An Automated Approach to Passive Sonar Track Segment Association

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Abstract

The primary objective of passive surveillance is to covertly develop situational awareness. In the underwater environment, passive sonar is commonly used to detect and track targets by their own acoustic emissions. Although significant advances have been made in sensor technology and front-end signal processing, much of the work of identifying targets from a series of intensity peaks in time and frequency is left to the human operator.

A single target vessel will typically produce acoustic emissions at multiple frequencies. These signals may travel along multiple paths to a receiver and may be intermittent in time. Each emission is represented to the sonar operator as a signal track segment from a potentially unique source.

Passive sonar association is the process of associating signal track segments across time, frequency or bearing into master tracks that are common to a single source vessel. Although rudimentary tools exist to assist the operator in this task, it can be very labour intensive and relies heavily on the operator's training and experience. The use of an automated passive sonar association system or aid has the potential to improve situational awareness in the underwater environment and reduce the response time to threats by increasing the effectiveness of the human operator and potentially making use of information not available to the human operator.

In this paper we discuss how background knowledge of the characteristics of an acoustic source, such as a generic submarine, and its environment can be used to identify signal track segments as candidates for association. This process can be described in three stages. In the first stage a rules-based approach is used to identify pairs of track segments as candidates for association, based on the plausibility of potential scenarios under which such a pair might occur. In the second stage, the degree of commonality between the candidate signal track segment pairs is evaluated to develop evidence for or against their association. In the final stage, the results of the commonality tests are digested into recommendations to the operator to take action to associate or disassociate track segment pairs.

1. Introduction

Passive sonar can be used in the underwater environment to detect and track vessels by their own acoustic emissions [Blackman, 1986; Hall, 1992; Iotek, 1992; McIntyre and Roger, 1993; Peters, 1991; Roger, 1994; Urick, 1983]. Tracking a vessel's own emissions holds several advantages over active sonar in that it can be done covertly, and has the potential to uniquely identify types or individual pieces of target equipment. In some cases, such as high reverberation environments or targets with very small scattering cross-sections, passive sonar may be more effective than active sonar. Conversely, signals of opportunity may be unstable in frequency or intermittent in time, making them difficult to follow when they can be detected. The passive tracking problem is further complicated by the lack of any obvious signal travel time information and the potential for multi-path propagation. However, much useful information can be derived using prior knowledge of the underwater environment as well as of some of the likely target types.

The acoustic signals available to an observer are a function of the target's relative position, course and signature, and the local environment. By making use of prior knowledge of the underwater environment as well as of some of the target types, the potential exists for an observer to determine the position, velocity and classification of local targets. The signals received by the observer typically consist of multiple series of energy peaks in frequency, bearing and time, which can be assembled into track[1] segments by automated signal trackers. Although some higher-level information can be derived from these signal track segments, their value can be greatly enhanced by associating track segments related in time, frequency and bearing into master tracks. This process has several advantages. It not only reduces the number of track segments that must be considered as potentially independent targets, it also increases the information content of the consolidated tracks.

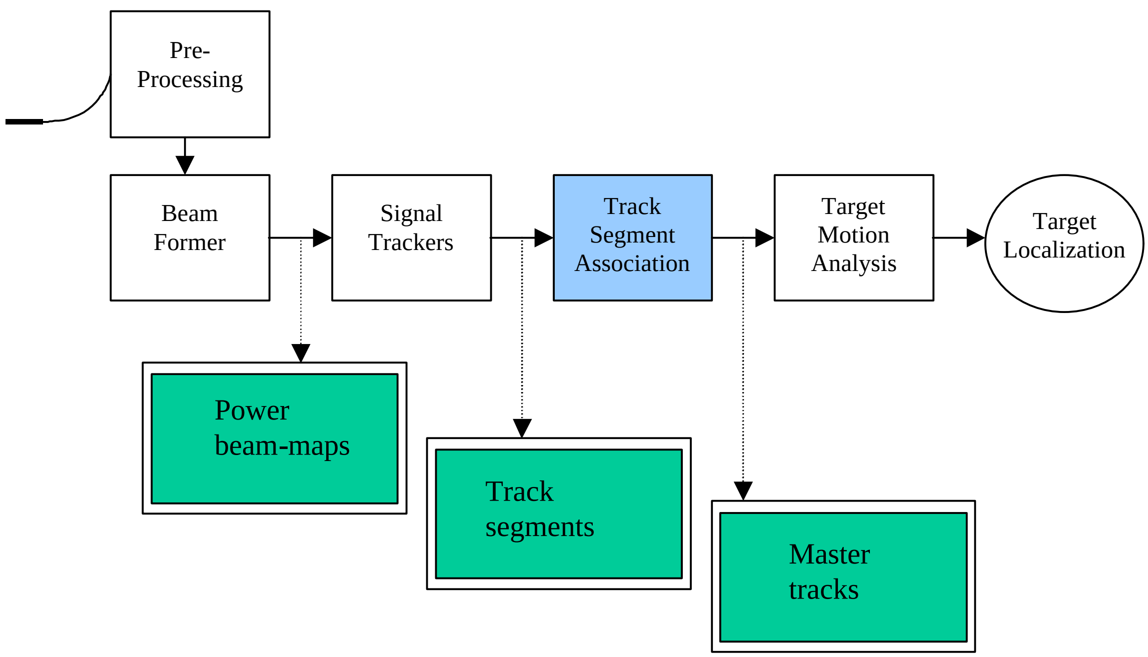

Figure 1. Block diagram of a typical towed array passive sonar system. The upper path represents the system processing flow, while the shaded rectangles below represent available displays.

[1] In this context we are tracking the target's bearing, and possibly frequency, in time. As passive sonar cannot determine range directly, target kinematic information is not available until the target motion analysis is complete.

Consider the block diagram of a typical passive sonar system shown in Figure 1. The sensor in this case is a towed array. It is currently the responsibility of the human operator to associate the signal track segments generated by the signal trackers into master tracks. These are then analyzed using target motion analysis to develop a target localization solution, i.e., target classification, position, course and speed. The quality of the track segment association can directly affect the quality of the localization solution. But in a modern scenario, searching for a quiet target against a background of multiple interfering sources in a highly reverberant littoral environment, the operator faces a daunting task. One method by which this role can be improved is with the use of an automated passive sonar association assistant.

The goal of this work is to develop a methodology that could be used by an automated system to provide assistance to the human operator in the passive sonar association task. The chosen approach is to divide this problem into three stages: identification of potentially associable track segment pairs, evaluation of the degree to which a pair of track segments might be associable, and reduction of the collection of evaluations into a recommendation to the operator.

2. Candidates for Potential Association

A single signal source may produce multiple track segments due to the characteristics of the source itself or the underwater environment. An understanding of the mechanisms by which these multiple segments are developed provides insight into the ways in which the related segments may be identified and evaluated for potential reassembly, one pair at a time, into a single master track.

2.1 *Temporal Association*

In the case of passive sonar, the range to and speed of a target vessel are not immediately apparent, but can be derived from its bearing and bearing rate before and after an ownship manoeuvre. The accuracy of a localization solution derived from a signal track is therefore strongly influenced by the length and character of the track. A number of factors can temporally fragment a track, including rapid changes in the apparent target vessel bearing, rapid changes in the apparent frequency of the source signal, low signal to noise ratio due to factors such as fading or a strong interfering signal, flexure of the towed array due to an ownship manoeuvre or intermittent operation of the source equipment. The ability to associate these fragmented track segments in time increases the accuracy of or may be critical to the localization process, especially in the case of segments fragmented by an ownship manoeuvre.

A number of criteria are available by which pairs of signal track segments that have significant potential for temporal association can be identified. Continuation of frequency and/or bearing is one such criterion. Consider the situation where the seduction of a signal track by a nearby source causes the tracker state bearing or state frequency to change rapidly, abruptly ending the signal track segment. In this case an additional track segment corresponding to the original source signal would likely soon be initiated at a similar bearing and frequency to the initial segment. Continuation of frequency or bearing could identify this pair of track segments as candidates for association.

In the case of an intermittent narrowband track, one segment of which is already associated with a broadband track, the bearing and bearing rate information of the broadband track can be used to select appropriate candidate track segments for association. This scenario provides the potential to form associations across ownship manoeuvres during which the towed array flexes and the apparent target bearing and range change significantly due to data corruption. Long narrowband tracks are potentially more useful to target motion analysis than broadband tracks as they contain frequency information that could potentially yield Doppler shift as well as classification information.

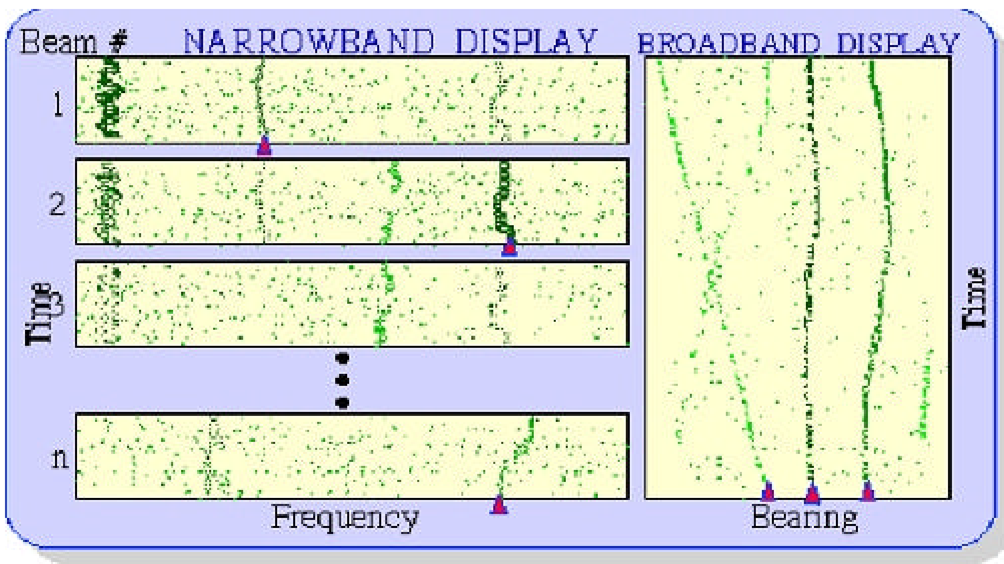

Figure 2. Typical passive sonar narrowband and broadband intensity displays. The narrowband display shows acoustic data as frequency versus time for each angular beam. The broadband display shows the same data as bearing versus time. Signal trackers are used to identify continuous signal segments in the acoustic data.

In some cases, the characteristics of the source signal are sufficiently distinct as to significantly reduce the likelihood of a coincidental track with similar characteristics. The characteristics may be structured variations in amplitude or frequency, for example, although the long integration interval of most sonar signal trackers severely constrains the range of useful variations. Given a sufficiently unique set of signal characteristics, association candidate pairs could be identified across bearing and frequency.

2.2 ***Frequency Association***

A single underwater target can generate acoustic signals at multiple related frequencies, typically described a fundamental, harmonics and sub-harmonics. These frequencies can arise as components of a complex signal from a single source, such as a tapping lifter, or from multiple pieces of machinery interconnected by sets of gears, such as the drive gear assembly. In either case, the relationship between a given pair of frequencies can be very stable and need not be an integer ratio.

Having identified an harmonically related pair of signal track segments, knowledge of their approximate frequencies and their highly stable ratio can be used to form additional temporal associations, even across extremely disruptive events such as a significant ownship manoeuvre. Sets of harmonically related frequencies are often unique to individual machines or classes of machinery and, given sufficient prior knowledge, can be used to classify the target vessel by type or even hull number.

Some harmonically related signals may also arise from equipment that is interconnected in a semi-synchronous manner, such as through a clutch or an electrical connection. As this relationship is much weaker, the criteria for this type of harmonic association would demand that the scale of the common frequency variations be much greater.

Variations in the signal propagation conditions may significantly degrade the amplitude of harmonic components in the band of interest. Whether by accident or design, the first noticeable harmonics of a target's main propulsion system might be a few decades above its fundamental.

2.3 ***Bearing Association***

Energy arriving at a towed array receiver is presented to the operator on both narrowband and broadband displays. An example of a typical set of displays is shown in Figure 2. On the broadband display, the information is presented as an intensity plot of bearing versus time, while on a narrowband display the same information is often presented as a series of intensity plots of frequency versus time, each plot corresponding to a given beam angle. Since the towed array is linear, the beam angles represent conical angles about the array.

Multiple signals which are not harmonically related, e.g., pumps, air conditioning, etc., may be produced by the same vessel. When these signals arrive along the same path they are aggregated into a single track at the corresponding bearing on the broadband display. In the narrowband case the signals can be tracked individually by frequency and bearing. The bearings and bearing rates in this case will be near, but not necessarily identical to the bearing and bearing rate of the broadband track. These signal track segments could potentially be associated into a master track.

The benefits of association in this case are multifold. The stronger broadband track provides a reference from which it may be easier to follow weaker narrowband tracks that may fade and reappear as equipment is cycled or as propagation conditions vary. The narrowband tracks, in turn may provide information as to the kinds or sequence of activity onboard the target vessel. Further, particular combinations of equipment at a common bearing may identify an individual vessel or vessel type.

Candidate signal track segment pairs may also be identified across bearings. A given signal may travel from the target vessel to the towed array along a direct or multiple reflected paths as shown in Figure 3. Due to the conical nature of the towed array beam pattern, the effect of one or more bottom or surface reflections is to bias the apparent angle of the target toward broadside. The Doppler shift along the longer reflected path is also smaller than along the shorter direct path. The reception quadrant, however, is invariant.

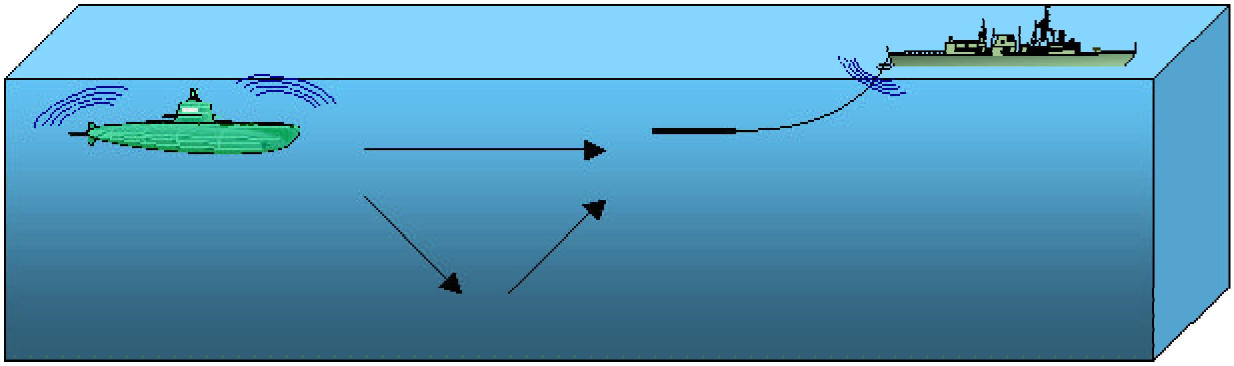

Figure 3. Direct and bottom reflected propagation paths between a target submarine and a towed array at the same depth behind the ownship.

The time delay between a pair of received transient signals at differing angles from the same source can provide an estimate of the difference in their path lengths. From prior knowledge of the local bathymetry, an operator can project these paths backwards from the towed array to determine the range and depth of the target vessel. In cases where the time difference is unavailable, the target vessel depth may be assumed and the time delay estimated.

In some cases, such as that of an extremely large signal to noise ratio, sidelobes in the beamforming calculation may cause artifacts to appear at bearings adjacent to a received signal. In this case the signals would be coincident in time.

3. **Gathering the Evidence**

Having identified pairs of signal track segments as candidates for association in time, frequency and/or bearing, the problem advances to that of developing a case upon which to make an association decision. A variety of tests have been proposed, each typically as a sole basis upon which to form an association recommendation or decision. While each test may be uniquely suitable within a particular set of circumstances, a more broadly applicable solution may be constructed by assessing the outcomes of a number of basic tests in some structured manner. Let us consider some of the tests that might be applied to the candidate pairs.

3.1 ***Tests for Temporal Association***

A correctly formed temporal association associates two signal track segments into the master track that would have been formed had the earlier signal track segment continued without interruption. Continuity of the signal track segment implies that the characteristics of the latter segment are consistent with those of the former and that the two segments are in no way coincident in time. The degree of temporal association between two track segments is a measure of the likelihood that the two segments refer to the same signal at unique points in time. Given sufficient evidence in favour of association, the track segments can be assembled into a single master track representing the received signal over the combined time of the segments. This evidence might begin with a test for temporal continuity, but is typically confirmed by recognized similarities in the segment bearing and frequency information.

The potential for temporal continuity can be established by determining whether the latter of the two track segments falls within a gate that slews and broadens in both bearing and frequency as it extends from the end of the earlier track segment. The degree of slewing and broadening in bearing and frequency is determined by their respective rate and variance near the end of the earlier track segment. It should be cautioned that the reliability of the parameters of a track segment diminishes significantly as the signal follower loses lock. The useful duration of the gate is often a function of the local environment, especially the reverberation time.

A primary test for temporal association therefore is the degree to which the bearing and frequency gates must be broadened to connect the two track segments. The track segments must do more than intersect, however, and the degree to which vectors representing their frequency and frequency rates and bearing and bearing rates coincide is another valuable measure of their associability. A second set of parameters may be developed to describe the texture of the bearing and frequency variations in time. In this case the characteristics of interest are periodic variations that may be separately considered as wander, having a period greater than the tracker integration time, and jitter, having a period shorter than the integration time. The texture in the former case may be further described by spectral content, while in the latter case may be indistinguishable from noise.

3.2 ***Tests for Bearing Association***

A correctly formed bearing association associates, into a master track, two signal track segments representing signals that originated from the same target vessel. As these signals have typically traveled along the same path between the target and receiver, important primary tests in this case are based on a common received bearing.

The bearing history of a track segment can be summarized using a vector indicating the track bearing and bearing rate over time. Track segments with similar bearing vectors are likely to have been developed from signals with a common origin. The bearing covariance or mean bearing difference of a signal track segment pair can give further evidence toward a common origin. Especially valuable in this case are unexpected bearing variations that are common to both track segments, although a useful description of these may be difficult to quantify.

A test for similarities in texture may be applicable in this case, although there is no expectation here that the track segment pair were developed from the same source signal aboard the target vessel. The common features in this case may be due to their common path.

Bearing associations can be established between pairs of track segments that were developed from the same signal having travelled along two different paths, e.g., direct and bottom-reflected, and arrived at differing bearings. The usual bearing association tests may be used here, with suitable adjustment for the difference in travel time. Unless the difference in the two path lengths is quite large, it may not be necessary to make adjustment for it in light of the typically large tracker integration time. A simpler approach here may be to consider harmonic association with a unit frequency ratio.

3.3 ***Tests for Harmonic Association***

A correctly formed harmonic association associates, into a master track, two signal track segments representing signals that originated from multiple spectral components of the same source. In the initial, more conservative, analysis the signals will also have propagated along the same path from the target vessel to the receiver. Tests can be applied in this case with limited need to account for differences related to propagation, such as arrival time, angle of arrival, or dispersion.

In the simplest case, the signal harmonics will have traveled along coincident propagation paths. An obvious test, therefore, might consider the mean bearing difference between the pair of candidate track segments. The stability of the harmonic relationship should also be evaluated, by both determining the mean ratio of the two frequencies and their covariance. Should the two signals have followed differing paths, e.g., direct and bottom reflected paths, this will be reflected in the results of a test for changes in the difference between their bearings.

A test for similarities in texture may also be useful in this case although the common features not already observed by other tests may be due to their common paths. As with bearing association, those components that are possibly most valuable in evaluating the potential for association are unexpected variations that are common to both signal track segments.

4. **Weighing a Decision**

In the previous section we considered a variety of tests that could be used to build a body of evidence from which to make a track segment association decision. A variety of methodologies have been proposed with which to distill track association decisions from this evidence, some of which will be discussed here.

A rule-based approach may be considered as the most straightforward methodology. In its simplest case, it can process unambiguous test results through a series of if-and-then-else conditions. The complexity of the system, however, increases rapidly as the test results become more ambiguous and/or the conditions become subtler, making the methodology unmanageable.

Association decisions may also be arrived at from a weighted sum of primary test results. This methodology has the advantage of accommodating continuously variable test results, but may have difficulty reconciling combinations of strong positive and negative test results. A weighted-sum methodology also requires prior knowledge of the cost function for each recommendation outcome, although this may be arrived at in an automated manner from a set of training data by using a neural network.

Probabilistic methodologies have been proposed which assign likelihoods to the association outcome based on the results of the primary tests. In a Bayesian approach, the tests results contribute to the likelihood of a particular outcome, but the method may be hampered by a lack of information as to *a priori* probabilities. A more significant shortfall may be its inability to adequately describe a scenario in which the appropriate outcome may be neither yes nor no, but maybe.

In the Dempster-Shafer methodology, probabilities are assigned to each of the three potential outcomes of a test: yes, no and maybe. This method combines the incremental approach to information of the weighted sum and neural network methodologies with a probabilistic approach that attempts to provide a natural representation of ignorance. The issue of appropriate weighting is still unresolved however, yet it may well be best dealt with initially by an ad hoc choice of values and later revised.

5. **Summary**

In this paper we have described a multi-stage approach to passive sonar signal track segment association. In the first stage, preliminary criteria are applied to identify pairs of signal track segments as candidates for association. Temporal associations may be formed between track segments that are disjoint in time, bearing associations may be formed between track segments that share a common bearing or bearing sequence, and frequency associations may be formed between track segments that are harmonic in frequency.

Having identified pairs of signal track segments as candidates for association, a series of tests can be applied to evaluate the compatibility of the tracks in terms of characteristics relevant to the association type. Not all tests are unique to a single type of association and no single test is used to independently determine an association result.

In the final stage of this approach, the results of the associability tests are processed to develop an association decision or recommendation to the operator. Use of Dempster-Shafer probabilities in this stage permits the intermediate outcome to represent not only the amount of confidence that the tracks should be associated, but also the amount of certainty that the tracks should not be associated, where the two values do not necessarily form a unit sum. From these numerical values, operator-specified thresholds can be used to make graduated association recommendations.

6. **References**

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