

Broadband Passive Sonar Tracking

Kevin Brinkmann and Jörg Hurka

ATLAS ELEKTRONIK GmbH, Sebaldsbrücker Heerstr. 235, 28309 Bremen

Email: {kevin.brinkmann, joerg.hurka}@atlas-elektronik.com

Abstract: Passive sonar sensors are the main source of information for a submerged submarine. Modern sonar systems like ISUS 90 offer a number of acoustic antennas and combined signal processing for broadband and narrowband analysis of target noise. While the narrowband processing is essential for target analysis and classification, broadband detection gives an overview of the targets surrounding the own ship. Tracking of the broadband target bearings followed by a target motion analysis (TMA) of the bearing histories to infer about target course, speed and range can be used to build up a tactical picture of the operational sea area. In order to reduce the errors in the TMA solution, high quality bearing tracks entering the TMA algorithm are essential. For an automatic tracking system, the number of false tracks should be as small as possible. This paper presents a multi-target tracking system for broadband passive sonar based on a multi-hypothesis tracking approach. It is designed to automatically track all of the broadband targets thereby releasing the sonar operator from routine tasks like track initialization, maintenance and deletion. The design goal is to track all detectable targets, including weak, low signal-to-noise ratio targets, while at the same time minimizing the number of false tracks.

1 Introduction

As electromagnetic radiation is severely attenuated in sea water, a submerged submarine almost entirely relies on acoustic sensors for long range detection and surveillance. Because stealth is a submarine's major advantage over other naval platforms, active operating sonars are only rarely engaged by submariners. Instead, passive sonar arrays are used for long range detection and ranging of other platforms. Figure 1 shows a typical ATLAS ELEKTRONIK ISUS 90 sonar suit for a modern conventional U 214 class submarine. The Cylindrical Hydrophone Array (CHA), located in the bow of the submarine, is the main antenna for panoramic detection and tracking of targets in the medium frequency domain. The Flank Array (FA), located at both sides of the submarine, is used for sound evaluation in the lower frequency band. The FA enables the medium to long range detection and classification of targets. The Towed Array (TA) is a flexible line array which can be deployed from a winch system in the rear part of the submarine. It is designed to achieve excellent performance for long range detection with high bearing accuracy and excellent target separation at low frequencies. The Passive Ranging Sonar (PRS) is an antenna system and signal processing method for ranging targets passively. With three antenna arrays fitted on a discontinuous line on the upper half of the submarine's pressure hull, the incident acoustic wave front curvature is measured by a correlation process. With the knowledge

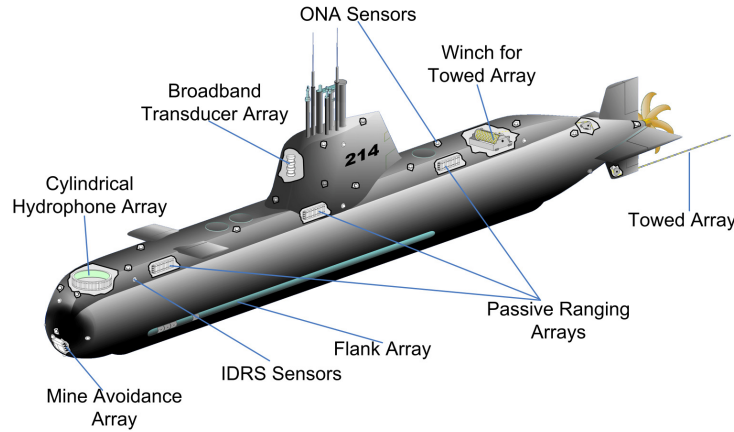


Figure 1: Location of sonar arrays on board of a modern conventional submarine.

of the wave front curvature, the target range can be calculated. The performance of the PRS depends on the acoustic transmission conditions of the sea area of operation and on target range. Surface ships and other naval platforms radiate broadband and narrowband noise originating from their propulsion system and other machinery into the water column. For the CHA, the FA, and the TA there are in parallel broadband and narrowband signal processing chains. While the narrowband processing is essential for target analysis and classification, broadband detection gives an overview of the targets surrounding the own ship. Apart from the Passive Ranging Sonar, passive sonar provides only bearing information. In order to derive target range estimates, bearing tracks of the detected targets of interest are formed. These target bearing histories are input to the Target Motion Analysis (TMA) module which estimates course, speed and range of the target under consideration. In this way, a tactical picture of the sea area of operation can be compiled. In order to reduce the errors in the TMA solution, high quality bearing tracks entering the TMA algorithm are essential. In current operational sonar systems, the initialization, maintenance, and deletion of target bearing tracks is typically performed by the operator.

In this paper we present a novel multi-target tracking algorithm for broadband passive sonar based on a multi-hypothesis tracking approach. It is designed to automatically track all of the broadband sonar targets thereby releasing the sonar operator from the tasks of track initialization, maintenance and deletion. The design goal is to track all detectable targets, including weak, low signal-to-noise ratio targets, while at the same time minimizing the number of false tracks.

This paper is organized as follows. In Section 2 we briefly describe our multi-target tracking system and the algorithms used within it. Section 3 reviews some broadband passive sonar specific features which are important for an automatic tracking routine. In Section 4 we present broadband tracking results for the Cylindrical Array obtained for a simulated scenario with four targets. In Section 5, we summarize and draw conclusions.

2 Multi-Hypothesis Approach

Modern tracking systems can be divided into single-target (STT) and multi-target tracking (MTT) systems depending on the number of simultaneously tracked physical objects (a detailed introduction can be found in [BP99]). An integral part of any such system is a physical sensor, e.g., a radar or a sonar sensor. In the STT case the sensor typically has a small field of view (FOV) and it follows the moving object during tracking, while typically in the MTT case a large FOV is scanned by the sensor and all objects in this region are processed at a time. The sensor signal processing periodically generates lists of detections, e.g., detected radar echoes in the case of the active radar, which are passed on to the tracking unit. The task of the tracking unit is the logical combination of recurring sensor detections which emerged from one particular object and the estimation of its kinematical parameters. Due to the fact that the list of detections per scan not only contains measurements from objects of interest but also false alarms this becomes a sophisticated challenge.

In many cases, the tracking unit is composed of three considerably interrelated main elements as depicted in Fig. 2. The *State-Estimation* block is responsible for estimating the

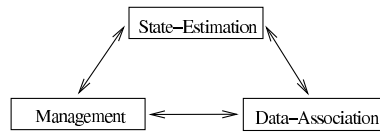


Figure 2: Schematic representation of the main elements of a tracking unit.

true path of an object which is build up by adding together the correct sequence of measurements. This is achieved in close relation with the *Data-Association* block which deals with the correct assignment of newly available detections to already existing sequences of corresponding measurements. Included in the estimator is a motion model for the objects under consideration and a measurement model which describes how the detections are related to the state of the objects whose parameters are to be estimated. For all target tracks the motion model predicts where a new measurement should appear at the next sensor scan. The detections from the actual list are compared with the predicted measurement and the data association routine creates a solution which assigns all detections of the list of measurements to tracks. All the estimated paths formed by the interplay of these two building blocks are called tentative tracks, because the tracking system will treat them as candidates for real tracks.

In the *Management* block it is decided whether a tentative track is to be extracted (confirmed) or terminated (deleted) or whether a respective track candidate will stay tentative. This is done by applying a sequential probability ratio test [vK98], where the probability of the measurement sequence being in accordance with the motion model is set in relation to the probability that the respective sequence represents only false alarms.

Under realistic conditions, the tracking system has to deal with a number of uncertainties

like erroneous measurements, limited sensor resolution, imprecise knowledge of the object motion and high false alarm rates. For that reason, a correct assignment of new detections to existing tracks is not often possible in real world applications. It is more appropriate to use the multi-hypothesis approach for data association. In this approach, multiple new detections are assigned to a particular track and a hypothesis tree of possible measurements is build up. The idea behind this formalism is to simultaneously process more than one data interpretation history. To avoid the combinatorial disaster involved in applying this method (number of hypotheses grows exponentially with number of detections) the implementation of the multi-hypothesis tracker (MHT) employs gating and pruning techniques that reduce the number of possible hypotheses [BP99, Koc01].

3 Broadband Passive Sonar

The main antennas used for panoramic detection and tracking are the CHA and the FA, see Fig. 1. From the viewpoint of the tracking system, these sensors are real MTT sensors with a large FOV. The quantity of interest processed in passive sonar is the incoming acoustic energy from all horizontal directions integrated over a certain interval of time and a certain (broad) frequency band. A beamforming operation is performed on the arriving signals in order to generate a discretized mapping of the surrounding sound intensity distribution. By the knowledge of the submarines own course, this can be transformed into a north stabilized energy distribution. A dedicated detection algorithm then locates potential target bearings (bearing angles) by analyzing the given energy distribution. From this, a list of target detections for the respective time interval is created. Beside true target detections, this list also contains false alarms.

Depending on the respective sonar array geometry and its location on board the submarine, a specific array exhibits one or more blind detection sectors. These are azimuthal directions from which no detections occur or where detections are severely erroneous. The CHA, for example, is obscured by the own submarine, therefore having a blind sector at the aft.

4 Results

In this section we present results of our multi-target tracking algorithm applied on a simulated scenario with a duration of 80 minutes. The scenario geometry is described in the next section, followed by a brief summary of how the simulation for the acoustic sensor is performed. In the last paragraph we discuss the MHT output.

4.1 Scenario Geometry

The scenario contains four different surface vessels traveling with constant course and speed. During the time of the scenario the own submarine performs typical TMA manoeuvres. The target trajectories are shown as red lines in Fig. 3. The inset magnifies the own submarines trajectory (black line).

Figure 4 shows a true, north stabilized bearing time record (BTR) which is computed based on the trajectories of the target vessels and the own submarine. It gives the true bearing histories that a perfect bearing sensor on board of the submarine would produce. As is seen from the BTR, the scenario provides a number of crossings between bearing tracks belonging to different target vessels and also a number of own ship manoeuvres.

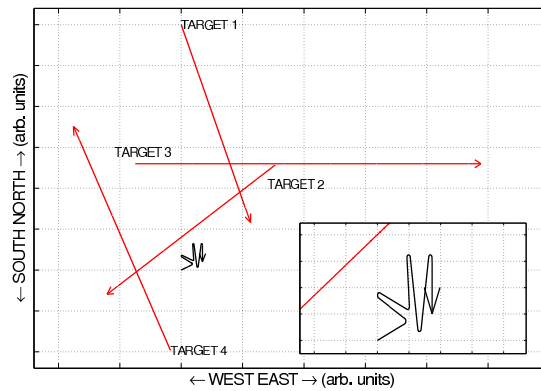


Figure 3: True BTR diagram showing the perfect target trajectories together with the own course.

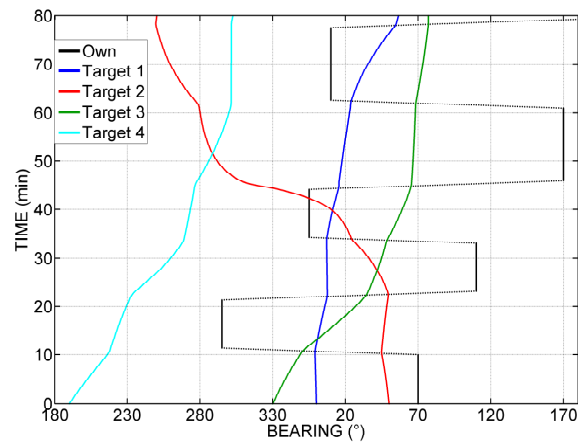


Figure 4: True BTR diagram showing the perfect target trajectories together with the own course.

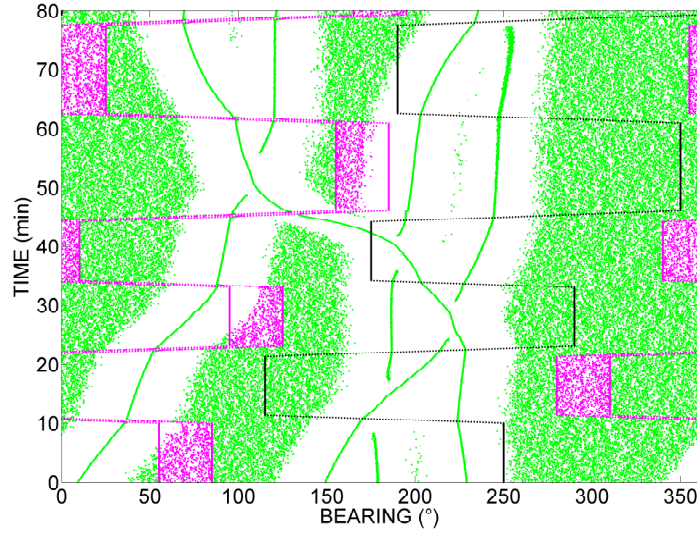


Figure 5: Simulated BTR for the CHA.

4.2 Simulated Bearing Time Records

Taking into account effects of the underwater sound channel and imperfections of the acoustic sensor, a simulation is performed based on the true bearing histories as depicted in Fig. 4.

Figure 5 shows the simulated BTR of the scenario for the Cylindrical Array Sonar (CAS) in broadband detection (BDT) mode, CAS-BDT for short. The green dots represent bearing detections extracted by the detection algorithm. The own course is drawn in black and the bounds of the blind sector of the array are marked with the lines in magenta. Each detection occurring in the blind zone is highlighted in magenta. Several typical features of broadband passive sonar appear: Among the detections originating from the true target vessels there are a number of false detections. Bearing accuracy depends on signal-to-noise ratio (SNR) and (platform relative) bearing sector. Problems often arise during own boat manoeuvres when the blind sector of the sensor crosses the bearing track of a target. As can be seen in Fig. 5, this leads to a distortion of the bearing tracks. Another salient feature of passive sonar is that weaker targets are typically obscured by stronger targets due to limited target separation capability of the sensor and therefore can not be detected during target crossing situations.

4.3 Tracking Results

The list of detections for each time step is subsequently fed into the MHT tracker which performs the estimation and data association steps described in Sec. 2. If a collection of

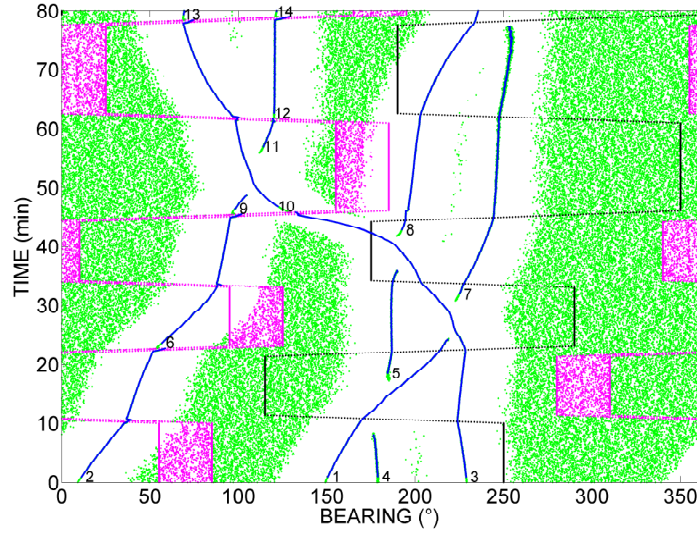


Figure 6: Tracking results for CAS-BDT.

recurring detections passes the sequential probability ratio test, the tentative track becomes extracted after a particular amount of time. At this time a track number is assigned to the estimated track trajectory. A track becomes deleted if the probability for the underlying detections to originate from a true target is low or if no more measurements could be found to extend the respective track.

Figure 6 presents the tracking results obtained for the CAS-BDT data. The detections and the own course (with blind zones) are shown as in Fig. 5. The confirmed tracks are drawn as blue lines with the respective track number displayed at the beginning of each track. As can be seen, the MHT tracker extracts only tracks which originate from one of the four vessels present in the simulated scenario. Due to the imperfections of the sensor described above, the trajectory for one particular target is usually build up by several extracted tracks. For example the blind sector at the aft of the CHA leads to the distortions seen in the detections from target 4 around 10 min, 22 min, 35 min etc., and similar for target 2 for times greater than 40 min. Some of these distortions result in the actual tracks becoming deleted, some distortions have no such effect and the respective tracks continue to follow the target detections (see, for example, track 2 and track 6 and track 9 which build up the trajectory for target 4 for the time $\lesssim 50$ min). The limited target separation capability with the weaker targets being obscured by stronger ones is another reason for the trajectories being made of several extracted tracks (extracted tracks 1 and 7 belong to target 3, track 4, 5 and 8 belong to target 1 etc.). A track-to-track assignment algorithm can be applied to combine those tracks which originate from one particular target [HMF⁺07]. This algorithm combines the tracks 2, 6, 9, 11, 12 and 14 to one target track (target 4). Tracks 3, 10 and 13 also assigned to each other and belong to target 2. Track 1 and 7 and the tracks 4, 5 and 8 are the other two target tracks which are assigned to each other originating from target 3 and target 1 respectively.

5 Summary and Conclusion

This paper introduced a multi-target tracking approach for broadband passive sonar targets. After a brief algorithm description and the review of some sonar specific features, an application of this algorithm on the BTR of a simulated scenario was presented. It was shown that this algorithm has the capability to automatically track all the relevant targets without a manual input by the user. It therefore offers a great potential for a future tracking system.

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