line (SWDZBL).

c. At a predetermined point, the planes cease deploying AdDA segments perpendicular to the shallow water defense zone border line (SWDZBL) and begin deployment parallel to the shallow water defense zone border line (SWDZBL), completing deployment by meeting or overlapping cables before the submarine could reach this barrier.

Figure 7 shows a graphical representation of this deployment tactic.

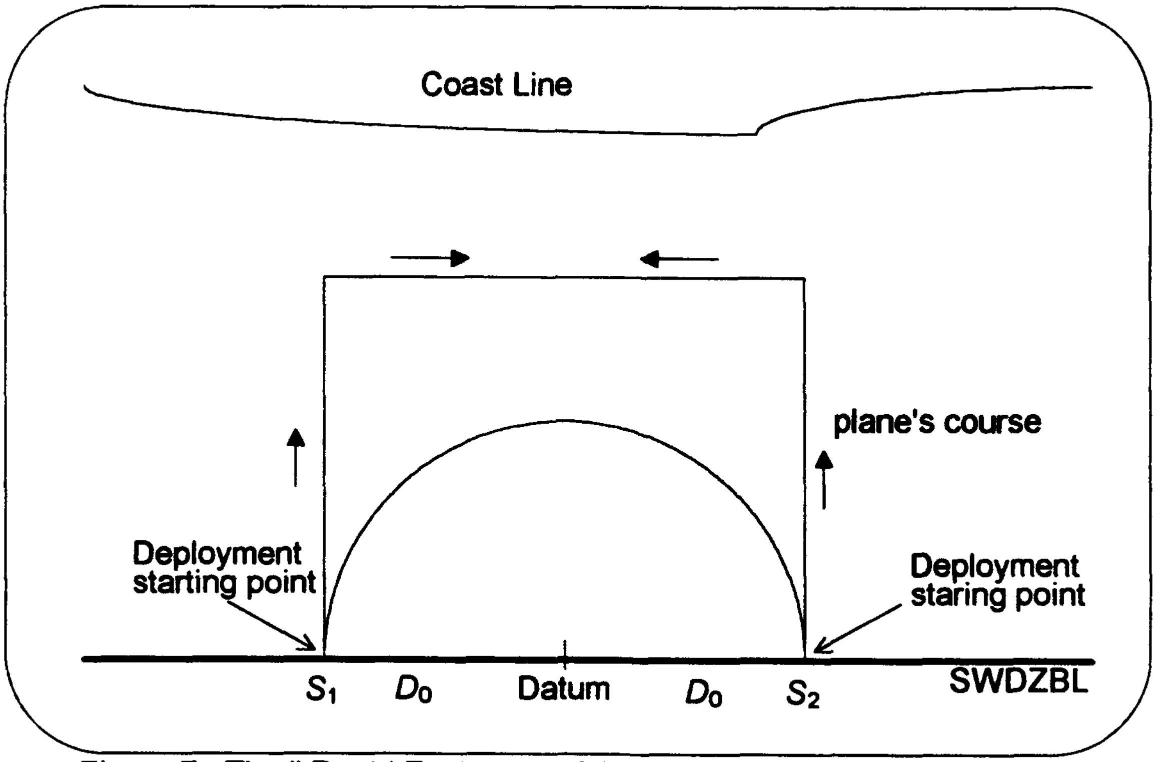

Figure 7. The " Rapid Enclosure of the Farthest - On Region " tactic.

5. Deep Water Parallel Enclosure

The "Deep Water Parallel Enclosure" tactic is also for dual aircraft. The starting point S for this tactic is not on the SWDZBL. It is on the intersection of the initial farthest - on circle and the line drawn from datum, perpendicular to the shallow water defense zone border line (SWDZBL). Each plane begins deploying AdDA segments from this point, parallel to the shallow water defense zone border line, and in opposite directions. At a predetermined point, the planes cease deploying AdDA segments parallel to the SWDZBL and begin deployment approaching the SWDZBL, to enclose the farthest possible progression of the submarine [Ref.2:p.19-20]. Figure 8 displays a graphical representation of this tactic.

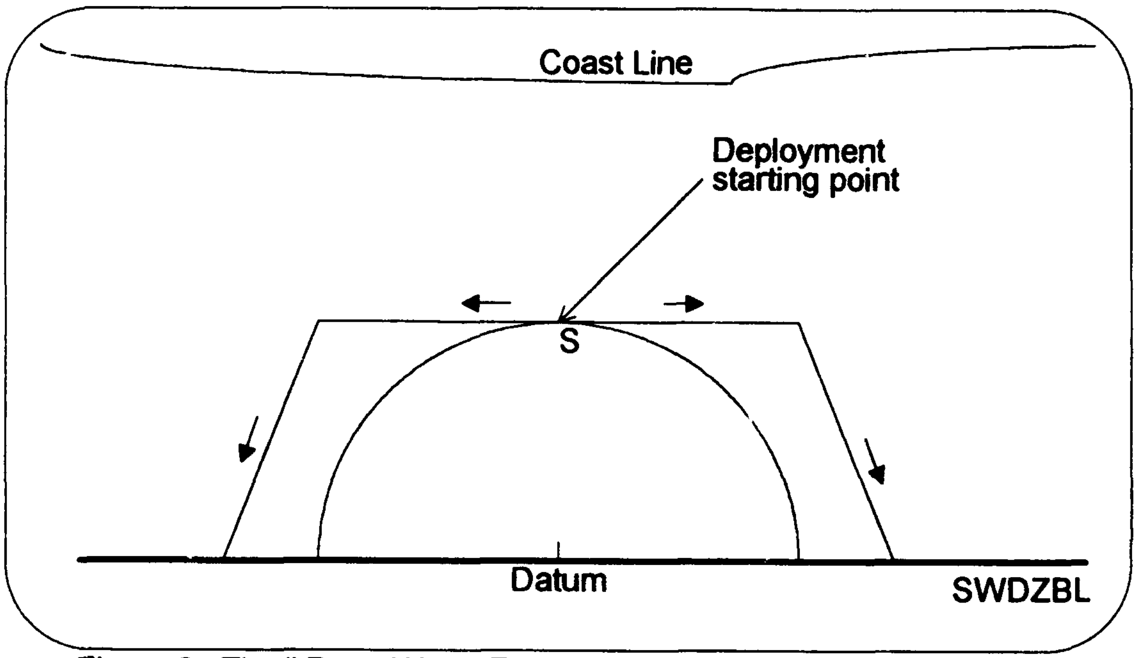

Figure 8. The " Deep Water Envelope Parallel Enclosure " tactic.

6. Triangular Cap (Tricap)

The triangular Cap tactic is also a dual aircraft tactic. The starting point S lies at a point on the line from datum perpendicular to the shallow water defense zone border line (SWDZBL). This point is far enough from datum that after the planes reach the point S, and begin to deploy AdDA segments, an isosceles triangle is formed which encloses the target's advance [Ref.2:p.21]. Figure 9 is a graphical representation of this tactic.

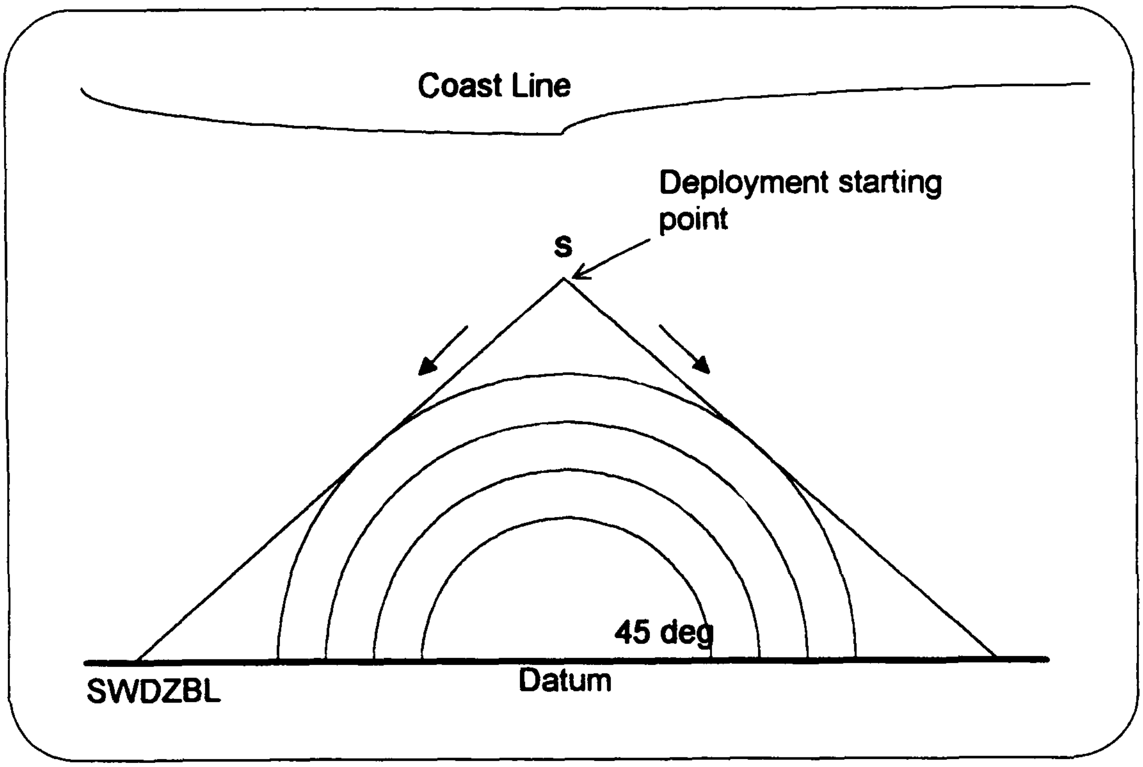

Figure 9. The "Triangular Cap (Tricap)" tactic.

E. THE NEXT CHAPTER

When these tactics were considered in the past, it was assumed that the aircraft's transit time to the deployment starting point depended only on the aircraft's speed and the distance between the base of the planes and the datum, which was 300 n.m. In the next chapter we will discuss the transit time and develop a mathematical model by which this time will be related to the maximum target speed S_e , the aircraft's cruising speed to the deployment starting point, and the activation time for an array segment, as well as the distance between the base and the datum.

III. TRANSIT TIME TO THE DEPLOYMENT STARTING POINT

In this chapter we will determine a mathematical model that can be used to find the aircraft's transit time to the deployment starting point, which is an important parameter in the analysis of the deployment methods. By knowing this time and other values characterizing a deployment scenario, we can find the isolation areas, the number of needed AdDA cables , and finally the deployment angles which determine course changes for the aircraft deploying the cable segments.

A. PARAMETERIZING THE DISTANCE TO THE AIRBASE

An assumption made in the previous studies was that for all the deployment tactics, the distance between the planes' base and datum was fixed at 300 n.m. [Ref.2: p.34]. In reality this distance may not be 300 n.m., and the value will influence the execution of a tactic and in some cases, the tactic's feasibility. In the current study (in order to overcome this restriction) we will let the distance between the base and the datum be d_D, which may be different than 300 nautical miles. Figure 10 is a graphical representation for the case of three deployment tactics, as they were described in Chapter II, and Figure 11 is for the last two deployment tactics, as they were described in the same chapter.

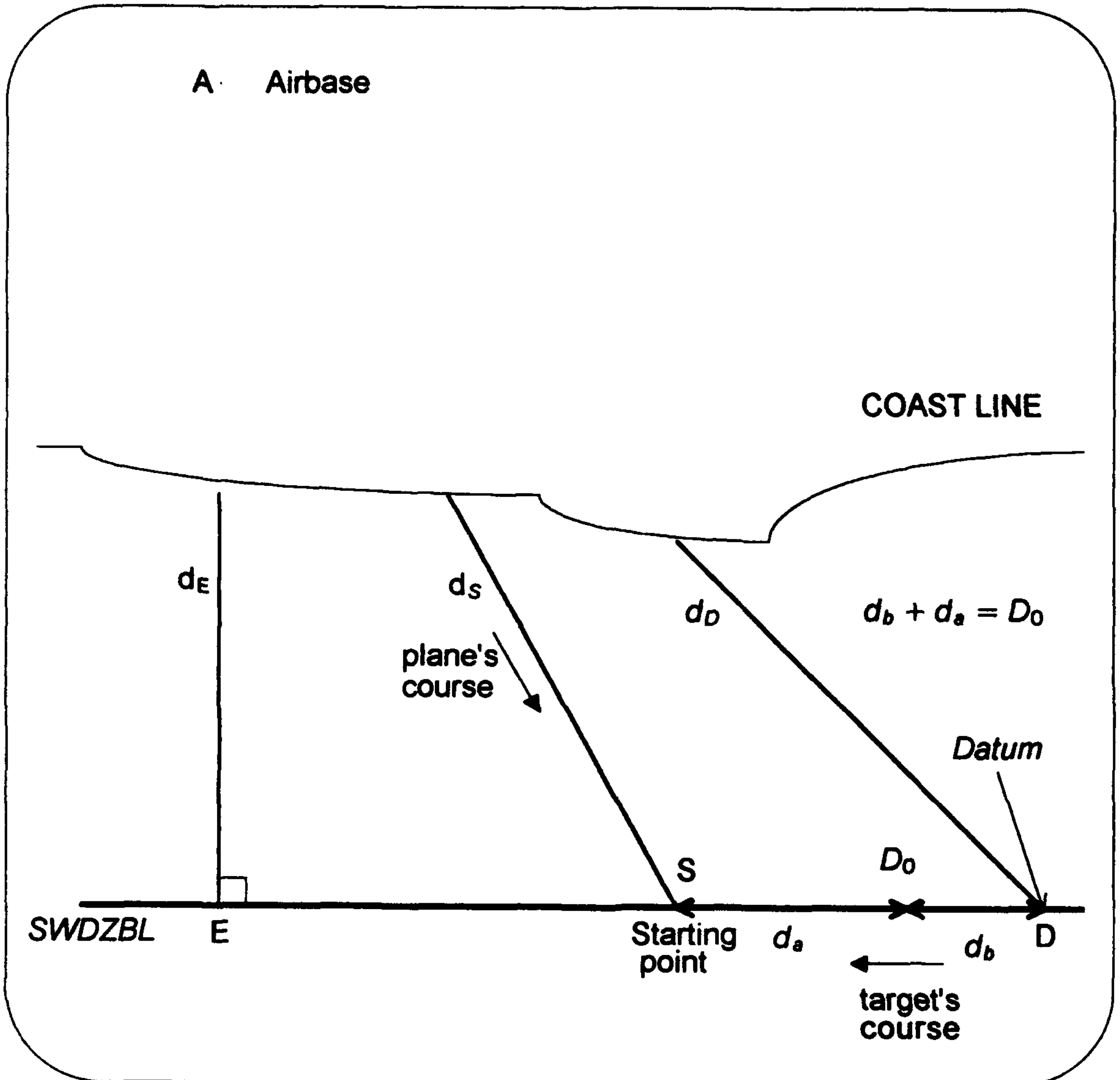

Figure 10. Placement of the first AdDA segment, when the starting point is on the SWDZBL.

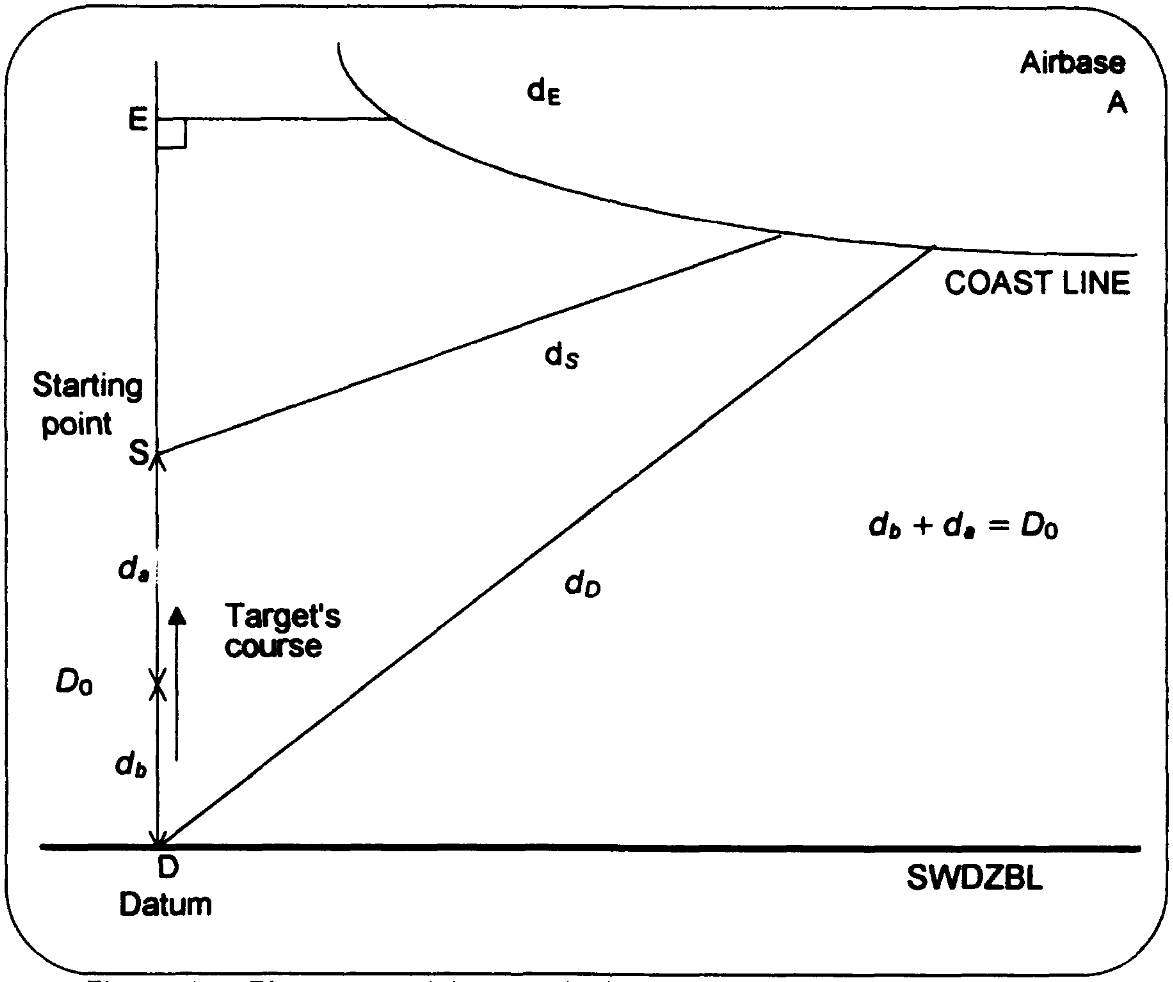

Figure 11. Placement of the first AdDA segment, when the starting point is **not** on the SWDZBL.

B. FINDING THE DEPLOYMENT STARTING POINT

How does the pilot know <u>where</u> to begin the cable deployment , when that point may depend on the location of his airbase, and his takeoff time? In order to locate the point where the deployment of the first AdDA segment starts, two elements are needed. The first is the distance d_S (shown in Figures 10,11) and the other one is that this point will be either on the shallow water defense zone border line (in the case of the first four deployment tactics, as they were described in Chapter II), or it will be on the line drawn from the datum and perpendicular to the SWDZBL (in the case of the last two deployment tactics, as they were described in Chapter II), which is known to the pilot. In the case of the "Bound the Expanding Farthest-On Circle" tactic and two others, the starting point S is as shown in Figure 10, on the SWDZBL a distance D_0 from the datum and d_S from the airbase. From Figure 10 (or Figure 11) it may be seen that with a knowledge of the Datum , airbase, and SWDZBL locations, and the distance d_S (or the distance D_0) the starting point may be located.

When d_S is the distance between the base and the starting point S, an aircraft cruising at transit speed S_T will require a transit time of about

$$T_S = \frac{d_S}{S_T}. \tag{1}$$

During this transit time T_S , the submarine at a speed S_e can travel a distance d_b from datum that will be,

$$d_b = S_e T_S$$

and thus,

$$T_S = \frac{d_b}{S_e}. \tag{2}$$

From Equations (1) and (2) we have,

$$d_b = d_S(\frac{S_e}{S_T}). \tag{3}$$

After the pilot reaches the starting point S he will begin deploying the first array segment for a time T_d. If an AdDA segment needs time T_{sk} to sink to the sea floor, then the activation time T_a for this array will be given by,

$$T_a = T_d + T_{sk} . \tag{4}$$

During the activation time T_a the submarine can travel an additional distance d_a which is given by,

$$d_a = S_e T_a . \tag{5}$$

From the right triangles AES and AED (shown in Figures 10 and 11) we have,

$$d_S^2 = d_E^2 + (ED - d_b - d_a)^2 \tag{6}$$

and

$$(ED)^2 = d_D^2 - d_E^2 . \tag{7}$$

Equations (3), (4), (5),(6) and (7) yield a quadratic equation in d_S, or

$$(1-\frac{S_e^2}{S_T^2})d_S^2+2(\frac{S_e}{S_T}\sqrt{d_D^2 - d_E^2} - \frac{S_e^2}{S_T}T_a)\,d_S-d_D^2 - S_e^2T_a^2+2S_eT_a\sqrt{d_D^2 - d_E^2} = 0. \tag{8}$$

If we set $A = (1 - \frac{S_e^2}{S_T^2})$,

$B = 2(\frac{S_e}{S_T}\sqrt{d_D^2 - d_E^2} - \frac{S_e^2}{S_T}T_a)$,

$C = (-d_D^2 - S_e^2T_a^2 + 2S_eT_a\sqrt{d_D^2 - d_E^2})$,

then Equation (8) can be rewritten as,

$$A \bullet d_S^2 + B \bullet d_s + C = 0,$$

which is a quadratic equation with the distance d_s between the base and the starting point S as the unknown variable. By solving the last equation we have,

$$d_S = \frac{(-B) + 2\sqrt{B^2 - 4AC}}{2A}. \tag{9}$$

Since the value of the distance d_s between the base and the starting point S is known to the pilot, his heading and flying time are completely determined.

After solving Equation (9), from Equation (1) we can have the value of the transit time T_s which is a necessary and critical parameter in finding the bounded area, the number of the needed AdDA segments, and the deployment angles.

These, equations can be used in all the proposed tactical deployment patterns to obtain the transit time to the deployment starting point S (shown in Figure 10), and the distance d_s between the airbase and this point, as a function of the following terms:

1. The maximum submarine speed S_e,
2. The aircraft's cruising speed S_T,
3. The activation time T_a for one AdDA segment, which is the sum of the deployment and sinking times for an array,
4. The distance d_D between the base A and datum D, which is known, and
5. The distance d_E which can be computed by using a chart.

C. THE NEXT CHAPTER

In the next chapter we will discuss in depth one of the single aircraft methods called "Bound the Expanding Farthest-On Circle" , which shows a great deal of promise in terms of minimizing the isolation area and the number of the needed AdDA segments.

IV. THE "BOUND THE EXPANDING FARTHEST-ON CIRCLE " TACTIC

In this chapter we will explore one specific tactical deployment pattern, which is the "Bound the Expanding Farthest-On Circle" tactic, with the objective of finding a basis upon which the deploying pilot can determine his course changes from segment to segment. First, we will introduce new rules for cable deployment, which should improve previous versions of the tactic. Employing these rules, we will identify feasibility conditions for the tactic. These conditions will permit specification of effective deployment angles. In order to better understand how this deployment tactic works we will compute and give the results for several representative cases.

A. CHANGES IN THE TACTIC. ASSUMPTIONS.

The "Bound the Expanding Farthest-On Circle" tactic was only proposed for a single aircraft. A detailed graphical representation of this deployment tactic is given in Figure 12. The plane arrives on the SWDZBL, at the starting point S , which is as far from the datum as the greatest distance traveled by the submarine during the aircraft's transit time to this point and the time for deployment and activation of the first AdDA segment [Ref.2:p.16].

The previous version of the tactic required that the last dropped end of the n^{th} AdDA segment was at a point on the (n+2)st farthest-on circle of the submarine, and that the first array segment was deployed perpendicular to the

SWDZBL. This is unrealistic, since a first segment of length L deployed in this manner, is unlikely to **end** on **any** farthest-on circle. In the current study we will

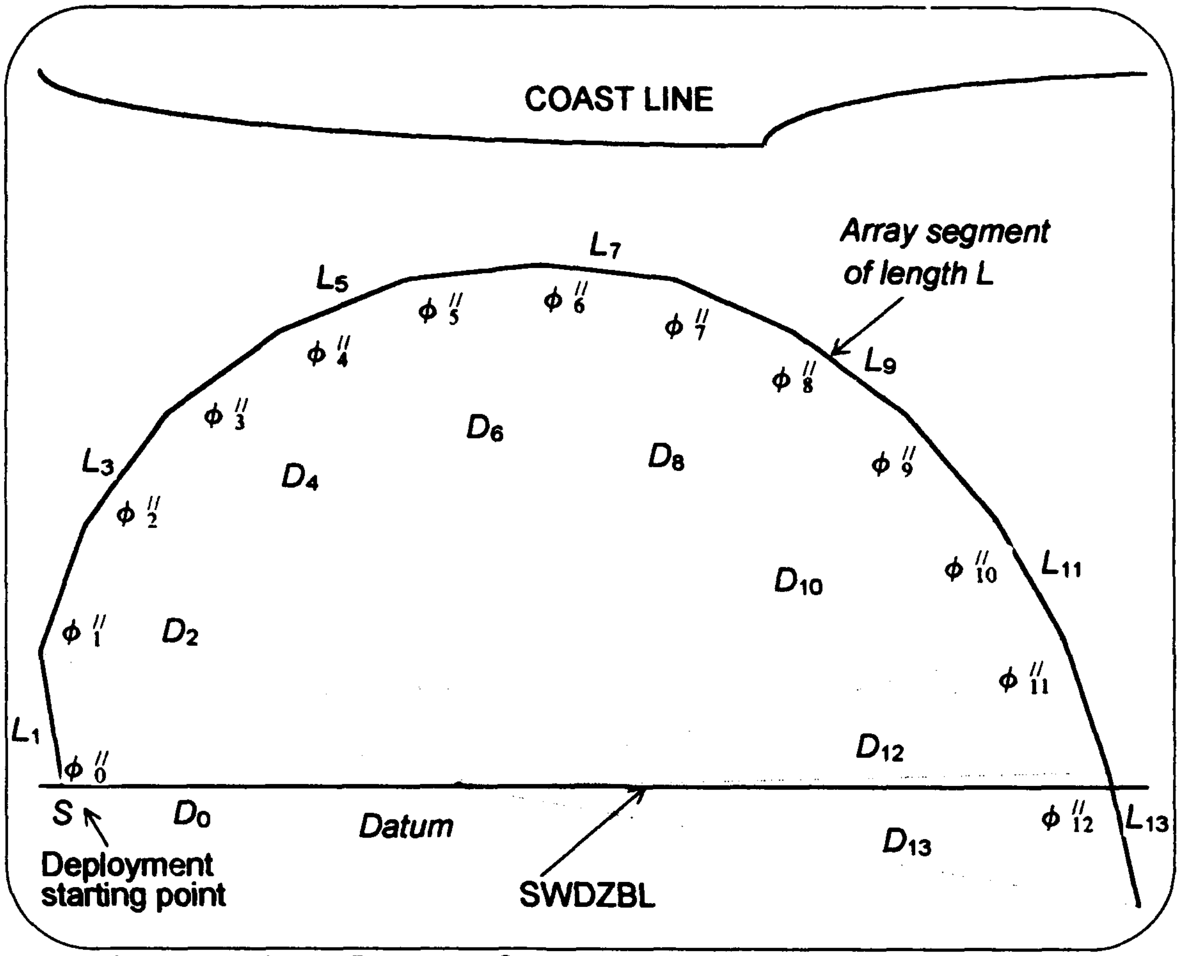

Figure 12. AdDA Deployed Segments for the "Bound the Expanding Farthest-On Circle" Tactic.

change these assumptions. We will require the last dropped end of the n[th] array segment be at a point on the (n+1)st farthest-on circle of the submarine, and allow the first AdDA segment to be deployed at an angle (with the SWDZBL) which can be other than 90 degrees. We made these changes because not only is deploying the first segment at right angle excessively restrictive, but for some cases, ending the n^{th} segment on the (n+1)st farthest-on circle could reduce the bounded area or the number of arrays needed.

When the tactic is feasible, deploying all the needed array segments will form a polygon with the shallow water defense zone border line. This is shown in Figure 12, where the length D_n is the radius of the (n+1)st farthest-on circle of the submarine, representing the greatest distance that can be traveled by the target from the datum, until the activation of the (n+1)st array segment.

For this study the radius of the initial farthest-on circle of the submarine will be denoted as D_0, so that D_0 is the distance from the datum to the deployment starting point S. The size of the radius D_0 can be found from the general expression for the radii of the farthest-on circles [Ref.1:p.31],

$$D_n = S_e(T_S + T_d(n+1) + T_{SK}), \quad n = 0,1,2,3....., \tag{10}$$

where S_e is the target speed, T_S is the transit time to the deployment starting point S, and T_d and T_{SK} are the deployment and sinking times for an array segment. Here D_n, represents the radius of the (n+1)st farthest - on circle of the target.

For the analysis we will investigate cases where the submarine travels directly to these farthest-on circles, since these are the critical points of the area for which the submarine will be bounded or detected. Since the successive arrays are connected, these values for D_n should correspond to a minimum distance (from the datum) for the (n+1)st array segment. Should the target reach this point, the (n+1)st array will have been activated. When arrays are deployed in this way, it should not be possible for the target to cross an inactive segment, (which is being deployed as close to the initial target sighting as possible). Cables laid in this manner will then hold to bound or detect the submarine's course above the shallow water defense zone border line. In the next section we will try to find constraints identifying feasible conditions for this tactic to be used. Then, we will show how the deployment angles for this tactic may be found.

B. FEASIBILITY CONDITIONS FOR THIS TACTIC.

Array segments laid according to this tactic can be considered a detection barrier if two conditions hold.

1. At the time the target could reach the end (or before the end) of an array segment, the next array has been activated. Any two successive AdDA segments are connected to each other.

2. The n^{th} array segment should be started from a point on or outside the n^{th} farthest-on circle, and end on a point on or outside the next farthest-on circle. To summarize this, **all** of the n^{th} array should lie **outside** of the n^{th} farthest- on circle with the radius D_{n-1}. **We will consider cases where the points are <u>on</u> the successive farthest-on circles.**

If the (n+1)st array segment starts on the (n+1)st farthest-on circle and is to be on or outside that circle, then the angle ϕ_n^* between the radius D_n and the (n+1)st array segment (of length L), must be equal or bigger than 90 degrees. If the angle ϕ_n'' is less than 90 degrees, then the enemy submarine can evade detection by being farther from the datum than all or a portion of the (n+1)st array segment, when it is activated. This is shown in Figure 13, where L_n is the n^{th} array segment of length L.

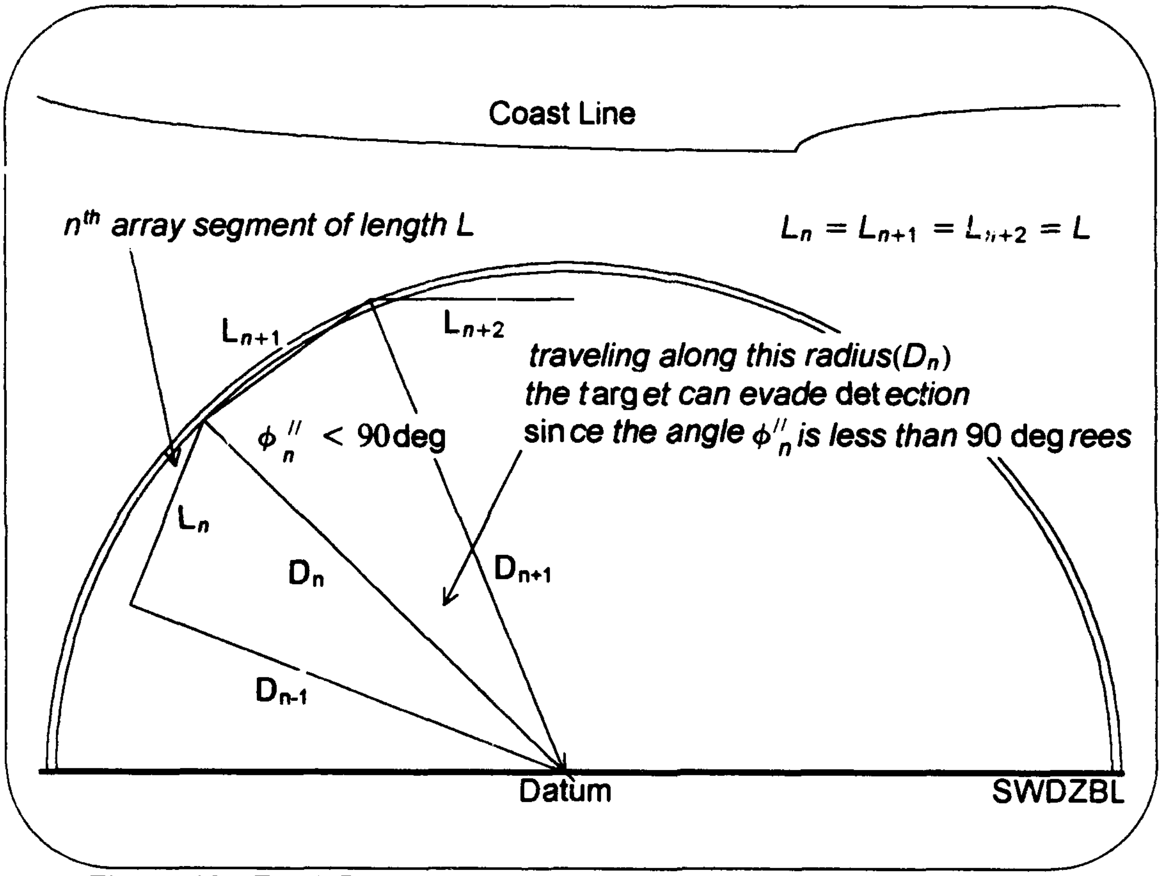

Figure 13. The " Bound the Expanding Farthest-On Circle " Tactic when the Target can Evade Detection.

When the angle ϕ_n'' of each of the formed triangles is equal or bigger than 90 degrees, the relation among the sides of each triangle is,

$$D_n^2 + L^2 \leq D_{n+1}^2.$$

and thus $$L^2 \le D_{n+1}^2 - D_n^2. \tag{11}$$

The difference (D_{n+1} - D_n) between the radii of any two successive farthest-on circles is given by,

$$D_{n+1} - D_n = S_e\,(T_S + T_d\,(n+2) + T_{sk}) - S_e\,(T_S + T_d\,(n+1) + T_{sk}),$$

or $$D_{n+1} - D_n = S_e T_d. \tag{12}$$

If we add the radii of two successive farthest - on circles we have,

$$D_{n+1} + D_n = (D_n + S_e T_d) + D_n$$

or $$D_{n+1} + D_n = 2D_n + S_e T_d\,. \tag{13}$$

From Inequality (11) and Equations (12), (13) we obtain Inequality (14),

$$L^2 \le (S_e T_d)(2D_n + S_e T_d),\ n = 0, 1, 2.... . \tag{14}$$

Substituting the expression for D_n ,the radius of the (n+1)st farthest-on circle (10) and doing some algebra, we obtain ,

$$T_S \ge \frac{L^2 - (S_e T_d)^2(2n+3) - 2S_e^2 T_d T_{SK}}{2S_e^2 T_d}\,,\ \textit{for}\ n = 0, 1, 2..... .$$

This inequality appears to give a lower bound for T_S , the transit time from the airbase to the deployment starting point. This bound will be at a maximum when n=0, and thus

$$T_S \ge \frac{L^2 - 3(S_e T_d)^2 - 2S_e^2 T_d T_{SK}}{2S_e^2 T_d}\,,\ \textit{for}\ n = 0, \tag{15}$$

is the consequence of our requirement that $\phi_n^* \ge 90$ degrees.

This curious result would have relevance when the radii of the first two farthest-on circles were so small that the aircraft could not "fit" between them a segment of length L while maintaining the $\phi_0^* \geq 90$ degrees requirement . Stated differently, if the obtained transit time for the radius of the first farthest-on circle (**n=0**) does not satisfy Inequality (15), then it would be impossible for the first array segment to end on the second farthest-on circle without crossing the first one. In this case the angle ϕ_0^* (shown in Figure 12) would be less than 90 degrees. This was shown in general case in Figure 13. When the constraint (15) is not met, the starting point S may be moved (by increasing D_0) until it is possible to lay the first segment, which will be at a right angle to the SWDZBL. In this case we have a right triangle with L and D_0 as sides, and D_1 as the hypotenuse. With this triangle

$$D_1^2 = L^2 + D_0^2$$

and

$$L^2 = D_1^2 - D_0^2 = (2D_0 + S_e T_d)(S_e T_d),$$

or

$$D_0 = \frac{L^2 - (S_e T_d)^2}{2 S_e T_d},$$

instead of the smaller lower value given in the last chapter.

In Table 1 we have computed and give the **minimum bounds** for the transit time T_S, for target speed and average depth combinations which result if we consider Inequality (15) as an **equality** requiring the first array segment to be perpendicular to the SWDZBL. The values used in this computation are :

- L: The length of an array segment equal to 30 n.m.,
- S_e : The target speed in the shallow water region, which is given inTable 1,
- T_d : The aircraft's deployment time for an AdDA segment equal to 0.24 hrs [Ref.1:p.25],
- T_{SK} : The sinking time of an array segment to the sea floor[1], and
- The average depth in the shallow water area, which is given in Table 1.

TABLE 1. PERFORMANCE OF THE " BOUND THE EXPANDING FARTHEST - ON CIRCLE" TACTIC. TRANSIT TIMES.

	AVERAGE DEPTH (fathoms)	MAXIMUM SUBMARINE SPEED			
		5 kts	10 kts	15 kts	20 kts
Minimum transit times T_S in hours (for n = 0)	100	N/A	N/A	6.8134	3.1675
	150	N/A	N/A	6.244	2.5975
	180	N/A	N/A	5.894	2.2475
	200	N/A	N/A	5.664	2.0175

After the time the target was lost (on the SWDZBL, by deep water assets) the plane should begin deploying the first AdDA segment at times as they are given in Table 1, otherwise the rules, which were determined in this chapter, do not hold.

Again, the results shown in Table 1 are curious, since they show that the slower the maximum submarine speed, the longer the aircraft may have to delay before deployment of cables may begin. The larger resulting values for D_0

1. This time for average depth 100 fathoms, 150 fathoms, 180 fathoms and 200 fathoms is respectively 1.16 hrs, 1.73 hrs, 2.08 hrs and 2.31 hrs [Ref.1:p.25].

suggest that when this constraint is applicable, other possible deployment tactics may out perform this one. According to the results from Table 1 for target speed 15 kts or 20 kts, we need more than twelve AdDA segments to form the barrier, as we see from Figures 14 and 15 respectively. In both cases the number of the deployed AdDA segments is bigger than the number of array segments one C-130 can carry, which is twelve [Ref.2:p.34]. Another constraint for this tactic is that closure of the polygon must be possible.

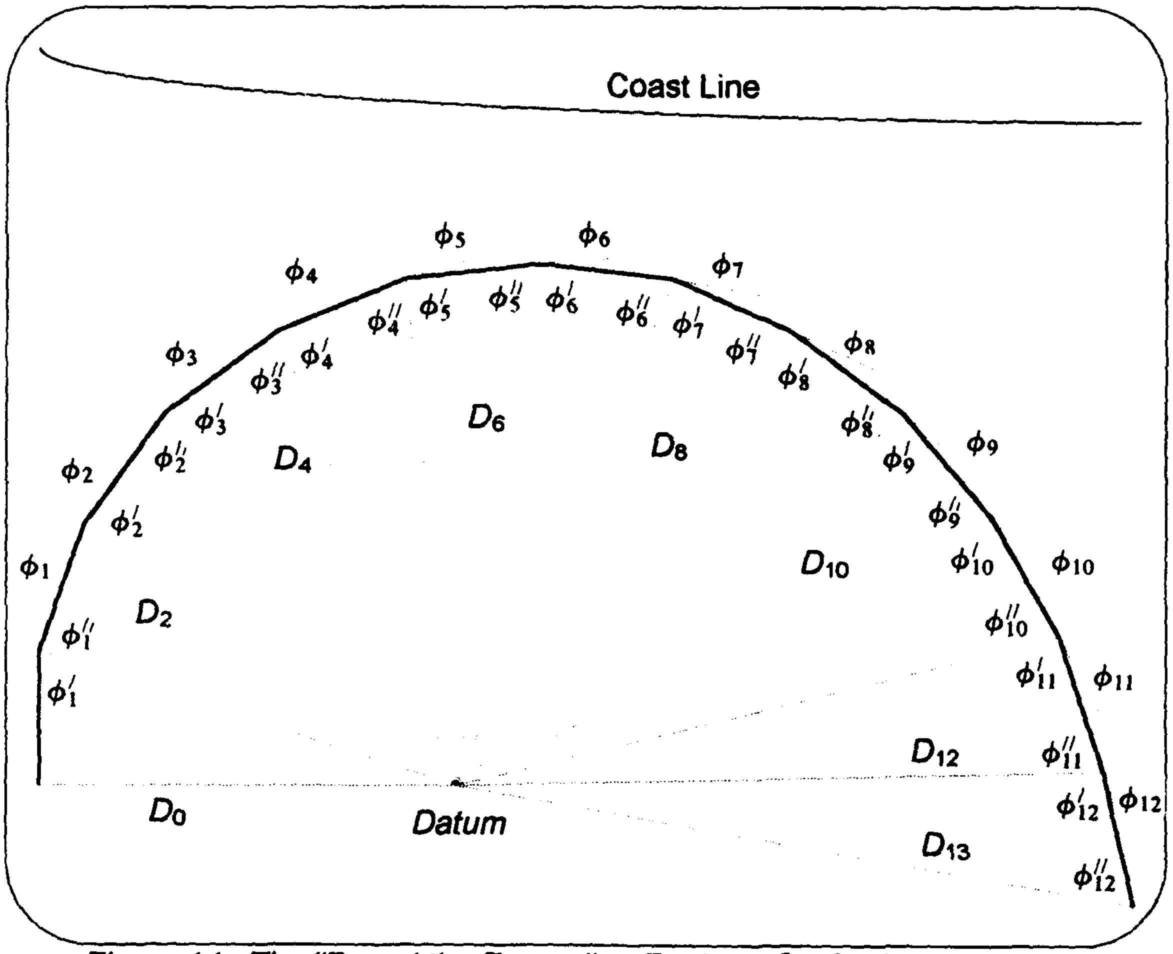

Figure 14. The "Bound the Expanding Farthest-On Circle" for Target Speed 20 kts when the First Array Segment is Deployed Perpendicular to the SWDZBL.

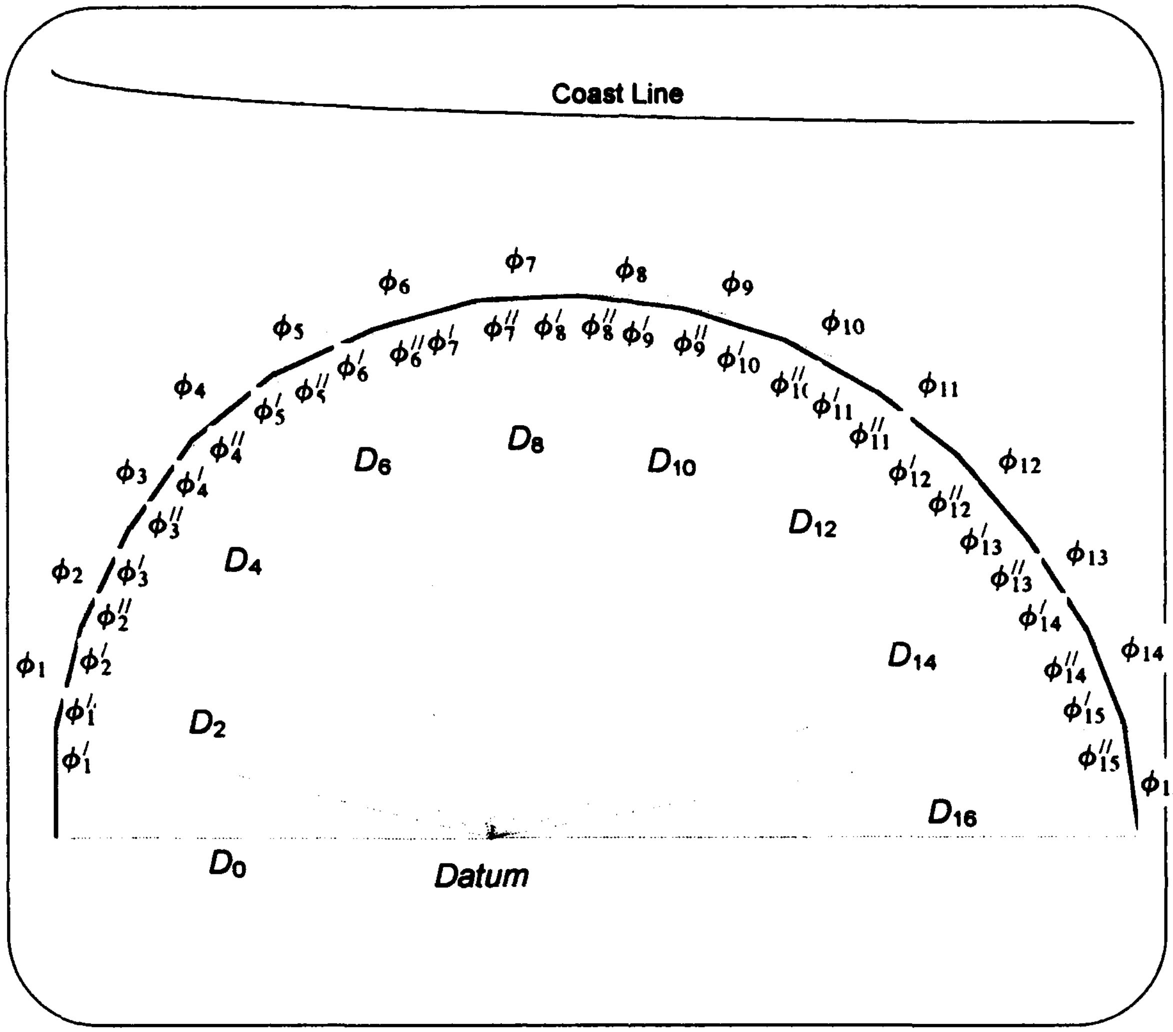

Figure 15. The "Bound the Expanding Farthest-On Circle" Tactic for Target Speed 15 kts, where the First Array segment is Deployed Perpendicular to the SWDZBL.

C. DEPLOYMENT ANGLES

As stated the pilot should deploy the AdDA segments in a way such that any angle ϕ^*_n between the radius D_n of the (n+1)st farthest - on circle of the target and the (n+1)st array segment should be equal to or bigger than 90 degrees, and the last dropped end of the n^{th} array segment to be a point on the (n+1)st farthest-on circle. If this angle is less than 90 degrees, the target could evade detection by being farther from datum than the (n+1)st active array segment, when it was activated.

Under these circumstances all the deployment angles ϕ_n can be characterized as "optimal", in that the cables are as close as possible to the datum while bounding the target . A graphical representation of these angles is shown in Figures 14 and 15. Each angle ϕ_n can be computed by,

$$\phi_n = 180 - \phi'_n - \phi''_n ,$$

where ϕ'_n is the angle between the n^{th} array segment and the radius of the (n+1)st farthest-on circle.

Using the cosine law this equality can be rewritten as :

$$\phi_n = 180 - \arccos\left(\frac{L^2 + D_n^2 - D_{n-1}^2}{2LD_n}\right) - \arccos\left(\frac{L^2 + D_n^2 - D_{n+1}^2}{2LD_n}\right), \qquad (16)$$

where L is the length of an array segment and D_n, D_{n-1} and D_{n+1} are the radii of the n, (n-1) and (n+1) farthest - on circles of the submarine.

In determining a relation between two successive optimal deployment angles we found Equation (17),

$$\phi_{n+1} = \phi_n \left\{ \frac{180 - \arccos\left(\frac{L^2 + 2D_nS_eT_d + (S_eT_d)^2}{2L(D_n + S_eT_d)}\right) - \arccos\left(\frac{L^2 - 2D_nS_eT_d - 3(S_eT_d)^2}{2L(D_n + S_eT_d)}\right)}{180 - \arccos\left(\frac{L^2 + 2D_nS_eT_d - (S_eT_d)^2}{2LD_n}\right) - \arccos\left(\frac{L^2 - 2D_nS_eT_d - (S_eT_d)^2}{2LD_n}\right)} \right\}. \qquad (17)$$

From Equation (17), for a particular target speed and average depth combination, we can easily compute all the deployment angles ϕ_n if we know the radius D_0 of the initial farthest - on circle of the target, and the first deployment angle ϕ_1 , which is obtained by using the cosine law. Each next length D_{n+1} will be equal to $(D_n + S_e T_d)$. Another way to compute the deployment angles is by using Equation (16).

D. EXAMPLES

Continuing the example that gave the results of Table 1, we obtain the deployment angles (shown in Figure 14) for target speed 20 kts and various average depth values. A similar case, but with different results (shown in Figure 15) is obtained for target speed equal to 15 kts and every average depth.

In Tables 2 and 3 we give the computed deployment angles for target speeds 15 kts and 20 kts respectively, where the given transit times have been taken as to the minimum bounds (Inequality (15)). For these cases the first AdDA segments will be deployed perpendicular to the SWDZBL, as was shown in Figures 14 and 15.

TABLE 2. AIRCRAFT COURSE CHANGES FOR THE "BOUND THE EXPANDING FARTHEST-ON CIRCLE " TACTIC FOR TARGET SPEED 20 kts

Target speed	Average depth (in fathoms)	(Lower) Transit Time T_s (in hours)
20	100	3.1675
20	150	2.5975
20	180	2.2475
20	200	2.0175

OPTIMAL DEPLOYMENT ANGLES Φ_n (in degrees)

$\phi_1 = 17.72$	$\phi_2 = 16.87$	$\phi_3 = 16.09$	$\phi_4 = 15.39$	$\phi_5 = 14.74$	$\phi_6 = 14.1$
$\phi_7 = 13.60$	$\phi_8 = 13.0$	$\phi_9 = 12.63$	$\phi_{10} = 12.19$	$\phi_{11} = 11.78$	$\phi_{12} = 11$

TABLE 3. AIRCRAFT COURSE CHANGES FOR THE "BOUND THE EXPANDING FARTHEST-ON CIRCLE " TACTIC FOR TARGET SPEED 15 kts.

Target speed	Average depth (in fathoms)	(Lower) Transit Time T_s (in hours)
15	100	6.813
15	150	6.243
15	180	5.893
15	200	5.663

OPTIMAL DEPLOYMENT ANGLES Φ_n (in degrees)

$\phi_1 = 13.49$	$\phi_2 = 13.11$	$\phi_3 = 12.76$	$\phi_4 = 12.42$	$\phi_5 = 12.10$
$\phi_6 = 11.80$	$\phi_7 = 11.51$	$\phi_8 = 11.24$	$\phi_9 = 10.98$	$\phi_{10} = 10.73$
$\phi_{11} = 10.49$	$\phi_{12} = 10.26$	$\phi_{13} = 10.05$	$\phi_{14} = 9.84$	$\phi_{15} = 9.64$

As it was said, if the transit time is bigger than the lower bound (Table 1), then the first AdDA segment will be deployed at an angle to the SWDZBL which will be bigger than 90 degrees.

The results of another example are given in Table 4. Here the transit time has been taken to be (arbitrary) bigger than the lower bound. In this example the target speed S_e is equal to 20 kts, the average depth is 200 fathoms and the transit time T_s is 3.0 hrs. Figure 16 is a graphical representation of this example.

TABLE 4. AIRCRAFT COURSE CHANGES FOR THE " BOUND THE EXPANDING FARTHEST-ON CIRCLE " TACTIC

Target speed	Average depth (in fathoms)	Transit Time T_S (in hours)
20	200	3.0

OPTIMAL DEPLOYMENT ANGLES Φ_n (in degrees)

$\phi_1 = 14.69$	$\phi_2 = 14.10$	$\phi_3 = 13.56$	$\phi_4 = 13.06$	$\phi_5 = 12.59$
$\phi_6 = 12.15$	$\phi_7 = 11.75$	$\phi_8 = 11.37$	$\phi_9 = 11.01$	$\phi_{10} = 10.68$
$\phi_{11} = 10.37$	$\phi_{12} = 10.07$	$\phi_{13} = 9.8$	$\phi_{14} = 9.53$	$\phi_{15} = 9.28$

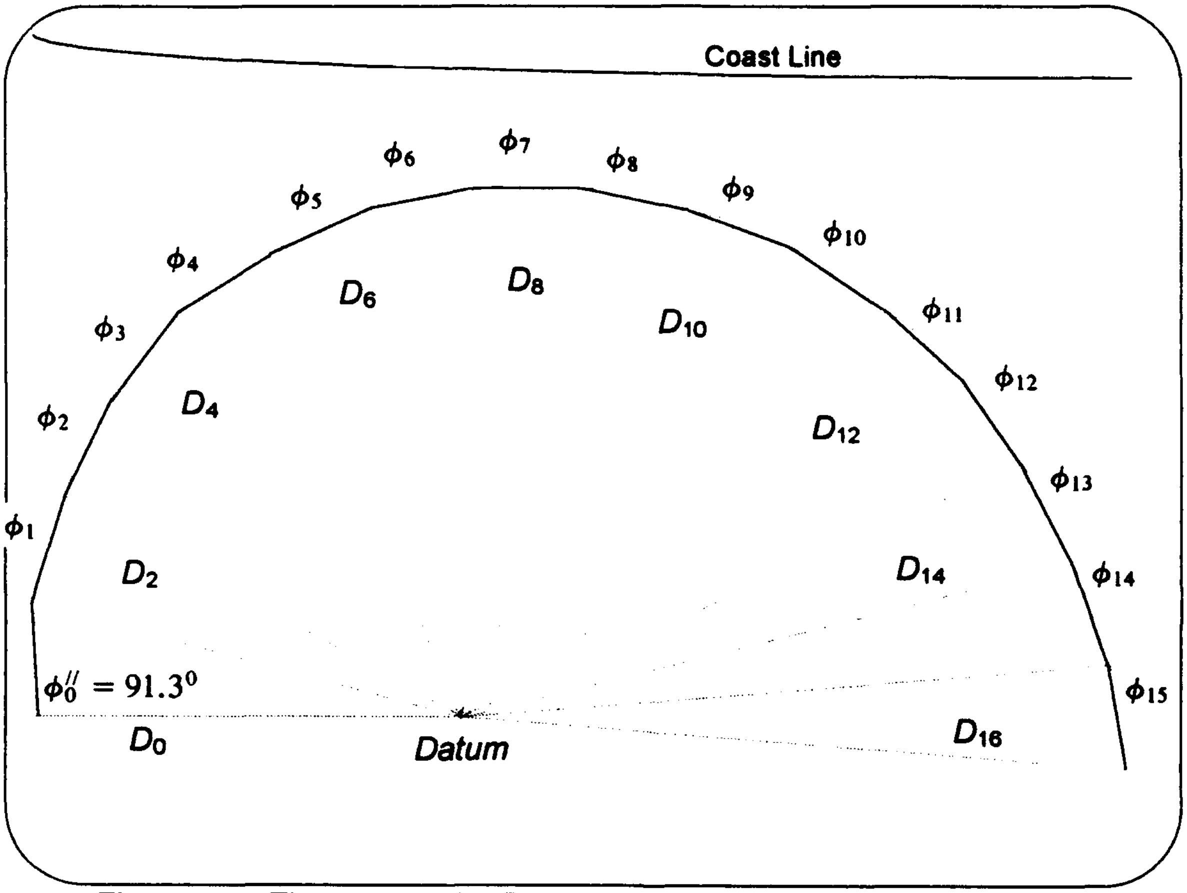

Figure 16. The "Bound the Expanding Farthest-On Circle" for Target Speed 20 kts when the Transit Time is **Bigger** than the Minimum Bound

E. THE NEXT CHAPTER

In the next chapter we will summarize our conclusions and make recommendations for further study.

V. CONCLUSIONS AND RECOMMENDATIONS

In this chapter we will discuss the conclusions that result from this work. Also we will give our recommendations and suggestions for further study of deployment methods for shallow water detection cables.

This thesis made an analysis for the deployment of the Advanced Air Deployable Array (AdDA), which is a modern air-dropped fiber-optic undersea warfare device for detection of an enemy submarine in shallow waters. An AdDA barrier will detect or bound the enemy submarine.

In Chapter III a mathematical model was determined for the aircraft' s transit time to the deployment starting point. This is of great utility, because it overcomes the restriction of previous studies to assume only fixed distance airbases from the datum, which may be in a distance from the datum different than 300 n.m. The utility of this variable is also revealed from the fact that several critical parameters are expressed as a function of it. These are the distance between the deployment starting point and the datum, the area where the target is to be bounded, the number of deployed AdDA segments for each tactical method, and the deployment angles.

In Chapter IV we modified and made an in-depth analysis for an important tactical deployment option called the "Bound the Expanding Farthest-On Circle". The analysis shows how the aircraft's course changes affect the number of needed AdDA segments, and the isolation area where the target is to be detected or bounded. The analysis shows that the slower the target speed the longer the aircraft may have to delay before the deployment of the first array segment, if the rules for this tactic are followed rigidly. Also, the analysis shows that this single aircraft deployment tactic may be feasible for target speeds bigger than or equal to 20 kts. This tactic provides a smaller isolation area and smaller number of deployed AdDA segments than if the first array segment is deployed perpendicular to the SWDZBL.

A continuation of the work reported here would be a stochastic model that uses previous known locations of the enemy submarine in order to determine a better starting point for the deployment of the first AdDA segment, saving time in deploying the remaining array segments.

Also, further research for the "Bound the Expanding Farthest-On Circle" tactic may be a different deployment pattern so that the isolation area could be the minimum possible. This can be done if all the angles ϕ^{*}_{n}, as they were described in Chapter IV, are all of 90 degrees. Inequality (17) on page 32 shows how we can do that if we consider this as equality, and we deploy each of the array segments with a different (increasing) deployment speed. Alternately, in some cases we can have smaller isolation areas if the successively deployed AdDA segments are of smaller length.

Another important deployment method is the "Deep Water Envelope Parallel Enclosure" which is also useful because it keeps the target away from land. In future research this tactic could be studied intensely with special consideration of feasibility conditions.

It is hoped that the findings of this study will expand what is known of AdDA deployment tactics, which may play an important role in the defense of the shallow waters region of Greece or other nations.

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