Insights Gathered from Recent Multistatic LFAS Experiments

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ABSTRACT

After conducting multistatic low frequency active sonar (LFAS) experiments in a shallow water area we propose a processing chain for optimal data analysis of the gathered data. Optimal means that it is aimed to maximally exploit the advantages of multistatic active sonar, e.g. the target strength diversity that increases the detection performance in the multistatic scenario and the localisation accuracy that can be increased via triangulation methods. Furthermore, optimal means that the proposed algorithm is able to handle the large amount of clutter echo returns that occur in shallow water scenarios. The latter is a hard problem because the analysis has shown that the position of clutter targets that are echoes from large structured underwater bottom features depend on the source receiver set-up that originated these clutter detections. Even with perfect localisation accuracy clutter target echoes of such type received at one antenna system cannot be just overlaid with the clutter detections of other receivers because they physically occur at different geographic positions due to the reflection law. This paper describes a way out of these difficulties. To optimally exploit the advantages of multistatic LFAS a statistical signal processing framework is proposed including sound waveguide estimation, bottom parameter estimation and sensor management.

1.0 INTRODUCTION

Inserting realistic values into the variables of the sonar equation [1](p. 406) for the LFAS systems of a surface unit [2] and for the e.g. flank array and/or towed array receive-only system of a submarine and comparing both results makes it evident that a submarine with comparable sonar system performance will always have a dramatic advantage against the surface unit.

The sonar equation combines in logarithmic units (i.e., units of decibels relative to the standard reference of energy flux density of rms pressure of $1\ \mu Pa$ integrated over a period of one second), the following terms:

$$(\mathbf{S} - \mathbf{TL}) - (\mathbf{N} - \mathbf{AG}) - \mathbf{DT} \geq 0$$

which define signal excess where:

- **S** source energy flux density at a range of 1 m from the source;
- **TL** propagation loss for the range separating the source and the sonar array receiver;
- **N** noise energy flux density at the receiving array;
- **AG** array gain that provides a quantitative measure of the coherence of the signal of interest with respect to the coherence of the noise across the receiving array;

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- **DT** detection threshold associated with the decision process that defines the SNR at the receiver input required for a specified probability of detection and false alarm.

For the description of active sonar the sonar equation has to be applied for the sound path from the source to the target where the received level plus the target strength (TS) is reflected to the receiver. Also important in the active scenario is that the target echo has to be compared not only to the surrounding noise level but also to the surrounding reverberation level (RL).

The reason for the advantage of a submarine against the surface unit is that the submarine is facilitated to operate silent and covert:

- The value for the noise level term improves her own bistatic or semiactive detection performance to better build up the underwater warfare scenario.
- She can find layers and areas with highest transmission loss and reverberation level minimising her own detectibility.The target strength that a submarine presents to an active source receiver set-up depends on her bistatic aspect angle in the given scenario. If the region, in which the target strength is at high risk for her, is small (e.g. only a few degrees if modeled as a cylindrical object [1](p. 302)), for a single source and a single receiver the submarine can easily minimise the risk of being detected.
- By operating smartly with zigzagging and avoiding approaching perpendicular to the heading of the active monostatic LFAS unit, she can even avoid to produce large Doppler frequency shifts of her echo, taking into account that small Doppler shifts require near-broadside aspect angles.

A principle well known in military operation to compensate tactical disadvantages is teamwork (Fig. 1). Almost all anti submarine warfare (ASW) concepts depend on or rely on the concepts of simultaneously operation of multiple sonar platforms [3].

In the following section we present some representative examples how the team can exploit the joint operation to increase its overall performance. These examples are taken from a very large data set: Twenty days of measurement with six different sonar systems in two years result in more than 4 TByte of acoustic data. The major interesting features discussed in the following are always present in these data sets. Because of classification issues of this data we are not allowed to present the complete analysis results but these are definitely proving the generality of our examples.

2.0 ADVANTAGES OF A MULTISTATIC LFAS OPERATION

2.1 Diversity Advantage

In the multistatic scenario the submarine cannot minimise the detection threats for all combinations of source receiver set-ups. If covert receivers are used this advantage of multistatic operations becomes most evident. This diversity advantage is theoretically understood and it has been demonstrated in various experiments that a multistatic operation is increasing the probability of detection (PD) viewed from the total system's point of view. To exploit this high PD, a data fusion centre is needed because the good (per-ping) detection opportunities will most probably only occur in a subset of all receivers involved in a multistatic operation. Furthermore, this subset is changing from ping to ping due to manoeuvres of the submarine or fading channel effects of the sound channel. At the fusion centre the concatenation of these (per-ping) detections is possible: Multistatic target tracking can be applied.

2.2 Localisation Advantage

Via triangulation the multistatic data fusion centre provides the ability to overcome the angular resolution limitations of the receivers (e.g. line arrays). If the detections are overlaid in a geographic display (Fig. 2) the cross-fixed position has a significant higher accuracy. For different source receiver set-ups this super-resolution of multistatic sonar has been analysed in [4] (p. 702).

2.3 Tracking Advantages

Finally, by optimising the localisation accuracy and by exploitation of TS, Doppler and RL diversity a tracking algorithm at the data fusion centre is able to continuously and exactly hold tracks of submarines even if they are strongly manoeuvring (Fig. 3).

3.0 FALSE ALARM ISSUE IN A CLUTTER AREA

Of course, the active sonar sound is reflected not only by the submarine but also by the sea bottom and surface. Every irregularity on the bottom causes echoes at the receivers. From the signal structure itself a differentiation between true targets (submarine) and clutter targets (bottom reflections) is not possible. In shallow water the operator has to deal with several hundred false alarms from every active sonar pulse.

A small bottom feature like a wreck produces its echo always at the same geographic position, so it can be easily identified as a non-moving object. But for large bottom features like underwater hills the received echo energy from its bottom cells is highly depending on the three-dimensional sound structure that ensonifies it [5]. With a moving source receiver geometry the positions of these clutter echoes are also moving which makes it very difficult to differentiate them from moving submarine echoes even with the help of tracking. Fig. 5 is an example for the observation that (whereas wreck detection are stable) clutter targets are moving from ping to ping consistent to the movements of source and receiver systems and the resulting changes in aspect. It is important to note that the false alarms occur in each of the monostatic and bistatic subsystems: Of course, they are not a product of the data fusion process. But if we do not care about the false alarms in our fusion centre, the algorithms there are just overloaded by them: E.g. having three LFAS vessels in a multistatic team, there are nine source/receiver combinations to be fused, i.e. in a worst case, there are nine times more false alarms to handle: An unrealistic scenario for the application of the state-of-the-art tracking algorithms.

In figure 4 an example for a complex reverberation limited LFAS scenario in shallow water is presented. The consistent and high correlation between depth changes and reverberation on the large bottom features is the major experimental basis for an algorithmic approach that we are proposing in the following section.

4.0 MULTISTATIC DATA FUSION ALGORITHM

After the problem formulation in the previous section we are describing the main idea for its solution. Afterwards we list up the major recommendations for an algorithmic approach. They should be interpreted as a survey collecting the relevant mathematical tools and exemplary references.

4.1 Main Idea

If we are able to model the generation of clutter

- we solve the data fusion problem for clutter targets in multistatic shallow water scenarios and
- we reduce the amount of false alarms presented to a sonar operator because the corresponding threshold crossings for reflected sound energy are classified as ’bottom false alarm’ consistent with our knowledge of the three-dimensional underwater scenario.

4.2 Recommendations for the Algorithmic Approach

- If we use the same mathematical formalism for the filtering of multistatic acoustic data, for the estimation of the underwater scenario, for multistatic submarine target tracking, sensor management and threat analysis, the result provides a complete concept for an optimal application of the multistatic LFAS ASW in shallow water. We recommend to use a Bayesian filtering concept.
- The data fusion has to exploit ping history information and perform a recursive Bayesian filtering to simultaneously track the rays (or other descriptive parameters of the sound channel) and estimate the bottom parameters.
- The knowledge about the sound channel and the bottom parameters is used to build up a database.
- Inconsistencies between this knowledge and further measurements are interpreted as submarine echoes and are tracked. The number of inconsistencies will be much smaller than the number of false alarms that a simple threshold detector would produce because no model knowledge is incorporated in a threshold detector. The inconsistency tracks are presented to the sonar operator for further assessment.
- The database can be used to continuously perform a model based optimal multi-sensor signal processing and environmental adaptive sensor management.

5.0 SUMMARY

Experimental results of multistatic active sonar experiments in shallow water are presented. The advantages of a multistatic sonar operation are obvious in these examples: increase of localisation accuracy and a better tracking performance. To exploit these advantages an algorithmic approach is proposed that takes the enormous amount of aspect dependent false alarms into account. The main idea of this concept is to model the generation of these clutter false alarms via a probabilistic/Bayesian approach. Experimental results indicate that there is a high correlation between clutter and features at the sea bottom. Examples of these results are shown.

6.0 REFERENCES

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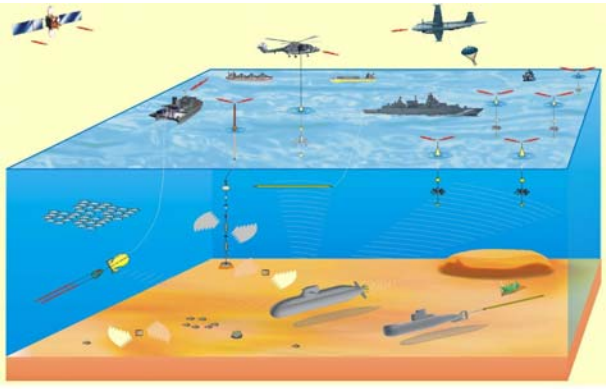

Fig. 1: In a multistatic scenario the ASW assets are simultaneously searching the submarine. Active and passive systems are used which can be airborne, moored or towed. If active sources are in action, all participating receivers are able to exploit its echoes. Communication, e.g. via satellites, allows the fusion of the receivers data at a fusion centre.

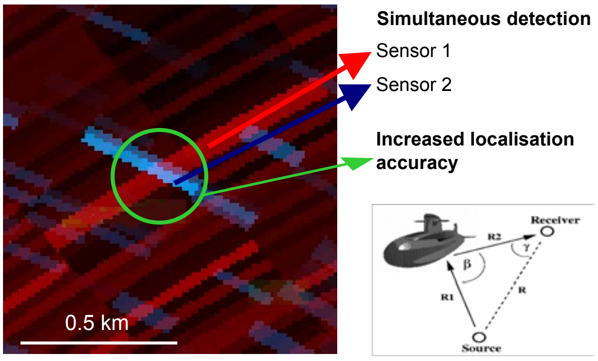

Fig. 2: Cross-fixing of acoustic detections improve the localisation accuracy after data fusion: The single systems suffer from the azimuthal resolution limits of their receiver systems (e.g. beamformed data of towed arrays). These limits have two sources:

(i) systematic: E.g. the beams resolution is limited by the size of the receiving system.

(ii) stochastic: E.g. the heading of the receiving system can only be estimated from a noisy measurement due to deficiencies of the heading sensors.

The localisation error after cross-fixing still suffers from the errors in calculating the distance from the receiver to the echo. Unknown velocities of targets, deficiencies in the knowledge about sound paths and sound velocities on these paths introduce an error into the absolute localisation. If signals with a Doppler estimation capability are used and if known fixed bottom features are close to the detection these errors can be adaptively minimised.

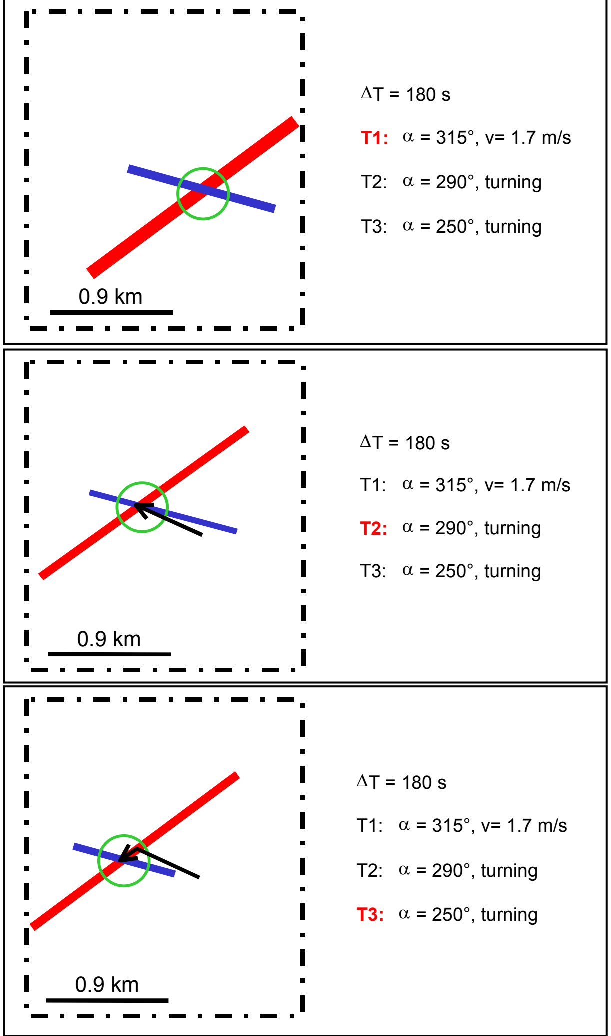

Fig. 3: At the fusion centre a track of a manoeuvring submarine can be build up with high accuracy: The sequence of the three pictures on the left show detections of echoes from a zigzagging submarine. Each picture belongs to one ping. The ping repetition rate was ΔT=180 seconds. The detections (marked with blue and red colour) where simultaneously gathered at two receiving platforms, respectively, in a distance of about 10 nm from the submarine. The acoustic source was located on a separate platform about 5 nm away from the submarine. On the right the information logged at the submarine's navigation system is given. The red marked T# is the ping corresponding to the detection picture on the left. The crossing points of the detection data and the navigation data correspond very well: The black arrow marks the heading of the submarine. Neither the "red" nor the "blue" receiver could produce such a precise track on their own because they would both suffer from their limited resolution. So, this example shows that the overall tracking performance of the multistatic system is systematically improved compared to the capability of stand-alone operating bistatic receivers.

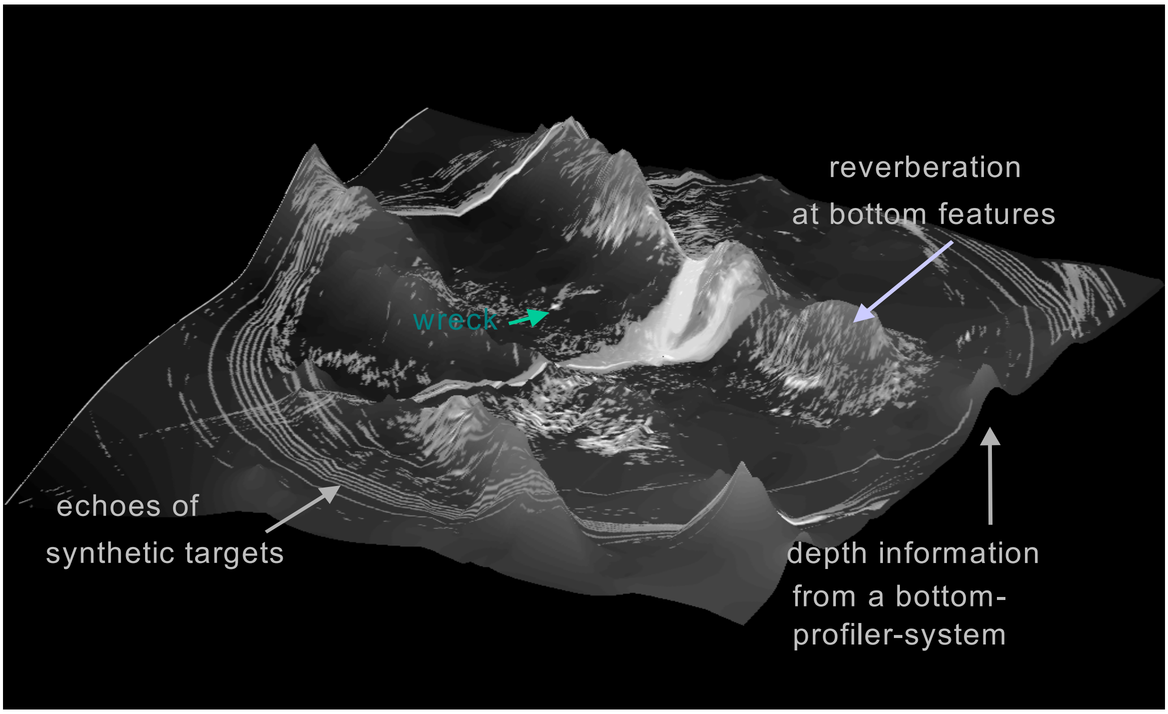

Fig. 4: The depth profile for 5000 km² (i.e., about 75 km length of each side of the quadratic area) of a shallow water area is displayed. Analyzing the overlaid reverberation data of 70 pings of a multistatic LFAS trial in this area the correlation between depth-changes and reflected acoustic energy is obvious. The analysis of the multi-aspect data at a fusion center together with the high resolution due to multistatic cross-fixing (Fig. 2) allows the construction of a database for an environmental adaptive sonar operation.

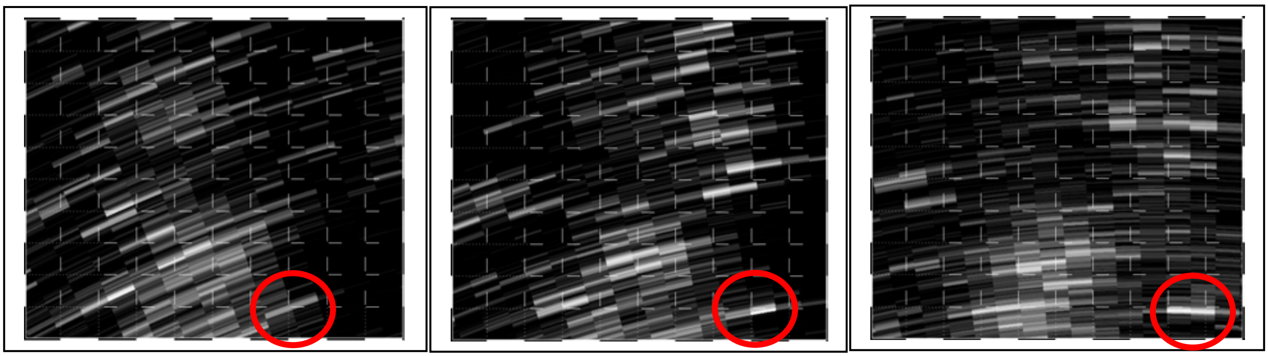

Fig. 5: Multiple aspect analysis of clutter: A monostatic LFAS unit is moving with a speed of 3 m/s westward. The images show at their true geographic location clutter echoes of an area that is located 12 km north of the LFAS unit The period of time between two of the geographic displays is 10 minutes and the left one is the earliest. While the LFAS unit is moving it is changing the aspect to this clutter area. The shape of the clutter returns is changing and it is possible to track specific clutter returns while they seem to move in the geographic display, e.g., the false alarm marked with a circle. Because we have checked with wreck targets that the geographic localization is correct in these displays, we are certain that these virtual movements of clutter targets are not because of an erroneous localisation. So, with the help of this sequence we are able to demonstrate the dependency of the clutter locations on their aspect to the LFAS unit.