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Robert Been, Stéphane Jespers, Stefano Coraluppi,
Craig Carthel, Christopher Strode, Arjan Vermeij

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Multistatic Sonar: A Road to a Maritime Network Enabled Capability

R. Been, S. Jespers, S. Coraluppi, C. Carthel, A. Wathelet, C. Strode, A. Vermeij

NATO Undersea Research Centre
Viale San Bartolomeo 400
19126 La Spezia
Italy
E-mail: Been@nurc.nato.int

Abstract

NATO's operational requirements emphasize interoperability of platforms participating in coalition task forces. Intelligently fusing data of multiple sensor systems and the development of adapted tactics are necessary steps towards a truly network enabled capability with improved performance.

In the last decade NURC has been a key player in the field of multistatic sonar research and experimentation. Technical feasibility of the concept has been assessed in a variety of multistatic settings and assets in collaboration with different partners across NATO. Good progress has been made in the field of tracking and data fusion. Moreover, a multistatic tactical planning aid (MSTPA) is currently under development, which will make tactical evaluation and optimisation of maritime sensor networks possible.

This paper summarises the progress to date and describes the current state-of-the-art. It also addresses ideas for the near future that include evolution of the multistatics concept towards a network enabled capability.

Keywords: ASW, sonar, multistatics, sensor fusion, operations research

1 Introduction

Although the discussion of ASW history is not the objective of this paper, we do want to mark two cold-war events that have been of key importance to the field: The Walker/ Whitworth espionage case and the fall of the Berlin wall; for further reading we suggest [1] and [2] that contain very interesting views.

Until the 1980s, ASW depended heavily on passive sonar. Walker's deflection caused the Soviet submarines to become increasingly quiet thereby causing a shift in emphasis from passive to active sonar (for *blue waters* at first). In the early 1990s, a large R&D effort was made in the United States, France, the United Kingdom, Canada and the Netherlands, see for example [3]; contemporary operational systems comprise United States' SURTASS LFA and the French SLASM.

The fall of the Berlin wall put an end to cold-war ASW competition without active systems really having been put to the test.

Figure 1. SLASM system

After the mid-1990s of the last century, a shift in operational requirements resulted in a re-focus on diesel-electric submarines operating in littoral waters. Hence, today's geopolitical situation requires coalition forces to operate in very difficult underwater acoustic environments with high false alarm rates (FAR). In addition, the number of platforms with ASW capabilities has reduced considerably [1]. As a result, there is a gain to be looked for in optimally combining the nations' efforts in ASW.

Figure 2. The Swedish HMS Gotland, AIP equipped, in San Diego, source www.navy.mil

Moreover, given the international aspect of coalition forces, interoperability and sharing contact and/ or track information is to be pursued and multistatics (MS), or creating a network enabled capacity in the broader sense, seems a logical and necessary way forward.

The first use of the MS concept dates back to the early 1950s. Advantages of MS [4] include covertness of the receive platform, extended echo range (or rather flexible echo range by optimally positioning the transmitter and receiver position), speed denial through ping diversity, multiple-angle observations and other tactical advantages.

In addition to the operational necessity, a revival in multistatics is generated by: COTS processing technology, an increasing variety in sonar solutions (VDS, HMS, dipping sonar, buoys and AUVs) and modern communication techniques.

What has been done? Advances so far have mostly been scientific/ technological. Signal processing issues as well as communication issues have been addressed. Tracking and fusion have advanced considerably, making the ensemble technologically mature.

One of the major issues in multistatic/ networked ASW now is operations analysis [5]. How should we go about in achieving our goals in current mission scenarios?

This paper presents an overview of recent advances, current state-of-the-art and a vision on the near future in ASW.

The remainder of this article is organized as follows. Section 2 addresses sonar systems in general; Section 3 discusses NURC advances in the field of multistatics. In Section 4, Operations Research aspects are highlighted and in Section 5 NURC sea-trial results are presented. Future developments are sketched in Section 6 and conclusions are drawn in Section 7.

2 Sonar Systems

Today, we consider towed Low Frequency Active Sonar (LFAS) sensors as the major potential components of near-future networked multistatic systems. Given current mission scenarios, the individual sonar systems need to have:

1. Powerful Transmit Capacity;
2. Large transmit and receive bandwidth;
2. Port/ starboard discrimination;

The major navies of the world are now in the process of renewing their LFAS systems, cf. [6] - [10].

Figure 3. Sonar 2087 and a Type 23 frigate
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One of the major technological sonar advances in recent years includes Free-Flooded Ring (FFR) sound projectors that offer a large bandwidth and high source level. Systems entering service now typically have a one octave bandwidth.

During the last ten years a large research effort has been put into LFAS key topics:

1. port/ starboard discrimination [11],[12],
2. reverberation suppression [13]-[16] and
3. false alarm reduction [13],[17].

A very good maturity level for monostatic systems has now been obtained, a *sine qua non* for good multistatics performance really; further optimisation of LFAS in littoral waters is currently pursued in programmes exploiting large bandwidths and environmental adaptation.

Besides LFAS variable depth systems (VDS), available systems include helicopter dipping sonar (such as Helras and Flash [18]) and buoys (e.g. DEMUS [19]), both of which build on the same transmit technology as the above mentioned LFAS VDS. Finally, sonobuoys like DICASS, ADAR and BARRA are widely used.

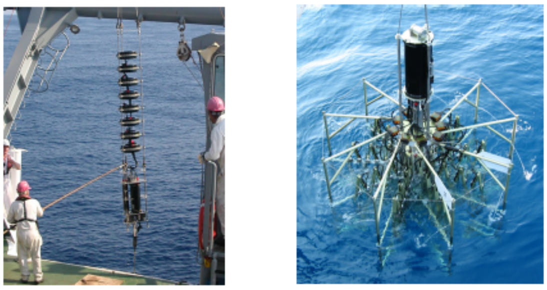

Figure 4. NURC's DEMUS system

Hull mounted sonar has been around for decades and certainly is part of the sonar systems to be considered for near future use in multistatic / networked scenarios.

Figure 5. AUV (courtesy MIT)

Future networked sonar solutions will surely include Autonomous Underwater Vehicles (AUVs). Current initiatives are described in [20]-[24]. Further ideas on future naval defence capabilities can be found in [25].

Finally, none of the above mentioned systems are to be considered as being exclusive; a mix of systems is very likely to be used. A standoff sound source in conjunction with AUVs and/ or buoys operating in a chokepoint area, for example, may be a very efficient and covert way of creating a barrier.

3 NURC's Advances in Multistatics

3.1 Signal processing

Although multistatic systems are not complicated from a conceptual viewpoint, quite a number of technical/ engineering/ interoperability problems need to be addressed before thinking about multistatic operations.

Issues like error sensitivity (and its impact on data fusion quality) to transmit times, receiver position, sound speed and platform positioning have been addressed [26], [27]. The sections that follow contain NURC's advances with respect to target tracking and operations research.

3.2 Fusion and Tracking

Robust and effective tracking & fusion is vital for networked multistatics. Positioning errors, contact redundancy and the high number of false alarms are the major challenges.

We consider three levels of tracking/ fusion:

- Tactical (human-in-the-loop type communication);
- Contact-based[1];
- Raw signal based.

NURC adopted the second option, since it has favourable properties w.r.t. communication load and w.r.t. false alarm rates (when compared to the 3^{rd} option).

NURC has advanced considerably in this field: a real-time, sea-proven, Multi-Hypothesis Tracker (MHT) is now available and ready for use in low-cost COTS-type systems.

[1] A contact is defined as a beamformed, matched filtered and data processed signal exceeding a detection threshold.

The MHT features:

- efficient multi-dimensional data association;
- high flexibility w.r.t. tracking and fusion stages: centralized vs. distributed;
- ping diversity: both FM and CW type waveforms are supported;

Originally, the data association was done using an immediate 'nearest neighbour' approach to data assignment [28]; currently a Multi-Hypothesis Tracker (MHT) is used. The latter may have a delayed association decision, since competing assignments are continuously evaluated. Performance of MHT is superior when compared to immediate assignment algorithms, both for real and artificial data sets, see [29], [30] and [31].

Track location and velocity estimates are based on an Extended Kalman Filter (EKF). Measurement covariance matrices account for numerous error sources including time, bearing, array heading, source / receiver locations and speed of sound. They have been generalised to cover bi-static source / receiver geometries; localisation issues have been studied and analytical expressions have been derived for localisation errors as a function of measurement errors [26], [27].

The multistatic fusion algorithm architecture allows both centralised tracking with a single MHT fusion stage and distributed tracking with multiple MHT stages. A mix of both is also possible. The centralised and distributed fusion/ tracking algorithms are depicted in Figure 6 and Figure 7 respectively.

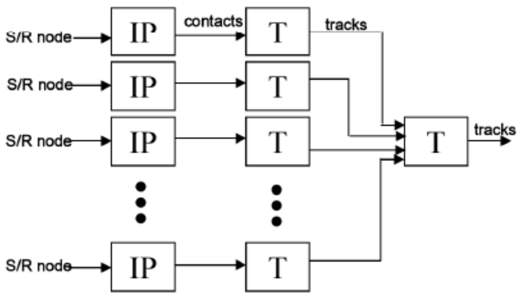

Figure 6. A two-stage distributed fusion/ tracking architecture, with contacts from multiple source-receiver nodes(S/R) input into their own MHT modules (T), and resulting tracks input into a final track fusion MHT module; this architecture implements an "OR" type fusion.

For the distributed tracking, however, the MHT module input may include tracks. A centralized tracker is performing best in the FAR sense when there is high detection redundancy, e.g. in a dense buoy field; distributed tracking performs best when there is significant target fading [30].

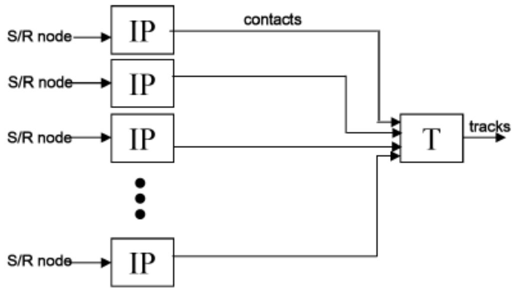

Figure 7. A single-stage centralized fusion/ tracking architecture, with contacts resulting from information processing (IP) of multiple source/ receiver (S/R) nodes, input into a one MHT module (T); this architecture implements and "AND" type fusion.

The FAR can also be lowered by exploiting both Doppler tolerant (FM) and Doppler sensitive (CW) waveforms. The MHT allows for simultaneous use of diverse pulse types.

Also from a tactical point of view, ping diversity is favourable, since the target is denied freedom in the both the *speed* and *target strength* sense, especially when there are multiple sources and multiple receivers involved, [32], [33], [34].

Below, we printed an example that shows the effect of combining multiple source/ receiver pairs as opposed to doing monostatics only. Our simulation-based testing has been based on internal simulation capabilities, as well as on datasets exchanged as part of the Multistatic Tracking Working Group (MSTWG), a multi-laboratory initiative to benchmark numerous approaches to fusion and tracking with multistatic sonar data [35].

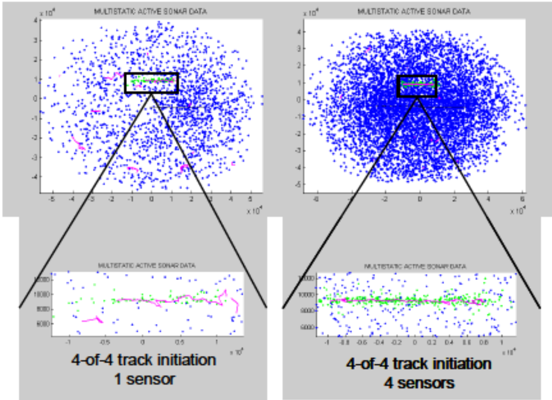

Figure 8. Single-sensor tracking (left) and multi-sensor tracking (right) illustrations confirm the improved localization accuracy and track-level PD of multi-sensor surveillance, with a small increase in false tracks.

We generally find that multi-sensor data leads to an improved track-level PD, at the cost of some increase in the false track rate. This increase is nonetheless much lower than the increased data rate, allow for the claim that the fusion gain is increased. Furthermore, there is generally an improved localization accuracy of target tracks.

3.3 Performance Modelling

SUPREMO (see [36] for details) is a sonar performance model that has been developed to evaluate MS scenarios in great detail and a large effort has been put into validating the model by means of sea-trial data gathered by NURC. The primary use of SUPREMO lies in the preparation of sea-going experiments and the analysis of sea-trial data.

In addition to SUPREMO, a closed-form model has been developed to allow very quick, good fidelity evaluation of MS scenarios, see [37] and [38]. This model has been included in the Multistatic Tactical Planning Aid (MSTPA) as a precursor to using SUPREMO.

The added value of MSTPA is in its ability to simulate key events in MS systems, from detection to tracking to communication to classification, end in generating statistics for effectiveness evaluation (using a metric that will be discussed in the Section 4). Future planned improvements include optimisation of the assets (placement, ping strategy). Details on MSTPA can be found in [39].

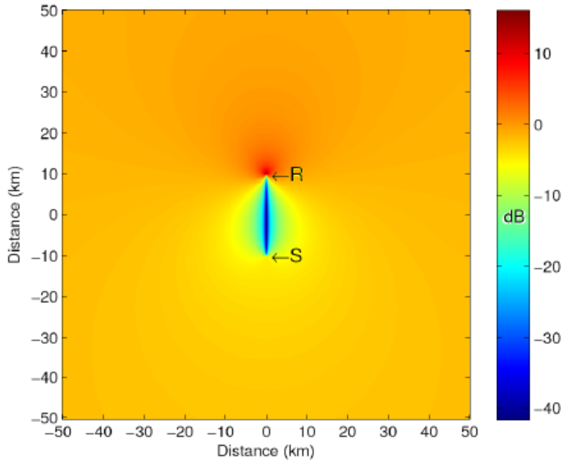

Figure 9. Example bistatic signal excess calculation using MSTPA, 'S' denotes Source and 'R' stands for Receiver.

3.4 Communication

Communication links are vital to the success of the networked system. NURC's approach to fusion and tracking employs contact data, for which transfer rates of ~100 kbps are required.

Experience during the CERBERUS sea-trial learned that fading occurs for (UHF-type) communication as the range between nodes increases. Hence the need for Delay Tolerant Networks arises [40], a principle that is used both for above and under water communications, cf. [41] and [42] for details on the latter.

The DTN architecture embraces the concepts of occasionally-connected networks that may suffer from frequent partitions and that may be comprised of more than one divergent set of protocol families.

This architecture, originally conceived for deep-space communications, can be applied to all environments subject to disruption and disconnection and/or high communications delay. Specific examples are sensor-based networks with scheduled intermittent connectivity, terrestrial wireless networks that cannot maintain end-to-end connectivity, satellite networks with moderate delays and periodic connectivity, and underwater acoustics networks with moderate delays and frequent interruptions due to environmental factors, again, see e.g. [41].
The key concept in DTN is the end-to-end oriented overlay called the bundle layer, which includes hop-by-hop transfer of reliable delivery responsibility and optional end-to-end

acknowledgement. The main difference from the Internet protocol is the focus on "virtual messages" rather than on "packet switching": interoperability between one and the other is however assured, and this will prove to be fundamental in the integration with existing networks.

It can be said that DTN provides a common method for connecting heterogeneous gateways that employ store-and-forward message routing to overcome communication disruptions. This concept, coupled with a flexible and enhanced naming system to track information across the networks, would enable the seamless integration of all kinds of sensors through transparent data-centric interfaces, hiding the complexities of the underlying networks to the end users, who are normally more interested in the results, rather than in technical details.

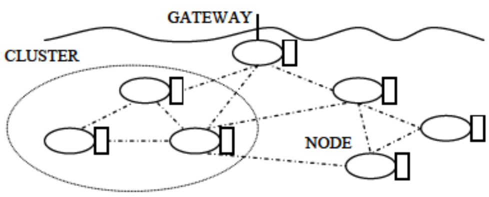

Figure 10. Decentralized network topology

In a nutshell, DTN addresses many of the problems of networks characterized by long transmission delays and discontinuities in end-to-end connectivity by using an asynchronous system modelled on postal mail, offering different service classes and delivery semantics. NURC is currently carrying out research and experimentation in the field of acoustic communications [43] and DTN.

4 Operations Research in multistatics at NURC

Planned expeditionary missions include barrier, area search and transit operations. MS networked operations form a key part to counter a credible submarine threat in shallow waters. The benefits of multistatics relate to tactical advantages (a.o. ping harassment) and covertness of the receivers (especially if we consider the use of buoys and AUVs). These benefits are obtained only through the well-coordinated use of MS assets.

Multistatic technology is now mature, a key question now is how to best use the assets equipped with such systems in an operation. Ways to quickly evaluate MS effectiveness and, more importantly, ways of optimally making the best operational use of MS systems are being investigated. The following sections outline NURC's efforts in this field.

4.1 Measures of Effectiveness (MoE)

With respect to evaluation of effectiveness we distinguish Measure of Performance (MoP) and Measure of Effectiveness (MoE); the former refers to system performance and the latter to mission success in a given scenario.

MoPs include the probability of detection, false alarm rate, probability of false alarm etc.

MoEs consist of broader concepts and may for example be chosen as the probability that a submarine goes through a barrier unchallenged or the probability that a submarine obtains a firing solution on a High-Value Unit (HVU).

Summarizing, given a network or ensemble of MS systems (with their respective MoP) and a mission (barrier, HVU protection or area search) in a specific area, the MoEs are the criteria to optimize, as they relate systems' performance and employment to mission success.

However, such criteria are impossible to evaluate and optimise analytically. This is due to the complexity of the relationships between the networked MS system employment, the environment and mission achievement.

The next section discusses NURC's approach to MoE and their evaluation. The approach, given the above mentioned problem of complexity, consists of (time-efficient) modelling and simulation.

4.2 MSTPA

The Multistatic Tactical Planning Aid (MSTPA) project was initiated at NURC to assist in planning successful tactics using a network of multistatic assets in a range of missions and scenarios.

The final aim is to provide a quantitative basis for making decisions regarding multistatic employment at the planning phase of an operation and to quantify the military worth of using networked multistatics capable platforms for ASW.

The approach taken in MSTPA is to model the multistatic system using NURC's research work on reverberation (see [37] and [38]), sonar performance and tracking/fusion. Supplement those with models of the communications network, simulation of false contacts and the task of classifying tracks. A Monte-Carlo framework ties the models together and allows the systematic analysis of the relations between systems employment and mission success.

MSTPA provides a workbench for analysts to investigate tactics in a range of NATO scenarios by simulating user defined tactics and providing feedback on the performance and effectiveness of the MS assets in the chosen scenario. Statistics can also be generated for analysis of the MoEs.

We will now give two examples of current MSTPA performance assessment capabilities. For the first one, a multistatic barrier scenario was created within the MSTPA model using generic environment and sonar parameters in order to provide an example of the type of studies the model facilitates. The barrier consisted of a source and three receiver platforms positioned along the y axis as shown in Figure 11. The barrier is assumed to be a line at x=5km. 150 (Monte Carlo) targets each with a full bistatic target strength representation transited on a course randomly chosen between 260 and 280 in order to penetrate the barrier somewhere along its length.

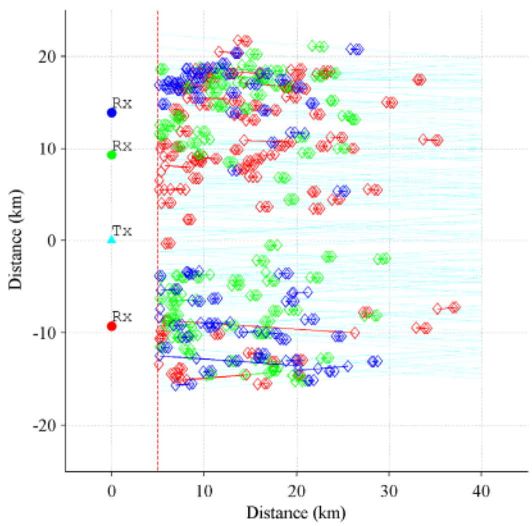

Figure 11. Barrier and random target tracks

Figure 11 shows the random target tracks together with the location of the target at the point where it was first detected, tracked and classified. These points are colour coded according to the receiver that made the detection. It can be seen that targets penetrating the barrier near the source are less likely to be detected. This observation is further highlighted in Figure 12, where the proportion of targets detected along the length of the barrier is presented.

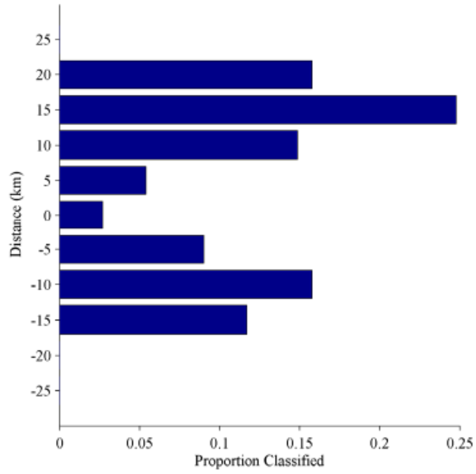

Figure 12. Proportion of targets detected along the length of the barrier.

Of the 150 targets 118 were detected, of these 113 were tracked and finally 110 were classified as a target. These figures highlight the importance of modelling the entire process from a detection (positive signal excess) to the correct classification of a track. A single detection is not enough for a search platform to initiate an attack.

The second example shows the worth of networking two LFAS sensors. The geometry is printed below.

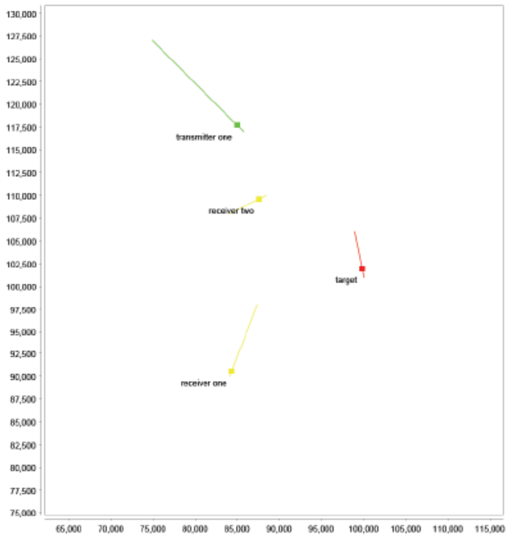

Figure 13. Geometry for the second example at the start of the scenario; the dots denote the actual asset position and the lines refer to the trajectory to be followed during the scenario.

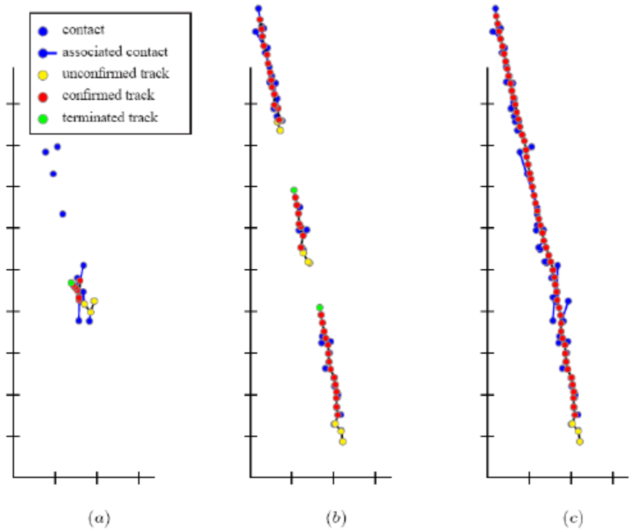

Figure 14. Tracking example: (a) tracks from receiver one, (b) tracks from receiver two, and (c) tracks from the fusion of both receivers

In Figure 14, we show the results for the case where there is perfect communication between both receiver platforms; as a consequence, there is a track with a good target hold and no fragmentation (c). On plots (a) and (b), the results of the two separate receivers are plotted, however, now the communication between the two platforms suffers from frequent interruption; hence, the formed tracks are very fragmented.

Future work will also consider representing a reactive target. This work will be pursued by investigating techniques such as, game theory, artificial intelligence and traditional operational research optimisation techniques, e.g. based on information theoretical aspects or artificial intelligence theory used in computer games[2], [44].

The next step in MSTPA's development is the optimisation of asset placement given a mission scenario such as: barrier operation, transit operation or area search.

For area search, a classic view with monostatic systems is given by Koopman [46]; a modern approach in this respect can be found in [47]. Intelligent ping sequencing is addressed in [34].

Buoy fields have been optimised in the information theoretical sense in [48]. Here, the condition number of the Fisher information matrix was optimised to obtain an optimal buoy placement. A different approach, based on acoustic performance modelling and stochastic optimisation is presented in [49].

Future developments in MSTPA aim at optimising both static and dynamic asset employment, i.e. in scenarios employing both static buoys and moving assets, such as helicopter with dipping sonar and surface combatants with towed sonar systems.

5 NURC Sea-Trials on Multistatics

Multistatic sea-trials employing LFAS systems that are now becoming operational started around 1999 [50].

NURC has been actively involved in multistatic experimentation since the very beginning, with a variety of systems and partners. The example printed below is taken from one of the sea trials and shows the added value of tracking and fusion for two LFAS VDS.

[2] There are companies that combine sonar modelling work for navies and developing computer games [45].

In this specific case, centralized tracking outperforms distributed tracking (the distributed solution is the outcome of track fusion on the faulty monostatic and bistatic tracks).

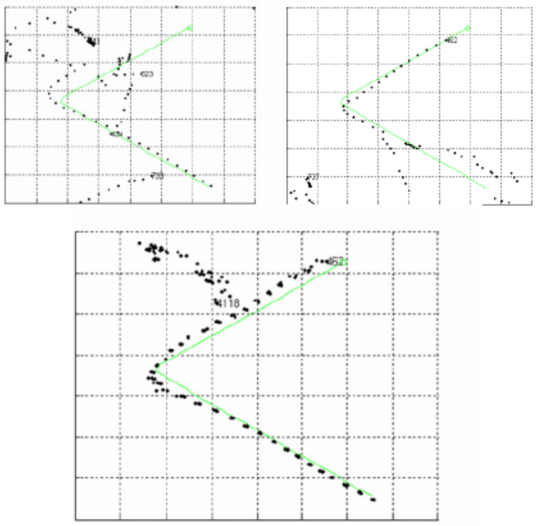

Figure 15. Monostatic tracking (top left) and bistatic tracking (top right) fail to hold track on the target; centralized tracking (bottom) succeeds by exploiting higher revisit rates and detection redundancy.

6 Future Developments

Near future developments will comprise getting multistatics LFAS systems to (net)work.

Future networked systems will very likely use a mix of LFAS, buoys and AUVs. Off-board reconnaissance and surveillance in littoral waters, employing AUVs in both active and passive mode, form a niche in the envisioned transformational initiatives; consequently, a focus towards this area of research and experimentation is foreseen. DTN and (underwater) communication are an integral part of this.

7 Conclusion

In this paper the state-of-the-art, recent developments and a vision on (near) future developments of networked multistatic sonar for ASW have been presented.

The technological advances necessary for networked capability are present in the field of: MS sensors, tracking and fusion; operational studies are advancing.

From a technical perspective, the performance improvements offered by multistatic sonar concepts apply to the detection, localization and tracking of submarines. These improvements are strongly linked to the availability of a network with sufficient bandwidth to convey the information to be fused. In essence, a multistatic sonar is by design a network enabled capability.

Operational networked LFA systems with contact sharing and interoperability are key elements to enhancing coalition forces in ASW. The military worth of network enabled systems is there, we will now have to focus on realising operational networked systems and the necessary tactics that go with it.

We will also have to safeguard long-term ASW health. The proliferation of submarines is bigger than ever [1], and the threat formed by AIP equipped submarines and midgets in shallow waters is enormous, [51] and [52].

Therefore, the quest for innovative, effective ASW solutions will need to continue. If not, NATO is facing the risk to become unable to project an effective anti-submarine warfare capability off the distant shores.

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This work has been only possible through collaborative research. NURC would like to acknowledge the outstanding level of contribution provided by the United Kingdom (DSTL) and Germany (FWG) during the CERBERUS sea trial of 2001, by The Netherlands (RNLN + TNO) during the ADULTS trial of 2003 and again the United Kingdom (DSTL) and the United States (ONR) during the DEMUS'04 sea trial.

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[5] Unfortunately, service officials in recent times "have largely abandoned operations analysis," Konetzni said. "Without looking clearly at the mission and rigorously analyzing the potential of new tactics and technologies to improve warfighting, we just get PowerPoint solutions," he said, adding, "I just can't take seeing another slide with red, yellow, and green blocks for effectiveness with nothing mathematical behind them."
A better path would be one in which proposals for innovation are studied analytically and developed with a "complete plan" - including concept of operations, training and maintenance - "before we throw these things on our ships," he said. , excerpt from:
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NURC
Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
NURC
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int