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Heterogeneous Underwater Networks for ASW: Technology and Techniques

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Abstract

NATO's research and technology objectives for anti-submarine warfare (ASW) include persistent scalable heterogeneous wide-area surveillance networks for the littoral environment.

Network and system design considerations for a defined mission objective include communication bandwidth, command and control, sensor type, sensor autonomy, interoperability, interference, data fusion architecture, on-board processing, and for the operational level sonar frequencies, pulse types and bandwidths. Moreover, sonar performance prediction tools, rapid environmental assessment (REA) and tactical planning aids are crucial contributions to mission success.

In the last decades NURC has extensively researched multistatic active sonar both for ship- and buoy-based systems. In the coming years NATO's emphasis for the underwater battlespace will shift towards networked solutions including both fixed and mobile sensor nodes. To facilitate this change, a research programme has been launched at NURC that employs both autonomous underwater vehicles (AUVs) equipped with towed arrays and autonomous bottomed nodes that include a cocktail of both acoustic and non-acoustic sensors. All sensors can be linked in a communication network. This article focuses on NURC's present research in the field, highlighting: system design considerations, progress to date and a proposed roadmap for future development.

Keywords: *NATO, ASW, sonar, multistatics, signal processing, data fusion, sensor fusion, AUV, underwater networks, acoustic communications, LFAS, stochastic control, path planning, autonomy.*

1 Introduction

Up until the 1980s, ASW had depended heavily on passive sonar. Walker's defection, [1], contributed to the dramatic quietening of Soviet submarines, thereby causing a shift in emphasis from passive to low frequency active sonar (initially for blue waters).

In the early 1990s, extensive R&D efforts were made in this field. The fall of the Berlin wall put an end to cold-war ASW competition without active systems really having been put to the test.

Toward the end of the last century a shift in operational requirements resulted in a re-focus on small and quiet 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 within NATO [1]. As a result, there is an expected and necessary gain in optimally combining the NATO nations' efforts in their area of ASW.

This move towards collaborative and co-operative ASW naturally lead to the need for protocols and techniques which would allow the exchange of information. In particular the need to exchange detailed information of the perceived battlespace in terms of individual detections and predicted tracks necessitated (at least at the scientific level) the development of – usually above the surface – multistatic active sonar networks. It is the natural extension of this, the move to underwater communications, that drives the present research and allows the gearing from many of the lessons learned during that earlier phase.

The first use of the multistatic concept dates back to the early 1950s. Even then it was realised that the advantages of multistatics [8] 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 increasing the chance of glint opportunities.

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

For Low Frequency Active Sonar (LFAS), advances so far have mostly been scientific/ technological. Signal processing issues[1] as well as communication issues have been addressed although many issues remain to be resolved, in particular in the realm of false-alarm reduction and covert data exchange. Tracking and fusion have advanced considerably: cf. [20], [21], [22], [23], [24], [31] and [32], making the ensemble technologically mature. Multistatics is being transitioned to industry and some NATO nations have started including a multistatic active capability into their low frequency ship-based sonar systems.

For this reason, NURC will now focus more on off-board sensors and networks. Such sensors are to be considered as complementary assets that will bring persistent wide-area area surveillance, on the one hand to be viewed as a means to reduce the risk posed on the warfighter and on the other hand as a means to reduce the burden of routine tasks.
As the 'crisis after next' may well include conflicts both in deep and littoral waters, it is essential to focus on a balanced fleet of which both platform-based and off-board sensors will play an important role.

The content of this article is organised as follows. Section 2 will discuss the ASW threat for NATO. Section 3 will outline the requirements of NURC's science and technology (S&T) effort and show how they can be mapped onto specific scientific objectives. Section 4 discusses network design considerations and preliminary simulation results using NURC's multistatic tactical planning aid (MSTPA) are discussed in Section 5. Current state-of-the-art of NURC technology is discussed in Section 6, followed by a roadmap in Section 7. Finally, a summary is provided in Section 8.

2 The threat

The number of submarines in the world is estimated at over 500 in total, of which more than 130 in Asia and over 45 in the Middle East.

The ASW community is faced with a set of difficult threats ranging from the deep to shallow water environments and from large nuclear to small few-men submersibles.

Part of the threat is caused by a proliferation of submarines which have become available in the international marketplace to any organisation able and willing to pay. Furthermore, present

[1] both for the individual sensors and for multistatics, cf. [9], [10], [11], [12], [13], [14], [15], [16] and [18]

thinking accepts that submersibles with relatively low specifications may produce an additional threat – e.g. short duration under water, shallow diving depths etc.

The threats, then, include AIP-equipped SSKs and midgets, where the latter threat is not considered as being technologically sophisticated. In some ways the tasks faced by the ASW community, nowadays, is similar to that of the MCM community in which the defensive measures put in place must not only cope with the most up-to date technology but also with relatively aged technologies which still provide a risk to sea-going forces.
The control and dominance of the sea remains the driving force in future conflicts: Sea Lines of Communication (SLOC) protection is one of them and continues to be very important in the modern world since:
* 95% of the world trade;
* 90% EU import & export and
* 40% internal EU trade is ship-borne.

Although near future geopolitical situation focuses on littoral, future use may well point towards a mix of shallow and deep and hence a balanced fleet is necessary, see [3], [4] and [5]. As we adapt to asymmetric threats and the challenges of irregular warfare we cannot lose sight of the navies' core war fighting competencies like anti-submarine and mine warfare, cf. [2], [6], [7].

Many of the issues for platform-based sonar have been well covered by the Nations, both for mono- and multistatic. The role of NURC in S&T focuses towards network enabled capabilities (NEC) and off-board sensors. The requirements for this science and technology effort are provided in the following sections.

Figure 1 An AIP-equipped U212 submarine. An example of the progressively more difficult target that ASW is expected to detect.

3 Requirements

The NURC S&T strategy is covered by a number of requirements, of which NATO's long term capability requirements are an important subset:
- All weather protection against a submarine threat in confined and shallow water areas;
- Common operational picture and
- Reconnaissance, Surveillance and Target Acquisition.

NATO's R&T investment in ASW focuses on three main areas: 1) implementing the NATO Network Enabled Capability (NNEC) concept with technologies to control and tailor sensing nodes and distribute knowledge and information in the maritime environment (with emphasis on undersea), 2) developing decision support tools that enable war fighters to take advantage of

NNEC shared tactical and oceanographic environment to improve detection, classification and localization, and 3) providing effective classification of submarines.

The NATO Research and Technology Objectives (NRTOs) relevant to ASW are detailed here with a reinterpretation of their scientific and technological implementations.

A requirement for scalable sensing networks will necessitate the development of technologies that enable self-forming, multi-modal undersea sensing networks, which can be used for wide area surveillance and to provide cueing and target discrimination in complex shallow water environments.

The *production of tailored tactical sensing fields* will need tools that can translate a NATO Commander's ASW requirement into optimised sensor fields to support reconnaissance, surveillance and target acquisition needs in the field.

Both *algorithms capable of translating data to information at the point of collection* and *comprehensive data fusion and distribution* can be seen as developments of existing research into the creation of algorithms which translate raw detections into useful information that can be transmitted using small bandwidths and the improvement of algorithms which fuse these results from multi-platform or multi-sensor surveillance and reconnaissance information**.**

NURC's S&T is to continue in the direction of distributed, autonomous sensing as a means of transforming the way naval forces conduct surveillance and reconnaissance by reducing the reliance on platform based approaches. The approach will emphasize concepts using long endurance ocean sampling platforms (such as glider technologies) which provide essential elements of the environment and which can persist without the need for significant manned presence or logistical footprint. Furthermore, any proposed systems must utilise active acoustic sensing techniques integrated with autonomous underwater vehicles (AUVs), with frequencies scaled to match platform characteristics and concepts of employment.
Ultimately, a prime enabler for these techniques is the development of communications, networking and command and control for mobile sensing nodes which will in turn lead to the development of NATO standards placing emphasis on approaches which may lead to common command and control of unmanned vehicles (Underwater, Surface, and possibly Ground).

At NURC we are working towards an end-state demonstration of this approach for a scaled set of nodes (mobile/fixed) in order to demonstrate real time sensing of the tactical and oceanographic environment and the reconfiguration of a distributed network of sensors to improve Detection, Classification, Localization and Tracking (DCLT).

4 Design Considerations

The use of a networked system provides the system designer with a rather different set of constraints than would be found in a traditional ASW system.

Whereas the traditional ASW system moved to lower and lower frequencies in the 1990's so as to obtain greater and greater theoretical ranges due to the reduced absorption characteristics – this reduction being offset by the reduced target strength of submarines at very low frequencies. The reduction in frequencies was further offset by the necessity of using large sources and long towed arrays at these low frequencies. A compromise was eventually found in the 600 to 2000 Hz range where detections could still be expected in excess of 50 km whilst having systems which were *relatively* easy to deploy.

The exact operational use of a networked system is not and cannot be known at the moment. In fact it is to be expected that the way in which system are used will differ in different environments and for varying operational requirements. One possible approach would involve a passive network, possibly consisting of bottomed sensors and AUVs with towed arrays forming a barrier to control a limited area, barrier region or choke point. On the detection of a threat the detecting node would send a message to a stand-off source which would insonify the area – moving into an active mode of operation, in fact this concrete example is one which NURC is currently working towards an end-demonstration of by 2011 as will be discussed below in Section 7.

The relatively short ranges of passive detection may then be expected to be mirrored in the ranges of interest for the active system i.e. operating at considerably shorter ranges than those of traditional modern ASW systems. So then if we consider, for instance an AUV with a towed array within our networked system the constraints and requirements are rather different than for conventional systems.

Mechanically we can expect a definite constraint on the length of the towed-array. The trade-off is to make the array as long as possible consistent with a system which will be expected to operate autonomously for long periods of time whilst making manoeuvres and with the requirement of minimising drag for extended AUV battery life. But, of course, longer arrays give better directivity index as a mitigating effect against both noise and reverberation.

The tendency therefore, should be to go higher in frequency and consider the attendant cost due to absorption. In a networked system the active detection ranges may be expected to not have to exceed 10 km. At such a range the difference in absorption between 1 KHz and 10 KHz is approximately 10 dB, using the well known expressions of Francois-Garrison. This loss is bought back by the greater directivity index of the higher frequency for a given physical length of the array.

Higher frequency also allows smaller sources which will be cheaper and easier to deploy. It also allows a smaller detectable speed (since Doppler is proportional to transmit frequency) so that slow moving targets can be detected more easily.

The upper limit of the centre frequency to be used for multistatic active sonar with AUVs is determined by the frequency at which the tactical paging for data communication takes place; given the expected inter-AUV distance of 5-10 km, an ACOMMS centre frequency of 8-10 kHz is likely to be used. Taking into account interference, using the assumption that the spectral sidelobe level of the transmissions is about -40 dB (at a sufficiently large frequency separation), an educated guess leads to a suitable centre frequency < 5 kHz for multistatic active use.

The need for technical expertise in active ASW for AUVs is currently being fulfilled by NURC. Current shortfalls include the lack of inter-operability, persistence etc. The AUV approach has been chosen in conjunction with a standoff sound source. Generally these assets may be operated solely or cued by passive and/ or non-acoustic sensor systems.

Although the role, constraints and limitations of underwater communications is a critical component of networked ASW systems it is outside the scope of this paper to detail the wealth of results and problems pertaining to this research topic – we rather point the reader at various excellent review papers to be found in the literature: [33],[34],[35],[41],[42] and [43], and constrain ourselves to the data communication requirements for a couple of relevant examples.

Within the expected experimental setup of Section 7 there are various communication regimes:

<u>From fixed nodes to fixed nodes: node-to-node distance less than 1 km.</u>
The reason for this communication is in the exchange of information once a detection is made as explained in Section 7. The exchange, of, perhaps, a snippet of time series from a magnetometer to provide signal free reference for improved local performance may require infrequent burst of less than a kilobyte of data.

Communication of contacts made at fixed nodes, communication up to 5km.
In this situation we envisage two types of contact formation. A single detection formed by non-acoustic detections, passive or acoustic detections or a fully formed track with both positional and directional information of the contact. Both approaches have attendant concerns. These concerns are exemplified by consideration of an active system

For the detection scenario
Each detection may be expressed by a set of simple physical parameters: (time of detection, bearing, Doppler) plus information overhead on the number of node etc. If the time of transmission is known we can map this into a (lat, long, Doppler). Consequently the message size per detection is quite small. However, for systems operating in shallow water it is well known that for detection thresholds of 10dB we can expect to have hundreds of contacts formed. We may therefore expect to have a total message content of kilobytes per pulse-repetition-interval.

On-board tracking
If our node is able to carry on-board tracking we can carry out a large false alarm reduction – maybe as much as a factor of 100 - by passing only fully formed tracks. The contact formed tracks contain the usual $[x, y, \dot{x}, \dot{y}]$ information plus the attendant error covariance matrices which are required for data-fusion at subsequent nodes. For this type of contact we may envisage a message for each of the formed tracks of perhaps 50 bytes but which can be sent intermittently – dependent on acceptable latency and uncertainty.

The communication requirements of such the networked system that is proposed, then, are seen to be rather undemanding at the individual contact level but may be expected to be overwhelming with regard to the full data throughput. This indicates that the correct choice of processing methodologies (false alarm reduction, CFAR) and the choice of message-form will be crucial to effective operating of such systems. Although, as detailed below in Section 6 the present assumed message size is 32 bytes the experiments and research detailed in Section 7 may well indicate a need for a more flexible approach.

5 Simulation results using MultiStatic Tactical Planning Aid (MSTPA)

Ever since its establishment almost 50 years ago, the simulation and modelling of sonar performance has been a focal point at NURC. One example is SUPREMO (see [44] for details), a sonar performance model developed to evaluate multistatic scenarios in great detail. Furthermore, a great deal of 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 planning of sea-going experiments and the subsequent analysis of sea-trial data. In addition to SUPREMO, a closed-form model has been developed to allow very quick, good fidelity evaluation of multistatic scenarios, see [45] and [46].

This background in *accurate and precise* multistatic modelling has allowed the *Multistatic Tactical Planning Aid (MSTPA)* to be developed with a useful and realistic model of background and target but the tool, as a whole provides the researcher or planner with much more. The added value of MSTPA is in its ability to simulate key events in multistatic systems, from detection to tracking to communication to classification, and in generating statistics for evaluation of Measures of Effectiveness (MoE). Optimisation of assets (placement, path planning) has been included in MSTPA recently, details can be found in [47] and [48].

Modelling of a multistatic active sonar barrier that comprises multiple sound sources and multiple AUV receivers can be done within MSTPA. One of the latest developments in MSTPA is the possibility to include autonomous asset path planning based on detections / tracks made by the multistatic receiver(s). The path planning strategy may e.g. be based on the current state vector estimate, the current error covariance matrix estimate and the optimization of an observability criterion over a certain horizon, cf. [26],[28],[29] and [30]. Measurement error estimates are based upon research documented in [19] and [20]. Various algorithms (applied for different horizons) are currently researched and a publication on the topic is foreseen in the near future.

MSTPA thus provides a flexible planning aid which will be of use not only in an operational environment but also for the researcher involved in the planning of, necessarily complex, experiments necessitated by the requirements of Section 7.

6 State-of-the-art Technology in NURC Programme

A. Autonomous Underwater Vehicles (AUVs)

AUVs have played a core role in many strands of research at NURC over the last decade. In particular the role of AUVs in the field of mine counter-measures (MCM) [50] has placed the Centre at the fore-front of synthetic aperture sonar (SAS). Supplementary programs have focussed on the role of autonomy within these systems [54]. The experience gained under those programs should give a straightforward leverage into the ASW arena.

The Centre currently has a bluefin-21 AUV and a REMUS system. Furthermore, the main platform for research for active sonar contribution to the planned network is the Ocean Explorer (OEX) AUV which has been fitted with acoustic modems and has had a towed array developed and fitted. This inventory will be further supplemented by vessels from the NUWC and from MIT.

The SLIm Towed Array (SLITA) has been designed to cover a two octave range. It has been specifically designed to be used with AUVs – designed round a 31mm diameter hose. Initial testing of the array system has shown that the array exhibits low self-noise and that a full acquisition system is in-place and is functioning well.

In line with other efforts the approach for controlling communication, algorithmic functioning and platform control is carried out under MOOS-IvP (Mission Orientated Operating Suite Interval Programming). The approach which has been developed at MIT and Oxford University [51] allows each module, behaviour and requirement to be compartmentalised and to allow the scientist and developer to rapidly insert new algorithms and autonomous behaviours into the system whilst leaving MOOS to cope with interface and the avoidance of internal conflicts. The IvP helm component is itself a MOOS process that uses multi-objective optimisation technique to determine platform motion. The so-called back seat driver paradigm [53] allows low-level tasks such as depth-keeping and vehicle safety to be controlled by the vehicle's main computer, the MOOS-IvP messages coming from a separate payload. The algorithms developed at NURC will be implemented on PC-104 stacks. Signal, data and information processing algorithms already exist, having been developed under NURCS multistatic program in recent years [17].

Initial at-sea tests have been carried out at the end of 2007 and the beginning of 2008. In the latter experiment, navigation messages were transmitted through micro-modems. The received messages were received and subsequently decoded on the CRV Leonardo allowing the OEX position and heading to be displayed on board. This, first step – the OEX was not controlled under the MOOS-IvP autonomy – was augmented by a demonstration of the autonomous tracking and trailing of the OEX by autonomous surface craft (ASC).
At the time of writing the preferred communication approach between all platforms is CCL [52] using WHOI modems. These messages, although limited in size (32 bytes) provide an accepted standard to act as a baseline for algorithm and technology development.

Consequently many of the enabling technologies of an autonomous networked system are in place to provide a full-scale demonstration. In Section 7 we detail how this transition will take place.

Figure 2 Ocean Explorer (OEX) with SLITA array (developed at NURC).

B. Bottomed Systems

The proposed use of mobile assets continues to be the predominant areas of research and technology drive within the networked ASW community.

The role of bottomed, stationary, platforms should not, however, be underestimated. They are likely to be used in regions where very long-term surveillance and monitoring is required. Such systems may be making direct physical measurements of the actual target – i.e. the acoustic and magnetic fields etc; or may be making measurements of the environment so as to support operations, modelling and prediction. In this section we will focus on the former mode of operation.

Physically such systems will be required to be trawl-safe since they may need to be deployed in regions with large amounts of shipping and fishing. They must be able to communicate both with the internal and with an external network. This may be by means of an acoustic link or by means of a pop-up gate-way buoy. In fact such a system has been employed by the SEPTR buoy to combine a reliable communications connection with a trawl-safe platform – for the measurement and transfer of environmental data, [49].

The platforms will be expected to operate autonomously for months at a time without physical interaction. This means that the system must be driven by batteries with an appropriate life of months and maybe years. To this end much research is ongoing on investing cells with more and more energy density or with systems which can generate their energy, on board [40].

The platforms themselves may consist of a mixture of sensors. Clearly the use of acoustic sensors has received the most research over the years with a long history going back to SOSUS. However the modern system will be expected to be autonomous, adaptive and to exhibit a high-level of covertness.

For such systems non-acoustic sensors have also prompted much research. The most important techniques which have attracted a great deal of attention are magnetic, electric field and pressure. It is envisaged that such systems will contain a cocktail of these sensors and that the ultimate benefit will be obtained from the diversity and fusion of the different systems.

For all of these techniques the detection ranges will be very short –typically less than a kilometre. Consequently their use may be expected to be limited to spatially constrained regions such as choke points. They may, however, play an important role in regions where acoustic detection may be difficult or impossible. An example of this would be regions in which ice-floe noise is dominant: drastically reducing acoustic detection ranges. It is important, however, to be realistic and note that real systems will be expected to incorporate acoustic capabilities along with the non-acoustic technologies.

It is often noted that such systems appear to have the characteristics of a *benign mine*. It is in fact important to stress this similarity allowing lessons learned from mine-type applications to be incorporated into these collaborative platforms. One possible difference which is still open for research is the role to be played by classification in these systems: in a one-off mine-type application a hard decision is made whereas in our collaborative application a soft decision – possible contact of interest - can be made, deferring decisions until a later time after a more detailed Detection Classification and Localisation (DCL) has been carried out.
In addition the classification offered by the diversity of sensors is as much a means of classifying non-targets as positively identifying an actual target. Note that tracking and fusion will be done on a multi-sensor level, using the ACOMMS network for exchange of contact-level data.

Magnetic
Magnetic detection is certainly the most researched of the non-acoustic techniques to be discussed here. The use of tri-axial magnetometers has been shown to facilitate the simultaneous measurement of contact position (including depth), speed and in some cases even magnetic moment. In other systems the use of highly sensitive magnetometers, such as Overhausers have shown that extended detection ranges may be obtained.

Many questions still persist on how such systems would be used as part of a network. In particular how much data would be required to be transferred between magnetic sensors? This is, indeed a complex question driven primarily by the observation that without using a direct link between magnetometers the acoustic medium will not be able to support the large bandwidths required to carry out a continuous comparison of the fields on the two platforms – the traditional method by which the Earth's geomagnetic background field can be cancelled. It has been shown recently that good detection statistics can be obtained on a single platform by using an adaptive pre-whitening technique followed to a matching of the Anderson functions which model the filed of a passing target, [38]. One can envisage then, in a networked system, detection being carried out on a single platform. Once a possible detection has been obtained the relevant snippet of information *around* that detection can then be passed to other magnetic platforms in the network. These platforms can then be used to carry out a more sensitive assessment of the detection and by using the information on two platforms it is possible to carry out a further classification – in terms of depth, speed and CPA. This step may be carried out by means of a Kalman filter, cf. [36] and [37], or in a bulk process – with attendant latency. Consequently the information transfer will be reduced to only times when a likely detection is present. When the magnetic network has made its detection and classification the contact – a packet of information which contains information on physically relevant parameters is sent to the rest of the network.

Presently no definite protocol exists for the transfer of such messages, and within a NATO context no STANAG for such communication exists.

Electric Field
Electric fields have also been used for a considerable period of time for the detection of both submerged and surface targets. Conceptually, the electric field sensor is two metal plates measuring the field between. Both the static – underwater Electric Potential (UEP) – and the alternating components are of interest. It is widely known that the bottom, surface interactions for these sensors play a much greater role in classification and tracking; see for instance [39]. The information from the UEP can be treated rather like that from magnetic sensors. The alternating currents exhibit characteristics rather like acoustic, with tonals – related to shaft rates and specific broadband features which are characteristic of vessels.

Pressure Sensors
Bottomed pressure sensors are designed to detect the pressure reduction of vessel passing over it. The pressure signature varies greatly with ship/target size speed, depth of target and depth of sensor. However, even in relatively deep water they provide a means of detecting the wake of a submerged vessel.

Other sensors
A host of other sensors have been suggested and are currently being researched for the *short range* detection of both submerged and surface vessels. These include seismic sensors, optical /electromagnetic sensors and flow sensors.

Research and development at NURC
NURC has been involved in research into the heterogeneous approach to target detection and fusion on-board such systems. The NGAS system has been engineered using readily available technology. Two platforms have been produced. Both incorporate:

- triaxial magnetometer;
- triaxial electric field sensors;
- a hydrophone;
- acoustic modem.

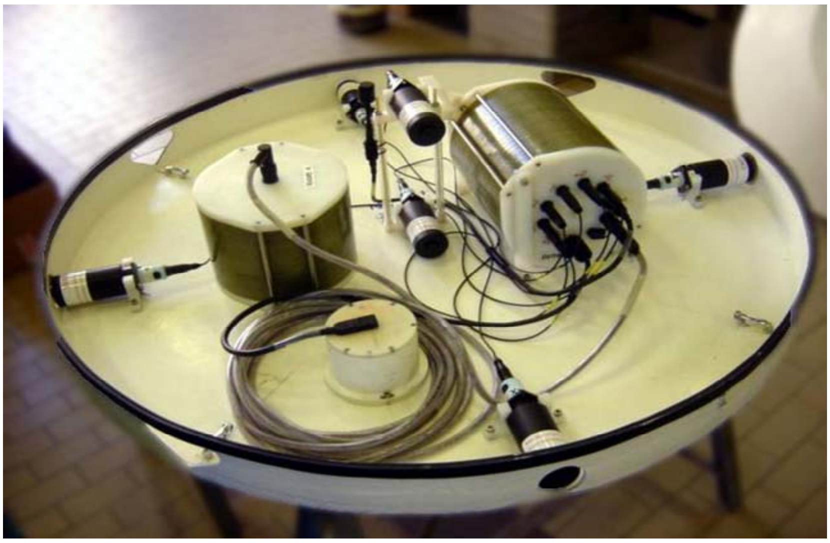

Figure 3 Opened multi-sensor unit. The unit is usually deployed with a fibre glass cover for protection

A photograph of the system can be seen in *Figure 3*. Usually the system is deployed with a fibre-glass cover to improve the durability and protection to the components. Presently the equipment is configured to run from a power cable fed to shore. Similarly the data collected is transferred to land by a fibre-optic cable (the system's modem can also be operated remotely through the same connection allowing detection and classification to be carried out off-board and allowing greater flexibility.) The equipment has been tested extensively in depths up to 100 metres with all sensors working well and showing detections which have exhibited different aspects of the target on the different sensors.

These NGAS platforms are expected to play a pivotal role in the demonstration of a system as detailed in Section 7. The incorporation of these devices into the overall network is expected to be straightforward since the algorithms developed will fit very easily into the MOOS approach as discussed above. An experiment is planned for Autumn of 2008 to demonstrate the automatic detection of a vessel by a bottomed sensor and subsequent cueing of the OEX AUV.

C. Deployed Acoustic Systems

Acoustic techniques are expected to remain the dominant means for detecting and localizing a target within future networked capabilities. As with all such discussions the role of such capabilities depends on the exact operational conditions under which systems are expected to work. However, it can be expected generally that both passive and active capabilities will be required. NURC's present priority is the incorporation of an active capability into a fully networked system and consequently we focus on that here.

We must consider within the role of active sonar both the receiver and the source.

*Receiver*s
The receivers may be the arrays which are towed by the AUVs of Section 7 and possibly gliders. They may, however, be fully deployed, fixed systems with large apertures and fairly advanced on-board processing. It is well known that in an active mode that fixed receivers offer

- better location accuracy to reduce the registration issues;
- better Doppler estimation using CW pulses.

Sources
The optimal use of acoustic sources remains a contentious point in networked systems for ASW. It is unlikely that they would be used except in extreme situations where the deployed system is within hostile waters. Even in home waters it seems unlikely that a constant ping cycle would be maintained due to limitations in battery life. Consequently the current thinking is that sources will only be triggered by a cuing mechanism taken from a passive sensor (either from a passive acoustic node or from a non-acoustic sensor or from some intelligence from above the surface which is passed into the network from a gateway portal).

The DEMUS system at NURC
Over recent years NURC has been investigating the role of deployed systems – mostly within an active context – primarily by use of the DEMUS (Deployed Experimental MUltistatic System). The system was designed as an experimental test-bed to aid data-collection and was not designed as to directly mimic what may be expected of an operational system.

It consists of three receiver and one transmitter buoy which are radio-linked to a central hub. In the experimental configuration this allows the system to be re-programmed over the radio-link – a role that may well be carried out by means of acoustic communications in future operational systems.

The receiver buoys are formed as volume arrays based on a multiple arm system having 64 hydrophones and a variable acoustic aperture (which can be changed by means of the radio link). The source consists of a stack of 8 rings which can be steered to various elevation angles – again by using the radio link.

The receiver buoys are equipped with enough processing to carry out signal processing of the data up to contact formation – these contacts would be small enough to pass the data over the radio link but probably would have been too big to transfer over an acoustic communications link.

Figure 4 shows a conceptual picture of the DEMUS set up highlighting the radio communications.

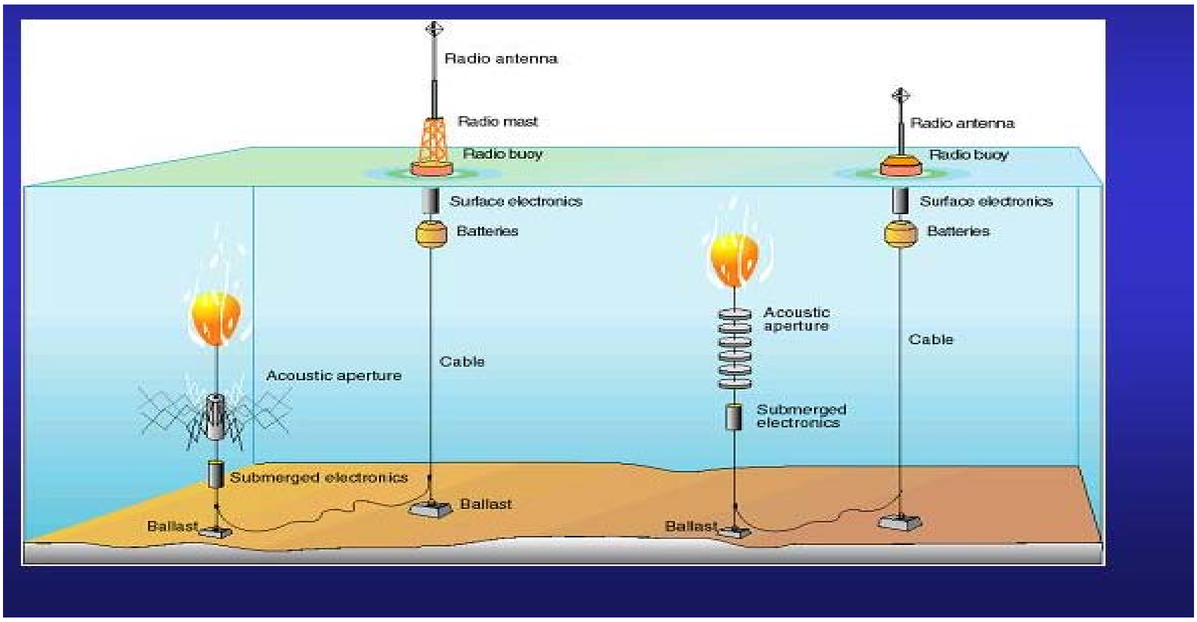

Figure 4 Schematic of the DEMUS system which has been used to investigate multistatics concepts by acquiring fixed-system data.

The DEMUS system has been used on several at-sea trials and has been shown to provide an acceptable level of data quality on the receiver buoys and excellent reliability from the source. It would not be envisaged that the system as a whole be further developed as part of a networked ASW demonstrator although the source will certainly be used in its deployed configuration to be triggered from a distant stand off node. (See Section 7)

7 Future R&T at NURC

NURC R&T will focus on a networked, multistatic undersea surveillance capability in water depths of less than 200 metres. The concept of a heterogeneous network, comprising one cluster of non-acoustic sensors and one of towed array fitted AUVs in conjunction with stationary and mobile sonar transmitters, will be demonstrated. This multistatic active sensor network has the potential for augmentation by other assets such as active sonobuoys and low-cost gliders; the latter in close collaboration with the project Battlespace Environmental Superiority (BES), with the objective to include rapid environmental assessment (REA) results in the planning of the end-state demo.

Besides scientific reports, the output will consist of:

1. An open-architecture multistatic active payload for AUVs; the elements specific for the multistatic active sonar application lie in the field of information processing, autonomy, high-fidelity simulation and planning aid.

2. Networked multistatic active sonar concepts of use (CONUSE).

Spiral development forms the basis for building up to a concept demo for a “system of systems” persistent network with distributed intelligence by 2011. The first step will be a basic concept that must be further improved and refined through trials (typically one engineering and one scientific per year) and experimentation. The end-state will be demonstrated in a sea-trial with military participation in order to facilitate development of CONUSE and transition to industry.

The technical challenges are:

- Data fusion capability of acoustic and non-acoustic sensors under the constraints of a low bandwidth networking environment;
- Autonomous platforms (mobile and fixed nodes);
- Acoustic sensors for AUVs (towed arrays, projectors);
- Robust/ interoperable wireless communications;
- Ad-hoc networks.

8 Summary and Conclusion

The challenges to ASW for NATO become progressively more difficult

- The need to operate in shallow water whilst maintaining a deep water capability;
- The continuing quietening of submarines
- The proliferation of smaller submersibles;

And the problem exacerbated by a diminishing budget and an increasing demand on NATO forces around the World.

The production of an autonomous system should allow operation in both deep and shallow water, over large areas of the underwater battlespace for long periods of time with minimal human interaction. And although it certainly should not be seen as a complete replacement for a traditional ASW capability it does deliver a means to reduce the risk posed to and a means of reducing the load on the warfighter and traditional assets, allowing other priority actions to be carried out.

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: multistatics 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.

None of this is exclusive, interoperability between platforms and sensors is key to the success of future operations. 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. Delay Tolerant Networks DTN and (underwater) communication are perceived to be an integral part of this process.

NURC finds itself at a turning point in the development of a new approach to ASW for which it is uniquely prepared. Technologically, scientifically and operationally an underwater networked capability can draw on research and development which has been carried out at the Centre over the last 10 years with an exciting and ambitious plan of development taking the Centre to a full-scale demonstration in 2011.

References

[1] The Unravelling and Revitalization of U.S. Navy Antisubmarine Warfare, John R. Benedict, Naval War College Review, Spring 2005, Vol. 58, No. 2;

[2] The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines, Owen R. Cote, Jr., Newport Paper No. 16, 2003**;**

[3] Swedish HMS Gotland remained undetected during an exercise with the US Navy; following this, the US Navy leased the Gotland (including crew) for a year to continue exercising, Wiebren Tabak in *Defensiekrant*, No. 10, March 2007, http://www.defensie.nl/binaries/LR%20DK10_tcm15-71528.pdf (*in Dutch*);

[4] China sub stalked U.S. fleet, Bill Gertz, *The Washington Times*, November 13 2006;

[5] Russian submarine activity off the coast of Norway, Author, *Journal*, Date: http://www.aftenposten.no/english/local/article2120697.ece

[6] Sea Power 21, Admiral Vern Clark, U.S. Navy Proceedings, October 2002: http://www.navy.mil/navydata/cno/proceedings.html

[7] http://www.comw.org/rma/fulltext/seapower.html

[8] Fundamentals of Bistatic Active Sonar, H. Cox, in Proceedings of NATO Advanced Study Institute Underwater Acoustic Data Processing, Royal Military College of Canada, Kingston, Ontario, Canada, Y.T. Chan (ed), Kluwer Academic Publishers, 1989;

[9] Adaptive Port/ Starboard Beamforming of Triplet Sonar Arrays, J. Groen, S.P. Beerens, R. Been, Y. Doisy and E. Noutary, IEEE Journal of Oceanic Engineering, Vol. 30, No. 7, April 2005;

[10] Port-Starboard Discrimination performances by a twin-line array for a LFAS sonar system, T. Warhonowicz, H. Schmidt-Schierhorn & H. Höstermann, in Proceedings of UDT Europe, 1999;

[11] Reverberation Suppression using Wideband Doppler-Sensitive Pulses, Y. Doisy, L. Deruaz, S.P. Beerens, R. Been, Accepted for publication, IEEE Journal of Oceanic Engineering;

[12] Sonar Waveforms for Reverberation Rejection, Part IV: Adaptive processing, in Proceedings of UDT Europe, 2002;

[13] Doppler-sensitive active sonar pulse designs for reverberation processing, Collins T., Atkins P., IEE Proc. F., 1998, 145 (6), pp. 347-353;

[14] Geometric comb waveforms for reverberation suppression, H. Cox, H. Lai, in Proceedings of the 28th Asilomar Conference on Signals, Systems and Computers, October 1994;

[15] Active Sonar Detection using the Page Test, D.A. Abraham, P.K. Willett, IEEE Journal of Oceanic Engineering, No. 1, January 2002;

[16] Performance of a distributed multistatic surveillance network during the DEMUS'04 sea trial, Doug Grimmett, Silvio Bongi, Stefano Coralluppi, René Laterveer, Alberto Baldacci, Warren Fox. NURC-FR-2006-015. November 2006. NATO CONFIDENTIAL

[17] Baldacci A and Haralabus G. Signal Processing for advanced Sensor Technology Applications and Environmental Adaption Schemes, 14th European Signal Processing Conference, September 2006, Florence Italy.

[18] Multistatic Sonar Localization, Coraluppi, S., IEEE Journal of Oceanic Engineering, Vol 31, No. 4, October 2006;

[19] Target Localisation with Multistatic Systems, Jean-Christophe Sindt and Pascal A.M. de Theije, in Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA 2004 Delft, The Netherlands 5-8 July, 2004

[20] Localization and Fusion in Multistatic Sonar, S. Coraluppi, in Proceedings of the 8th conference on Information Fusion, July 2005, Philadelphia, PA, U.S.A;

[21] Multistatic Sonar Tracking, S. Coraluppi and D. Grimmett, in Proceedings of the SPIE Conference on Signal Processing, Sensor Fusion and Target Recognition XII, April 2003, Orlando, FL, U.S.A.;

[22] Multi-Hypothesis Sonar Tracking, S. Coraluppi and C. Carthel, in Proceedings of the 7th International Conference on Information Fusion, June 2004, Stockholm, Sweden;

[23] Distributed Tracking in Multistatic Sonar, S. Coraluppi, C. Carthel, IEEE Transactions on AES, Vol. 41 (3) July 2005;

[24] Multi-Static Sonar Tracking: Algorithmic Advances and Sea Trial Evaluation, S. Coraluppi, C. Carthel, D. Grimmett and O. Gerard, to appear in U.S. Navy Journal of Underwater Acoustics;

[25] Coraluppi and Carthel C. Distributed tracking in multistatic sonar. IEEE transactions on aerospace and electronic systems. 2005, vol. 41, no3, pp. 1138-1147

[26] Sonobuoy placement for optimal multistatic detection and localization, Ozgur Erdinc, Stefano Coraluppi, Peter Willett, Doug Grimmett, NURC Technical Report, NURC-FR-2006-020, NATO unclassified releasable for internet transmission;

[27] Intelligent Ping Sequencing for Multiple Target Tracking in Distributed Sensor Fields, David W. Krout, Ph.D. Thesis, University of Washington, 2006;

[28] On improving Target Motion Analysis through own ship manoeuvring, R. Been, W.L. de Koning en J.H. de Vlieger, in proceedings of Digital Signal Processing, 1991, Florence, Italy

[29] Adaptive Control of Heterogeneous Marine Sensor Platforms in an Autonomous Sensor Network, Donald P. Eickstedt, Michael R. Benjamin, Henrik Schmidt, John J. Leonard, IEEE International Conference on Intelligent Robots and Systems (IROS), Beijing, China, 2006;

[30] Multi-Objective Optimization of Sensor Quality with Efficient Marine Vehicle Task Execution, Michael Benjamin, Matthew Grund, Paul Newman;

[31] Multi-Sensor Placement to Exploit Complementary Properties of Diverse Waveforms, in Proceedings of the 9th International Conference on Information Fusion, July 2006, Florence, Italy;

[32] FM-CW Tracking and Fusion in Multistatic Systems, D. Hughes, S. Coraluppi, M. Micheli, C. Carthel, MAST 2007, Genova, Italy;

[33] Delay Tolerant Networks (DTNs): A Tutorial, Forrest Warthman, March 2003;

[34] Wireless Underwater Communications and Networks: Current Achievements and Future Research Challenges, M. Stojanovic, Massachusetts Institute of Technology, 2006, available via TeachWare: http://distlab.dk/122/01/UnderwaterCommunications.pdf;

[35] The State of the Art in Underwater Acoustic Telemetry, Daniel B. Kilfoyle, Arthur B. Baggeroer, IEEE Journal of Oceanic Engineering, Vol. 25, No. 1, 2000;

[36] Hermand J-P. Tracking and detection of moving magnetic dipoles by kalman filtering techniques. SACLANTCEN Report SR-197.

[37] Sullivan E. Detection and tracking of a submarine with an array of ocean bottom magnetometers. SACLANTCEN Report SR-313.

[38] Otnes R. Static magnetic dipole detection using vector linear prediction, Anderson functions and block-based adaptive processing. Oceans-2007 pages-1-6

[39] Dalberg E, Lauberts A, Lennartsson M and Persson L. 'Passive acoustic and electromagnetic underwater tracking and classification using data fusion.' FOI-1727-SE.

[40] Daniel R. Bond, Dawn E. Holmes, Leonard M. Tender, and Derek R. Lovley, MUD Battery Electrode-Reducing Microorganisms That Harvest Energy from Marine Sediments (18 January 2002) SCIENCE.

[41] Sozer E.M, Stojanovic M and Proakis J.G. Underwater Acoustic Networks. IEEE Journal of Oceanic Engineering Volume 25. No 1.

[42] Partan J, Kurose J and Levine B.N. A survey of practical issues in underwater Networks. International Conference on Mobile Computing and Networking .
Proceedings of the 1st ACM international workshop on Underwater networks. Pages 17-24.

[43] Wide Area Ocean Networks: Architecture and System Design Considerations, Sumit Roy, Payman Arabshahi, Dan Rouseff, Warren Fox, WUWNet '06, Los Angeles, CA, September 2006;

[44] Multistatic Reverberation and System Modelling using SUPREMO, C.H. Harrison, M.K. Prior and A. Baldacci, in Proceedings of ECUA, Gdansk, Poland, June 2002;

[45] Closed-form Expressions for Ocean reverberation and Signal Excess with Mode Stripping and Lambert's Law, C.H. Harrison, Journal of Acoustic society of America, Vol. 114, No. 5, pp. 2744-2756, November 2003;

[46] Closed form bistatic reverberation and target echoes with variable bathymetry and speed, Chris H. Harrison, IEEE Journal of Oceanic Engineering, Vol. 30, No. 4, October 2005;

[47] Advances in the Multistatic Tactical Planning Aid. Armand Wathelet, Christopher Strode, Arjan Vermeij. NURC report NURC-FR-2006-022. December 2006. NATO RESTRICTED;

[48] Optimisation in the MultiStatic Tactical Planning Aid, A. Wathelet, C. Strode, A. Vermeij and R. Been, NURC-FR-2008-XXX

[49] Grandi, V. Carta, A. Gualdesi, L. de Strobel, F. Fioravanti, S. An overview of SEPTR: Shallow Water Environmental Profiler in a Trawl-Safe Real-Time configuration.

Current Measurement Technology, 2005. Proceedings of the IEEE/OES Eighth Working Conference. June 2005 pages 142-146.

[50] Schmidt, H. "Bistatic scattering from buried targets in shallow water". In: Bovio, E., Schmidt, H., editors. *GOATS 2000*, SACLANTCEN CP-46, 2002.

[51] Benjamin M.R. Interval Programming: A Multi-Objective Optimisation Model for Autonomous Vehicle Control. PhD. Dissertation, Beown University, Providence, RI, May 2002.

[52] Stokey R.P, Freitag L.E and Grund M.D. Oceans Europe 2005 pp 1133 -1137.

[53] Benjamin M.R., Battle D, Eickstedt D, Schmidt H and Balasuriya A. Autonomous Control of an Autonomous Underwater Vehicle Towing a Vector Sensor Array. 2007 IEEE International Conference on Robotics and Automation. Rome, Italy 10-14, 2007. pp 4562- 4569.

[54] Evans B.S. and Williams D.P. MCM AUV autonomy: requirements, approach and system implementation. NURC report. NURC-FR-2007.

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