Archipelagic ASW - a Difficult Enterprise in Need of Holistic Approaches

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Abstract

The paper discusses architectural options for providing *Dominant Battlespace Awareness* (*DBA*) for *Archipelagic Anti-Submarine Warfare* (*AASW*) in the Baltic Sea, against experience from submarine intelligence data analysis and fusion research during the recent historical episode which involved recurrent submarine intrusions into Swedish coastal waters.

Introduction

As was drastically demonstrated in Sweden not so long ago, during the dozen or so years when a total of more than 6000 reports on sightings or detections of possible foreign underwater activity were collected by the Swedish Armed Forces, *Archipelagic Anti-Submarine Warfare* (*AASW*) is a previously largely neglected but surprisingly difficult undertaking.

From a background as research leader in information analysis and fusion, performed in close contact with naval intelligence analysts who had to provide statistics, analyses, and forecasts of foreign undersea intrusions, I will share below my perception of the technical options for future *Dominant Battlespace Knowledge (DBK)* [Johnson & Libicki 1995], or *Dominant Battlespace Awareness* (*DBA*) as it has more aptly been rephrased, in AASW scenarios. The introduction of the concept of DBA into the world of AASW was made in a recent study for the Swedish Armed Forces and is not our own invention, nor do we possess any tactical experience in ASW.

The reasoning in this paper is based instead on our group's more than decade-long research into methods and technology for interpretation and fusion of high-level observational data from AASW operations, or more precisely, submarine *intelligence, surveillance, and reconnaissance* (*ISR*) operations. The views expressed here are entirely my own and do not represent the official standpoint of the Defence Research Establishment nor of the Swedish Armed Forces.

The DBK/DBA concept has been characterized as follows [Alberts 1995]: "A baseline assumption for DBK is that we know, in near real time, the positions of all friendly, neutral, and enemy objects of interest; we have more limited information regarding their current conditions and recent histories; and we have somewhat less information about enemy intents and plans".

In a recent, non-technical but comprehensive survey of ASW [Gardner 1996], the concept of *Littoral ASW* is briefly touched upon and judged to be growing in importance, while ASW as a whole seems to be a retracting business, at least in the short and medium term. We will discuss here from a data fusion perspective, a subclass of littoral ASW which deals with operations "in the very close inshore area" [*ibid*]. Part of the work to be surveyed and discussed here has been reported in scientific papers [Bergsten & Schubert 1993][Bergsten & al 1997][Jöred & Svensson 1998][Schubert 1993, 1996a, 1996b]. Some of these publications are theoretical in nature and their relevance for the AASW application may not be immediately obvious.

Complementing and contrasting purely theoretical investigations of data fusion methodologies for AASW, we will discuss the issue of information fusion from the perspective of a now historical but until quite recently serious military (and, as a corollary, political) problem. Our aim will be that of finding, if possible, technological conditions sufficient for barring through the achievement of DBA, future repetition of the events of the 80's and early 90's. During this period the defense against foreign undersea intrusions consumed roughly half a billion dollars of Swedish taxpayers' money, without achieving perceivable success in its assigned task to force the intrusions to stop.

Can a new, more holistic DBA-inspired technological approach to AASW remove the submarine threat from Sweden's strategic agenda ? For this to be possible, data and information fusion methods will have to undertake crucial roles. We will discuss below some scenarios in which these roles will be played out.

Part I. The Submarine Issue in Sweden 1980-1994

The report of the 1995 Submarine Commission

In 1980, an event occurred which caused considerable military and political commotion in Sweden, a country which has officially pursued a policy of non-alignment since the mid-1800's and has enjoyed peace since 1814. For a period of several weeks, the Swedish Navy hunted what it later judged to be two foreign submarines operating in the country's inner territorial waters, near Sweden's largest naval

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base.

This event commenced a more than decade-long period of political uneasiness and increasing military, as well as public, vigilance. The period was characterized by an inflow of final event intelligence reports to the Swedish military headquarters, which during the years of 1986-88 reached a peak of about 1000 per year. In total, more than 6000 reports were collected which may refer to independent sightings or detections of foreign underwater activity.

Today, the episode is generally considered by public opinion to belong entirely to history, although the Supreme Commander still delivers a yearly report to the government on the topic.

In February 1995, the Swedish government formed an independent commission “with the task of assessing and analyzing the underwater violations and indications of these that have existed since the beginning of the 1980’s...” [*Ubåtsfrågan 1981-1994* 1995].

Until the Submarine Commission’s report [*ibid*] was published, very little was known to the public about the size and character of the intelligence material that had been gathered. From those who were involved in the Swedish defense effort one way or another, absolute secrecy had been required.

Most of the collected reports, roughly 80%, are of human observations. Of these, 80% were made by civilians. With regard to these reports, the commission states that “in our opinion, credible observations of foreign submarine activity have been made”. The more than 6000 reports were classified by the defense authorities in four quality categories, plus the categories “No submarine activity” and “Not decidable”. More than 1500 reports claim a target distance of less than 100 m. Of these, about 400 had been classified as belonging to the categories 1-3, and 40 to category 1.

The Commission report declares that “in our opinion, it is not possible to state the number of credible observations, and, by doing so, to draw a line between these and other observations”. In the classification scheme used by the military, the top category “Confirmed activity” was intended to include only such observations that were provably true in a legal sense. As the above citation shows, the relevance of this classification was rejected by the commission. Their approach was to base their conclusions on the relatively few instances of foreign submarine activity that had been recorded in such a way that they could be repeatedly analyzed using physical principles. As a consequence, the commission refrained from analyzing the collection of ISR reports.

The Baltic Sea and the AASW problem

To begin perceiving the physical complexity of the AASW surveillance problem, we need to set the problem in its environmental and tactical perspective.

The Baltic Sea is a large body of relatively shallow water, whose exchange with the North Sea is restricted by two shallow and fairly narrow thresholds, making its water brackish. Its total area is roughly $4 \cdot 10^5\ km^2$, its average depth about 60 m, and its salinity at the surface varies geographically between about 0.2 and 1.0 %. Its geological origin and bottom-topographical features vary from relatively recent and also flat southern areas to ancient and, in some areas, broken, rocky terrain, including instances of steep karst formations and canyon-like structures. Partly situated in the subarctic zone, large portions of its surface are ice-covered during the winter months. Its salinity, and in particular, temperature depth profiles show large seasonal variations.

Certain areas, in particular large areas between south-western Finland and Åland and east of Stockholm, are pocked with tens of thousands of small and large islands. It is in the Stockholm archipelago, and in particular in the area close to the inlet to Stockholm and also close to Sweden’s largest naval base, where most of the submarine sightings were reported.

Insufficient knowledge of the seabed topography in the archipelago caused occasional difficult problems for the submarine defence. Vast areas outside busy traffic channels were inadequately mapped. More recently, a significant effort has been launched to provide the navy with detailed bathygraphic map coverage of Swedish coastal waters, but the size of this undertaking makes its completion a long-term prospect. Also, large areas in the archipelago are difficult to navigate and map using conventional means.

The complexity of archipelagic undersea topography presents advantages for the defense as well as for the intruder. For hundreds of years, the inlet to Stockholm has been protected by stone caissons which were strategically located to prevent entry except through very narrow passages. More recently, submarine nets and linear, electromagnetic sensors have been extensively used to lock out or detect unwelcome undersea visitors. In a coastal area south-east of Stockholm which includes Sweden’s largest naval base as well as a busy ship route to the city, a system of such “sensor gates” has been installed since at least the mid-eighties. Keeping these sensor systems on constant alert to detect any submarine without confusing it with the intense surface traffic presented a challenge for the Swedish Navy, which was met mainly by systematic visual inspection of the sea surface. The need for developing automated alarm systems based on sensor fusion is evident.

Part II. Methods Proposed for Fusion of Sparse Observational Data

We will review here early efforts by our research group to provide methodological support to the effort of analyzing and fusing the submarine ISR reports. The main characteristics of the collected reports with which our techniques had to cope were sparseness in space-time and qualitatively estimated, widely varying degrees of credibility. The submarine intrusion problem represents a class of data analysis problems where observations form a complex structure, in relation to which it is unknown where and how to find useful information. Much of the analysis effort must then be devoted to looking for possibly relevant “signals” hidden in the data collection.

In target tracking research [Bar-Shalom & Li 1993], the usual assumption is that the visibility of the target(s) is fairly stable, so that targets can be tracked in real time, perhaps with some ambiguity arising from target multiplicity and/or noisy and fluctuating signals. The situation we describe here is very different: the targets are usually seen only in short glimpses, precise classification or identification is almost never possible, target location is often poorly defined, false alarms occur frequently (some say always), and the “sensors”, including human observers, are of many different kinds, each with its own special characteristics.

On the lowest level of aggregation one faces, e. g., problems of constructing possible paths from uncertain point data, of “counting” the number of targets using only indirect evidence such as time and distance in relation to possible or probable speed, and of finding indirect support for target detection from coincident, more easily observable processes such as radio signals from non-submarine sources, possibly related surface ship traffic etc.

On a more aggregated level, one wants to find spatio-temporal patterns that might be used to predict future behavior, and in general, to help understand the observed phenomenon, if indeed there is one.

Early on we decided to base much of our work on the Dempster-Shafer theory of evidence [Shafer 1976], which permits effective representation and analysis of the propagation of arbitrary degrees of belief, ignorance, and conflicting evidence.

The few and and partial application tests of these methods to real ISR data we could perform implied that even methods designed to take into account all available information on the single report level, including partial and negative information (such as non-firing sensors), were unable to significantly improve the level of understanding of the relationships between neighbouring reports because of their sparseness. Incidentally, if the plotted reports were indeed caused by a submarine, tracking it using these reports would not have been possible since the density of observations is usually less than once a day. Even a very cautious and therefore slow submarine could traverse the large archipelago of Stockholm from north to south in 24 hours.

Another difficulty which should have warranted its own in-depth study was the need to translate the qualitative categorisation of the quality of reports into a quantitative, probabilistic one. We implemented techniques for sensitivity analysis [Andersson & Sjölander 1992], originally proposed by Strat and Lowrance [Strat & Lowrance 1989] which should have been useful in such a study but we never had the opportunity to apply them to the ISR data.

Thus, the applicability of the evidential approach to the historical ISR database was less than expected, although we concluded that with reasonably dense observations, such methods should have been quite valuable. Only by use of statistical and graphical data mining techniques were we able to extract some meaningful information from the historical database [Bergsten & al 1997].

Statistical Analysis

During the summer months, the Stockholm archipelago is host to large numbers of pleasure boats, so civilian observers may constitute the least spatially biased “sensor system”, although the temporal bias of such reports may be considerable.

Thus a key question when analyzing data from suspected intrusions is whether the observations form a non-random distribution over time.

A preliminary statistical analysis of the database was performed. It was based on human observations of the categories 1-3 in the period 1986-1991. This set includes roughly 800 reports. The purpose of the statistical analysis was to examine whether the observations occur randomly in time and space. Even if they do not, other explanation factors have to be eliminated before we are able to draw the conclusion that the set of observations arises from foreign submarine intruders.

Cluster formations in the time dimension may arise during summer holidays and weekends because more people are then visiting the archipelago, possibly leading to an increase in the number of observations (whether true or false). Clusters in the spatial dimension may arise in areas with many observers. A mass media effect may also be present, i.e. individuals may show a greater tendency to observe and report phenomena in the sea when mass media have announced an ongoing suspected submarine activity.

For each seasonal period considered, the analysis result stated that the hypothesis of randomness should be rejected.

To determine the influence of the number of observers in the archipelago the hypothesis “observations occur with the same frequency workdays and weekends” was tested and consistently accepted.

Associating Non-Specific Intelligence Reports

When several similar submarines are operating concurrently, reports never tell which target they refer to. Therefore, methods are needed which enable an analyst to separate the intelligence reports into subsets according to which target they are referring to [Schubert 1993, 1996a]. Schubert employs the concept of *conflict* in Dempster-Shafer theory [Shafer 1976] between the propositions of two or more intelligence reports as a measure of the probability that the reports are referring to different targets. He uses the minimization of a criterion function of overall conflict (the *metaconflict* function) as the method of partitioning the evidence into subsets representing events related to different targets.

The cause of the conflict can be non-firing sensors placed between the positions of two reports, the required velocity to travel between the positions of two reports at their respective times in relation to the assumed velocity of the submarines, etc.

The method of finding the best partitioning is based on an iterative minimization of the metaconflict function. When this has been done, each subset of intelligence reports refers to a different target and the reasoning can continue with each target treated separately.

Target Path Reconstruction from Sparse Observations

To make more sense out of very sparse, uncertain observational data, we have studied ways in which a small collection of clustered observations could be combined with a-priori information about sensor deployment, topography including islands and shallow water. These methods were designed and implemented as components of a prototype analysts's workbench, DEZZY [Bergsten & al 1989].

Based on the Dempster-Shafer theory of evidence, Bergsten and Schubert [Bergsten & Schubert 1993] have shown how to efficiently weight and rank according to their a posteriori probabilities, the possible target paths through the nodes of a complete directed graph, induced by a set of pointlike intelligence reports. When computing the potentially large number of pieces of evidence which are associated with the arcs of such a graph, both positive (i. e., the reported probability of correct detection at each of the nodes) and negative information (e.g., too long probable transportation times from one node to another, silent but favorably positioned sensors, low underwater trafficability) was taken into account. To compute the many potential transportation times between all pairs of nodes, a fast method for computing shortest travel paths, based on precomputation of a reduced visibility graph was developed [Elg 1992].

Another analysis tool in DEZZY computed and displayed spatio-temporal probability maps which were computed under the assumption of a given probability distribution for the speed of the submarine, given sensor deployment and detection probabilities, and trafficability as estimated from water depth and submarine speed.

Making Tactical Predictions from Learned Patterns

From the experience of testing the methods discussed in the previous section, we concluded that the available information was almost always too sparse to allow meaningful spatio-temporal network analysis. Schubert [Schubert 1996b] [Bergsten & al 1997] therefore developed a machine-learning system for making short-term predictions, based on a machine learning method which recognizes an incoming sequence of intelligence reports as belonging to a certain category of sequences among a large set of categories, previously learned from historical data. Having found such a category he obtains probabilities for different future developments given the current situation.

By use of a genetic algorithm, the system learns the categories of sequences of (hitherto only simulated) intelligence reports. After receiving a new scenario it is analyzed using the learned categories. If the system finds a category of sequences with a beginning similar to the current sequence, the remainder of the historical sequences are used to give a prediction about the future.

Schubert's studies indicate that prediction rules such as these should be useful if the efficiency obtained in simulated scenarios could be approached in practice, which requires a well-populated and relevant historical database, i.e., the target maneuvering patterns of the current sequence have to be sufficiently correlated to those of geographically similar historical sequences. Obviously, the more paths are randomized, the less useful information can be extracted.

On the other hand, when a large database of intelligence reports is available it seems logical to test in practice the assumption that movement patterns are frequently repeated. Key to the understanding and evaluation of this concept is the realization that the "patterns" found are not prespecified with regard to location, shape or size, but are discovered by the process and thus not subject to human prejudice or any other bias than that determined by the composition of the learning set.

Part III. Design Factors for a Future AASW DBA Architecture for Sweden

In order to obtain information about undersea target movement in the Baltic sufficiently complete to attain DBA, a vast, networked array of undersea sensors would seem to be required. The only alternatives to this we can imagine would be a high-altitude, possibly space-born, surveillance system using some (hitherto probably non-existent) kind of scanning or imaging sensors, or a large fleet of low-altitude or surface moving platforms which scan the water volume in a coordinated manner. The latter options do not seem realistic to us since we are not aware of any space-born system able to penetrate both thick clouds and the sea to sufficient depth; furthermore, even fast ladar scanning systems are limited to scanning about 10 km^2 per hour per platform in favourable weather conditions (see below), far less than required for DBA. Ladar may well be used to complement other sensor systems, however.

We conclude that for the foreseeable future only an underwater sensor network would seem technically feasible. This network would have to be complemented by a surveillance system (presumably mainly radar-based) which can provide continuous tracks and classifications of surface targets, and a fusion component able to distinguish surface ships from submarines.

What emissions or other signatures could be used for the purpose ? Sound emission and extremely-low-frequency electromagnetic fields (ELF) carried by the water body are proven possibilities and should probably be used in conjunction, to improve the prospects for correct classification. Other more exotic possibilities, such as SAR radar observation of surface wave patterns caused by submarine-induced internal waves have been proposed [Gardner 1996, p. 149], but do not seem to warrant further attention in this scenario.

Undersea Sensors for AASW

As a result of the perceived submarine threat in the 80's, the Defence Research Establishment has gradually built up a world-class center for research into the interaction between submarine sensors, targets, and shallow-water environments [Hydroakustik 1995] [Hydroakustik 1997]. Less emphasis has been given to the issue of interaction between sensor system architecture, surveillance tactics, and interpretation of reports, including issues of higher-level information fusion. In this section, we will briefly and qualitatively survey the sensor options and problems that are associated with AASW. We must apologize to the true experts for necessary oversimplification and possible omission of important aspects.

Clearly, from the tactical viewpoint clandestine passive sensors will be superior to active or semi-active ones, if they can provide sufficient coverage at a reasonable cost. Thus, we restrict our attention to passive sensors which are deployable on the sea-floor and may be left without maintenance for a long time, in spite of biological activity and possible mechanical disturbance caused, e.g., by waves and currents.

A passive sonar registers not only the sound from a possible target, but all sounds above a certain level and within the frequency range of the sensor. Other sound sources could, e.g., be surface boats and ships, animals, divers, waves, or wind. The background noise from such sources makes the signal of interest uncertain and hard to distinguish. There is always a possibility that the sonar system will make a wrong decision (false alarm, no-detection possibility). Distinguishing the signal of interest from background noise will become increasingly difficult due to the likely development of extremely quiet submarines, whose unavoidable sound emission will generally consist of low-frequency, broad-band noise.

In a shallow-water archipelago, these problems are further compounded by strong reverberation effects, caused by sound reflection from the sea-floor, the surface, and nearby islands, which may give rise to various interference phenomena. In good conditions, a 100 dB re 1 μPa at 1m source level target could be heard over a distance of several kilometers while the same source level may only be heard over a distance of a few hundred meters at a position where the conditions are poor.

In "well-behaved" environments, acoustic sensor arrays may provide much better range and angular resolution than single, pointlike sensors, but in difficult archipelagic conditions these advantages will not persist. Although large areas of the Baltic may provide adequate conditions for using sensor arrays, we will assume for the purpose of this paper that it does not. Thus, our estimates of the necessary number of sensor elements may be unnecessarily pessimistic. On the other hand, in relation to ocean environments it is to our advantage that across vast areas, the shallowness of the Baltic makes localization of the target an essentially two-dimensional problem.

Historically, electromagnetic loop detectors (using the same operating principle as common metal detectors) have been extensively used to guard narrow straits in the archipelago. They have the geometrical advantage of being able to watch a linear strip, but their range is very limited and they would not be useful in the open sea, even one as shallow as the Baltic.

A particularly interesting development is fibre-optic sensor technology, which can be adapted both to acoustic and electromagnetic measurements [Zyra & al 1995a, 1995b, 1997] (and to many other kinds of measurement as well). These sensors share the properties of requiring no submerged electric components, they are difficult to detect and intercept, can be connected by optical fibres tens of kilometers long, are highly sensitive across a wide frequency band, including extremely low frequencies, are free from electromagnetic interference, and can work across a large dynamic range. Signals from several sensors can be multiplexed in the same fibre. Fibre-optic hydrophones can be made entirely from non-metallic parts. The main drawbacks of fiber-optic sensors are that they require complex signal processing, require special skill in handling when disassembled and are more expensive than conventional underwater sensors. Except for the higher unit cost, for use in large DBA sensor networks their properties seem close to ideal.

There have been considerable advances in the design and use of electromagnetic sensors in recent decades, both with respect to so-called *SQUID* (*Superconducting Quantum Interference Device*) sensors, employing the quantum-mechanical Josephson effect at superconducting temperatures, and to fibre optic sensors, as discussed above. The sensitivity of SQUIDs is extremely high. Employing such sensors, a moving submarine, or rather the field change it induces when water is moved, might be detectable at a distance of several hundred meters. SQUIDs require cryogenic temperatures to operate, however (this will be the case until the Holy Grail of room-temperature superconductivity is found). For this reason, they are at present not candidates for inclusion in a vast, largely unattended sensor network.

The difficulty and high cost for conventional mapping of the archipelagic seabed has created an interest in developing new, faster and safer methods for shallow-water mapping. Steinvall and his colleagues at the Defence Research Establishment developed a laser bathymetry system [Koppari & al. 1995], which has since been refined into a commercial product. With this system, it is possible to map shallow water areas from a helicopter flying at an altitude of 300 m, down to a depth of about 30 m in favourable sight conditions. The system is theoretically capable of scanning an area of more than 10 km^2 per hour in favourable weather conditions. A possible use for the equipment is *difference detection*, in which an emerging target would be found by subtracting the current image from a previously recorded one.

Sensor System Architecture

In the following sections we will discuss architectural concepts for a future underwater surveillance system for the Baltic, which could conceivably detect and track any incoming submarine. Eventually, we need to find criteria for selecting and structuring future sensor systems in such a way as to achieve a specified capability across a wide surveillance area. Given such criteria, it might be possible to decide the critical parameters, including cost, of a fielded system.

Key tasks for a DBA ISR architecture, apart from initial detection, are classification, prediction, and tracking of targets. Past failures of classification, in which swimming minks and possibly other biological activity as well have been classified as certain submarines, and more than a few instances of firing against rocks on the sea-floor have occurred, show that this is a difficult problem which can not always be reliably solved by human sonar operators even in the case of a single sensor system. In a DBA architecture, human target classification must be the exception rather than the rule and multi-sensor fusion techniques must carry the bulk of the burden of classification. This means that precise depth measurement and tracking to determine the target's detailed dynamical behavior, as well as concomitant measurement of electromagnetic properties which distinguish a large, moving metallic rigid body from biological phenomena will be needed.

Prediction will be required in near real time, and will be desired also for the short (minutes), medium (hours), and long term (days or more). Clearly, the concept of prediction has a somewhat different meaning when performed in real time where the target movement is largely controlled by immutable physical laws, than over longer time periods where likely intents, available experience, and historical patterns have to be invoked. If continuous real-time tracking is required, as when the target is to be attacked, it should be based on real time prediction using Kalman filters. Otherwise, unless observations are too sparse, the tracking methods for sparse data discussed above should be useful.

The geometry and topology of the sensor network needs to be adapted to the characteristics of the local environment, to the required level of protection which of course may vary considerably across the surveyed area, and to the need for redundancy in the communication network.

These requirements should be satisfied under a range of difficult conditions such as bad weather, in difficult terrain such as canyons, steep island shores and rock-strewn areas, and for a large range of target speeds. In critical situations, the target might resort to using countermeasures such as decoys, bubble curtains and sound generators, or it may dwell silently on the sea-floor or decide to accompany a merchant vessel.

Because of the very limited guaranteed range of underwater sensors in the archipelagic environment, a common solution to all these problems will require a dense and multi-faceted sensor network. But considering the vast area to be covered, we see as the only feasible solution the combination of a sophisticated, static network of undersea multisensors with varying areal density, and an alert fleet of manned or remotely controlled airborne vehicles which can deploy additional sensors, such as passive sonobuoys and/or ladar, to track the target in real-time once it has been initially detected by the stationary network. Below, we will discuss a novel technique for doing this, which is heavily dependent on data fusion techniques.

Is Dominant Battlespace Awareness a Future Possibility in AASW ?

The concept of DBA is a revolutionary one and its imagined application to AASW perhaps even more so. Rather than rejecting the concept out-of-hand, however, we should seriously consider the conditions for its feasibility.

Let us assume that we have available a radar or combined radar-optical surveillance system which can detect and localize any surface vessel to within a few tens of meters. Such a system, or an equivalent method for continuous localization of surface vessels, will be required to separate submarine and surface targets. We also assume that the undersea sensor deployment problem is to be solved entirely by use of passive point sensors.

To estimate the number of underwater sensors needed to cover a certain (large) area, one may reason as when estimating the mean free path of a molecule in an ideal gas. Assume that a large number of pointlike sensors with the same circular detection radius *r* have been randomly distributed across the bottom of a shallow sea. First, note that the probability of detection of a pointlike target moving with constant speed *u* along the planar sensor field during one unit of time, will equal the probability of a rod of length *2r* (and perpendicular to its direction of movement) and the same speed hitting at least one of the sensor locations. With *n* sensors per unit area, the rod will hit an average of $\bar{z} = 2 \cdot r \cdot u \cdot n$ sensors while travelling for one time unit. The mean free path becomes $\bar{\lambda} = u/\bar{z} = 1/(2 \cdot r \cdot n)$ units of length. Thus, with $u = 1\ m/s$, $r = 100\ m$, $\bar{\lambda} = 1000\ m$, which are conservative but not entirely unrealistic figures, we get the sensor density $n = 5$ sensors per km^2. Recall that the area of the Baltic is $4 \cdot 10^5\ km^2$. Thus, to cover one fourth of the area of the Baltic with a sufficient number of sensors to achieve this mean free path would require the deployment of half a million sensors with associated cable connections! Or one can check the mean free path obtained with $u = 5\ m/s$, $n = 10^{-2}$ sensors per km^2, i.e., a total of 1000 sensors uniformly dispersed across a fourth of the area of the Baltic, assuming (again, very roughly) $r = 10^3\ m$. We get $\bar{\lambda} = 5 \cdot 10^4\ m = 50\ km$. So with 1000 sensors, a modern submarine speeding at 10 knots could penetrate on average 50 km into the sensor field before getting detected, which does not seem much of an achievement for the money.

To reduce the number of sensors, one could perhaps use instead a band-shaped sensor deployment area, e.g., 10 km wide and 500 km long. At the sensor density $n = 5$ sensors per km^2, such a band would contain 25000 sensors and provide almost certain detection of even very silent submarines.

A word of caution is appropriate here: these are very rough estimates which depend strongly on target source level as function of its speed, as well as on weather conditions and various other environmental factors (see, e.g., [Burdic 1991]). But the calculations should show, within perhaps an order of magnitude, the maximum required number of pointlike, passive acoustic sensors needed to achieve detection at two different target speeds in non-extreme weather conditions.

Using Multi-Sensor Data Fusion and Reactive Planning in AASW Target Tracking

The goal of achieving complete DBA from stationary sensors alone seems to us economically unattainable. Therefore, we have investigated the effect of employing multisensor data fusion and optimal real-time sensor allocation in shallow-water target tracking using passive, non-directional sonobuoys [Jöred & Svensson 1998]. Specifically, assuming a single target moving along a predetermined two-dimensional path, we have developed a tracking method which maximizes the tracking path length subject to the two conditions of a limited supply of sonobuoys and a prespecified tracking performance.

We have developed a simplified two dimensional model without islands and bottom structure although we expect our main conclusions to be valid if the model were applied to real sonobuoy data.

In the model's world, it is possible to track a hostile submarine in shallow-water environments using only passive, non-directional sonobuoys. With four or more sonobuoys in suitable positions the submarine's position can be estimated and a confidence ellipse for this position calculated. A Kalman filter is used to obtain a prediction of the target's motion, as well as a reduction of the uncertainty in the position estimate. By determining the uncertainty of a future measurement as a function of buoy placement, an optimization algorithm can calculate a near-optimal position for the next buoy to be deployed. A critical factor in the simulation is the time span from the initial observation until contact has been regained.

We find it encouraging that the notoriously difficult problem of tracking a submarine in an archipelagic environment might lend itself to a solution which requires neither sophisticated and inherently uncertain modelling of long-range signal propagation patterns nor a vast network of static sensor elements.

Discussion

Any sensor network capable of delivering DBA will produce a deluge of data which will have to be interpreted, fused, and acted upon in real time in order to be of significant defensive value.

Presumably, each sensor system automatically produces its own target tracking information, expressed in global space-time coordinates. Tracks that have been produced by more than one system will then have to be fused. The system will be required to routinely distinguish submarine targets from surface ships through fusion of radar and undersea sensor information, perhaps even if the submarine "hides" underneath a large surface vessel.

Historically, Sweden has been reluctant to spend significant resources on round-the-clock ground and subsea surveillance, although its air space and sea surface have been continually watched from control centers. Will a system that is not on continuous high alert be at all useful in a crisis situation (the famous "Whiskey on the rocks" episode in 1982 [*Ubåtsfrågan 1981-1994* 1995] took Swedish authorities by complete surprise although the sub travelled only half-submerged through a military protected area) ?

If the answer is yes, what will be required to raise the awareness, and how quickly can it realistically be done if a crisis were to occur ?

What size and kind of organization, with what skills, will be required for full-scale operation of the control centers ?

Conclusions

AASW is not a platform problem, nor is it a sensor problem, a depth sounding problem or a weapon problem. Neither can AASW be won by ever so careful planning of force deployment. Successful AASW, if at all possible, will have to develop its own DBA architecture and an associated array of information fusion methods in order to materialize. This architecture, in turn, will rely heavily on state-of-the-art sensor technology and environment measurements. Our largely qualitative and admittedly superficial analysis makes us believe that a combination of a dense fibre-optic multisensor network, perhaps banded rather than homogeneously and densely area-covering to reduce costs, in combination with a data-fusion-controlled sonobuoy delivery system or/and a difference-detection-based ladar system would provide a cost-effective solution of the problem. The next step in our analysis should be to calculate an optimal mix of these system components, based on realistic cost figures.

The last link in the AASW chain, to effectively hunt down a submarine once it has been located, identified, and tracked, is of course no less critical and will require employing intelligent, autonomous or remotely-controlled underwater weapons, but knowing accurately and in real time the space-time coordinates of the targets, as well as having them reliably classified, are certainly the most critical conditions for success.

References

Alberts, D. 1995. The Future of Command and Control with DBK. In Johnson & Libicki (Eds), *Dominant Battlespace Knowledge* 67-88.

Andersson, P. och Sjölander, R. 1992. *Förklaringsgenerering med hjälp av Glenn Shafers och Arthur P Dempsters evidensteori*, FOA C 20867-2.7. Stockholm: Försvarets forskningsanstalt.

Bar-Shalom, Y., and Li, X.-R. 1993. *Estimation and Tracking: Principles, Techniques, and Software*. Boston: Artech House.

Bergsten, U., and Schubert, J. 1993. Dempster's Rule for Evidence Ordered in a Complete Directed Acyclic Graph, *International Journal of Approximate Reasoning* **9**(1):37-73.

Bergsten, U., Schubert, J. och Svensson, P. 1989. Beslutsstödssystemet DEZZY - En översikt, *Dokumentation 7 juni av Seminarium och fackutställning om samband, sensorer och datorer för ledningssystem till försvaret* (*MILINF* '89). Växjö, Sweden:Telub AB.

Bergsten, U., Schubert, J., and Svensson, P. 1997. Applying Data Mining and Machine Learning Techniques to Submarine Intelligence Analysis, *Proceedings of the Third International Conference ond Knowledge Discovery and Data Mining*, 127-130. Menlo Park, CA: The AAAI Press.

Burdic, W. S. 1991. *Underwater acoustic system analysis*. Englewood Cliffs, NJ: Prentice Hall Inc.

Elg, R. 1992. *Sökgraf för kortaste vägen i planet*, FOA C 20891-2.7. Stockholm: Försvarets forskningsanstalt.'

Gardner, W. J. R. 1996. *Anti-Submarine Warfare*. London: Brassey's.

Johnson, S. C., and Libicki, M. C. (Eds) 1995. *Dominant Battlespace Knowledge*. Washington, DC: Institute for National Strategic Studies, National Defense University.

Jöred, K., and Svensson, P. 1998. Submarine tracking in Archipelagic Submarine Warfare: A Not-So-Impossible Proposition ? *Proceedings of the Conference Undersea Defence Technology Europe 98 (UDT Europe 98)*. Swanley, UK: Nexus Media Ltd.

Koppari, K., Karlsson, U., and Steinvall, O. 1995. Airborne Laser Depth Sounding in Sweden, *Proceed-*

ings Hydroakustik 1995.

Proceedings Hydroakustik 1995. 1995. FOA-R--95-00173-2.2--SE. Stockholm: Försvarets forskningsanstalt.

Proceedings Hydroakustik 1997. 1997. FOA-R--97-00552-409--SE. Stockholm: Försvarets forskningsanstalt.

Schubert, J. 1993. On Nonspecific Evidence, *International Journal of Intelligent Systems* **8**(6):711-725.

Schubert, J. 1996a. Specifying Nonspecific Evidence, *International Journal of Intelligent Systems* **11**(8): 525-563.

Schubert, J. 1996b. *Prediktion av främmande ubåtars framtida position*, FOA-R--96-00296-3.4--SE. Stockholm: Försvarets forskningsanstalt.

Shafer, G. 1976. *A Mathematical Theory of Evidence*. Princeton, N.J.: Princeton University Press.

Strat, T. M., and Lowrance, J. D. 1989. Explaining Evidential Analyses, *International Journal of Approximate Reasoning* **3**(4): 299-353.

Ubåtsfrågan 1981-1994. Rapport från Ubåtskommissionen. 1995. Stockholm: SOU 1995:135.

Zyra, S., Kullander, F., and Laurent, C. 1995a. Fibre-Optic Sensors for Underwater Acoustics. In *Proceedings Hydroakustik 1995*.

Zyra, S., Kullander, F., and Laurent, C. 1995b. Fibre-Optic Magnetic and Electric Field Sensors and Fibre-Optic Sensor Multiplexing. In *Proceedings Hydroakustik 1995*.

Zyra, S., Kullander, F., and Laurent, C. 1997. The Fibre-Optic Hydrophone: Limitations and Performance Characteristics. In *Proceedings Hydroakustik 1997*.