Data Association and Interoperability of Multi-Static LFAS Platforms

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ABSTRACT

Multistatic LFAS systems have potential to provide increased ASW effectiveness. However, in order to achieve improved performance by multiple systems, a high degree of interoperability is required. In addition, multi-platform data need to be associated/fused in order to take full advantage of this networked LFAS concept. The CERBERUS’01 sea trial was a successful experimental demonstration of this concept, with 3 LFAS-equipped ships operating in a coordinated, interoperable way. This was achieved through high bandwidth encrypted communication links for the exchange of operational and acoustic contact data (Figure 1). These data were then visualized on a common Geographic Information System. The resulting system analyses of these data show performance improvements made possible through multistatic data fusion. This paper is focused on a detailed description of the CERBERUS’01 multi-static network.

Figure 1: Two Cooperating Ships Exchanging Sonar Contacts Across the Wireless Network.

1.0 INTRODUCTION

Anti-submarine warfare operations are increasingly challenged due to the quiet nature of current threat submarines, and the complexity of shallow water acoustic environments. Active sonar systems have become an important addition to passive systems in the detection of submarines under such conditions. However, active sonar systems must be able to overcome unfavourable propagation conditions, high levels of obscuring reverberation, and increases in the number of confusing target-like false alarm clutter.

Multistatically operating LFAS-equipped naval assets have the potential to improve submarine detectability by increasing detection range, area coverage, and signal excess. With multiple sonar receivers deployed, the number of detection opportunities increases for each transmitted ping. Increased opportunities to detect will result in better overall probabilities for detection, especially when it is possible to exploit the geometric diversity that is inherent within multistatic geometries. Variations in target detectability are a function of the presented target aspect angle and Doppler, and are also dependent on local environmental conditions (acoustic propagation and noise/reverberation backgrounds). Where one source-receiver sonar pair is faced with challenging detection conditions, another may be more favourably situated to detect well.

The increased number of detections from multistatic assets will also lead to better target tracking and localization. Where one system loses a target track, another system may be able to fill in the gaps. When multiple, simultaneous detections are made from several source-receiver sonar pairs, the resulting sonar echo data can be associated, fused, and cross-fixed, yielding more accurate localization estimates of targets and fixed false alarm clutter features. The advantage is not only to achieve better localization, but also to provide higher probability target tracks and classification information more quickly than a single system could, reducing the time to verify and react to the presence of a threat.

Multistatic operations may also provide tactical advantages. Target submarines may not be aware of, or concerned about, the presence of nearby ships which are equipped with receive arrays capable of bistatically detecting them. When more than one LFAS ship transmits, the submarine’s tactics for attack or evasion are more complicated than with a single monostatic system. The potential advantages of multistatics will not come without a cost. In order to operate LFAS multistatically, there must be a high level of inter-asset cooperation, coordination, and communications. There must be sonar system compatibility in the operational frequency bands, and the resulting data must be associated and fused into a tactical picture that is superior to that obtained by a single monostatic system. In addition, appropriate tactics and concepts of operation (CONOPS) should be developed to make the best overall use of multistatic assets in achieving the desired objectives.

2.0 OVERVIEW OF THE CERBERUS’01 EXPERIMENT

The CERBERUS’01 sea trial was an at-sea platform multistatic experiment. The objectives were to demonstrate the feasibility of coordinated, interoperable, bistatic and multistatic operations with tactical towed array LFAS sonars in a shallow water reverberation-limited environment. Both single-source and multi-source geometries were tested with a variety of ping transmission management schemes to reduce mutual interference. Processed sonar contact data from each active sonar transmission were exchanged between ships and visualized for trial monitoring, and to determine the feasibility of multistatic data fusion.

The trial was carried out under a Joint Research Project (JRP) agreement between three institutions: NATO’s SACLANT Undersea Research Centre (SACLANTCEN), Germany’s Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (FWG) in Germany, and the United Kingdom’s Defence Science and Technology Laboratory (DSTL). The private industrial company QinetiQ was DSTL’s prime contractor for the work done under this collaboration. The name “CERBERUS” comes from the Greek mythological figure of a three-headed dog, reflecting the three organizations and their ships that participated together as parts of a multistatic sonar network. The trial was held in August 2001, in an area located in the Southwest approaches to the United Kingdom.

This is a shallow area with water depths around 100-200 meters. The acoustic characteristics of this area include a large amount of obscuring reverberation and confusing clutter due to intense interaction of the sound
with the sea bottom. There are also a large number of shipwrecks in the area, which have been found to produce false alarm sonar echoes. In addition, the area is located in a very high-noise shipping zone.

Three LFAS-equipped ships participated in CERBERUS’01, one from each institution. The SACLANT Centre provided their ship R.V. ALLIANCE, which was equipped with a broadband, port-starboard discriminating cardioid towed array, and a high power towed source. This ship served as the experiment’s command and control ship. FWG provided their research vessel R.V. PLANET, which was equipped with a port-starboard discriminating twin-line towed array, and a high power towed source similar to that deployed from ALLIANCE. QinetiQ chartered the vessel BREMEN, which was outfitted with their broadband towed array and broadband source. A common acoustic frequency band below 3 KHz was identified and used, which was compatible with all three of the LFAS systems. The processing systems for each sonar were capable of processing not only their own source transmissions (monostatics) but also some of the transmissions coming from the other ships (bistatics).

The German Navy provided a diesel-electric submarine that served as a target during a large number of structured run geometries. This submarine was augmented with an acoustic transponder source that emitted known transmissions. This provided data to obtain an acoustic truth track reconstruction of the target trajectory. In addition, it cued the operators and analysts to more easily assess target detection performance in real-time. The submarine was also outfitted with a set of hydrophones, which recorded the impinging source signals. These data can be used to measure one-way transmission loss and to estimate actual target aspect angles during the experiment, as well as providing an alternate approach to truth track reconstruction.

Various run geometries were executed with one, two, or all three of the LFAS sources transmitting. During multiple source scenarios, various ping management schemes were implemented in order to minimize the effects of mutual signal interference. In some scenarios, all sources transmitted a common waveform, but their emissions were staggered in time and interleaved (staggered in time). Ping repetition intervals (PRI) were selected to be of sufficient duration to give all sonar source-receiver pairs (monostatic and bistatic) uninterfered detection opportunities. In other scenarios, the sources transmitted simultaneously, but with different waveforms that were in separated non-overlapping frequency bands. Receivers were able to record the data on their arrays, and monostatic and bistatic processing of various signals for detection analysis was done in real time on each ship.

Various voice and radio communication links allowed for the operational management of the experiment. In addition, the radio links allowed for a significant amount of data to be passed from ship-to-ship, giving each platform a multistatically network-centric view of the trial. This network will be described in more detail in the next section.

The CERBERUS’01 experiment produced a vast data set for various multistatic scenarios. About 33 multistatic runs were successfully executed with the submarine target present. CERBERUS’01 demonstrated the feasibility of interoperable multistatic operations and the possibility of achieving improved ASW surveillance performance using such a network.

3.0 THE CERBERUS’01 MULTISTATIC NETWORK

It is useful to characterize the various assets and equipment used during CERBERUS’01 as a “multistatic network”. A network is composed of both “nodes” and “links”. In this context, a “multistatic detector-node” is one of the individual sonar detectors within the network that produced contact data, and a “fusion-node” is a data fusion process based on data coming from a number of detector-nodes. A “link” is a communication
connection between nodes, passing data and/or information. The multistatic network implemented during CERBERUS’01 will be described in further detail in the following sections. Figure 2 shows a schematic diagram of the CERBERUS’01 network.

![Diagram of the Network as Implemented during CERBERUS'01.](image)

**Figure 2: Diagram of the Network as Implemented during CERBERUS’01.**

### 3.1 Multistatic Detector-Nodes

Each multistatic node applies appropriate signal and information processing for detection to the data from a particular sonar receiver, using an active transmission from a particular sonar source. Multistatic detector-nodes can be further categorized as “monostatic nodes” (output of monostatic processors), and “bistatic nodes” (output of bistatic processors). For CERBERUS’01 there were three sources and three receivers, and therefore the network included up to nine detector-nodes, with each ship operating up to three detector-nodes (one monostatic and two bistatic), as shown in Figure 3.
In the CERBERUS’01 experiment, the number of multistatic nodes available in real-time varied, depending on the objectives of the experimental run and the various systems’ availability.

Figure 4 shows a diagram of a generic processing string for a detector-node. In reality, the three ships used slightly different detailed implementations of this processing chain. In general, each node’s signal processing included the elements of band-pass filtering and data decimation, beamforming, and matched filtering to the active sonar transmission. At this stage the data were subjected to information processing, which included normalization, sonar echo clustering, application of detection threshold, and forming of the sonar contacts. Irrespective of the differences in each ship’s processing implementations, all of the resulting sonar contacts were packaged into computer files with a common file format. At the contact forming stage each node’s data rate has been reduced significantly, but the important information for each of the sonar contacts is preserved.
Each contact describes a target-like echo object present in the processed sonar ping data and occupies only 48 bytes (per contact) within the contact file. All sonar contacts were packaged together for each detector-node, into separate files for each processed sonar transmission (ping).

The average contact file (for a single ping from a single source-receiver node) contained 300-500 sonar contacts, and was around 30-40 Kbytes in total size. Of course, in addition to describing submarine target echoes, most of these contacts also describe random false alarms and fixed-feature clutter. Computer files of this size were sufficiently small to easily pass over the contact data link from ship-to-ship. As an example, the amount of data size reduction for the ALLIANCE beamformed, matched filtered data to contact data was more than three orders of magnitude (92 MB to 40 KB), i.e., the output contact data is about 0.05% the size of the processed data). Even though these files were very compact, they still allowed an enormous amount of contact information to be exchanged and shared. This is important, because the increased performance potential of multistatic networks will depend on the ability to combine and fuse the data coming from the various detector-nodes in the network, both for submarine targets and for false alarm echoes. At this level of contact exchange, algorithms for multistatic data fusion and tracking may be implemented. These enable the multistatic system to become an actual multistatic network, where the node data may be fused at a low level to directly produce multistatic tracks, versus a fusion of independently formed tracks from each node. This approach also has the advantage that it leaves the sonar system designers free to implement their own signal and information processing strings, which may be difficult or impossible to standardize, especially if the operations will involve assets from different nations using different sonar technologies.

3.2 Contact Sharing Data Link

The Contact Sharing Data Link was implemented in the CERBERUS’01 experiment to allow the exchange of the sonar contact data. A detailed description of this data/radio link and its performance during CERBERUS’01 can be found in [1].

Figure 5 shows the computer network configuration for the data link. Each of the three LFAS ships had a Pcom Datametro 320 microwave spread spectrum radio and antenna installed. These radios operate in the ISM (Industrial, Scientific and Medical) frequency band (2.4 GHz), with a maximum power of 1 Watt. The links were set up as point-to-point links, i.e., each ship had a two-way TCP/IP Internet Protocol connection with the other two ships. The radio network was configured to allow pass-through of data, where two ships that were unable to communicate directly were able to communicate through a relay of the information through the third ship.
The radios have a bandwidth data rate specification of 320 Kbit/sec, and range connectivity up to about 10 nmi (line of sight). This throughput was amply sufficient for the exchange of contact data, which was being generated only at about 5 Kbit/sec. In fact, the radios would have supported much higher rates of contact data exchange if it had been required. In order to maximize ship manoeuvrability, limiting system complexity, it was chosen to adopt omni-directional antennas (Figure 6).

The whole network was supervised from NRV Alliance, where a network monitoring station had been installed. Remote system updates and reconfigurations were also performed centrally from there.

Remote control and operation of the different network nodes has been demonstrated using tools such as Symantec pcAnywhere. Information security has been ensured at all times using the NX-1010 NATO-approved crypto equipment.
Specially-built software modules were used to retrieve the processed contact files from the sonar systems and to transmit them respecting the real-time constraint. The real-time constraint has been coded in a way such that a sonar contact file, to be considered valid, had to be received not later than one minute after generation.

Network synchronization has been applied to all network nodes using the Network Time Protocol (NTP). This feature has proved to be essential in order to perform the correlation between the log files generated on the different ships. In addition to that, the availability of reliable time synchronization makes possible the geo-referencing.

The following results were obtained:

- average throughput of 27.4 KB/s at the range of 9.5 nautical miles for direct ship-to-ship communication
- 100% link availability (BER 10^-6) over substantial periods of time (Figure 7)
- range extension to 19 nautical miles has been demonstrated using a multi-hop configuration (with one ship acting as a gateway node), with average end-to-end data throughput of 14.1 KB/s
- a good match has been obtained between system performance predictions (EREPS model) and field results. In order to validate this, a link balance equation was prepared, to account all relevant system parameters. This is fundamental in order to decide whether the communication system is capable of delivering the desired performance.

![Figure 7: Link Reliability Versus Range.](image)

The performance of the radio link was subject to the quality of the at-sea electromagnetic propagation and its dependence on atmospheric conditions. The performance was also a function of the various inter-ship ranges and aspects during the experiment (Figure 7). The ships were generally closer than 10 nmi and the link’s connectivity (availability) was demonstrated in certain cases beyond this range. Inter-ship range for which propagation “holes” existed was experienced and this correlated well with an electromagnetic propagation model [2]. In addition, the performance of this link was dependent on the aspect angles of the ships relative to each other. It was found that in certain run geometries, the link became unavailable, due to shielding effects of the radio antennas with ship structures and masts. In many cases, the unavailability of the link connection was overcome by passing the data traffic through the third ship, which acted as a relay.

The local sonar processors generated the contact files and these were written to computer hard disk and made available to the contact-sharing network. An automatic file-retrieving program was running on these...
computers onboard each ship. This facilitated the automatic transfer of the files from ship-to-ship, where all available remote files were copied to the local computer hard disk and made available for further analysis.

The contact sharing data link was encrypted to allow the passage of data up to the NATO CONFIDENTIAL level. This was done with NX-1010 equipment, which is a NATO authorized encryption device. This hardware was inserted between the ships’ local computers and the Datametro radios, and provided a secure, seamless, transparent computer network with Internet Protocol to be realized.

The primary purpose of the contact sharing data link was to pass each ship’s contact data to the other two ships. In this way, each ship would have the sonar contacts generated from the functioning parts of the entire multistatic network. These data were then visualized on a custom Geographic Information System (GIS), in real-time. In the event of a lack of link connectivity (usually due to antenna shielding problems) the data exchange was interrupted, but after the connectivity was restored, the link was able to quickly transmit the queued files and catch up to the present set of ping contact files. The data link successfully passed a large number of contact files during the course of the CERBERUS'01 experiment. For example, R.V. ALLIANCE (RV1) successfully transferred 8600 contact files to RV2 and RV3, and received 18,400 contact files (totalling 156 MB) from RV2 and RV3. In addition to the contact file sharing, the link also provided the capability to share environmental data, intermediate analysis results, experimental logs, etc., in real-time.

The availability of the wireless link enabled also the exchange of command and control traffic, such as operational orders from the Cruise Director to the participating vessels. Preliminary experiment reports and multimedia data sets were also exchanged across the wireless network, to improve the effectiveness of experiment execution.

3.3 Operational Data Link

An “operational data link” was implemented to exchange the minimal information necessary to enable bistatic processing on board each ship. It was not the purpose of this link to pass any contact information. This link was implemented to allow the passage of the operational information between ships with high reliability at long range, and without depending on the higher bandwidth contact data link. This data link was based on VHF radios which had a bandwidth data rate of 9.6 Kbits/sec. Radio modems and software were provided by FWG, and these enabled the passing of the following data from ship-to-ship through a serial RS-232 connection:

- GPS positional information of ship
- Transmission time and waveform identifier for current ping transmitted
- Transmission time and waveform identifier for the ping to subsequently occur

These information were inserted from each ships processor into ASCII string sentences which were passed over the radios in a NMEA-like format\(^1\), once a minute corresponding to the transmission times. The operational data link was reliable for the most part, and provided each processor the necessary information to process bistatically in real-time. In addition, it provided the information necessary to map and visualize acoustic contacts on a geographic screen in real-time.

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1 NMEA is an organization that defines standards and data protocols for communications between marine instrumentation.
3.4 Additional Supporting Data Links

In addition to the spread spectrum radio links between the three LFAS platforms, the computer network onboard R.V. ALIANCE was connected to SACLANTCEN’s internal computer network via a satellite VSAT connection in the KU band, implemented using the Nortel Dasa SkyWan system. This link worked very well and had nearly constant connectivity. It was also fully encrypted using the NX-1010’s, with a connection between the shipboard and the land-based NATO RESTRICTED computer networks. The bandwidth of this satellite connection was set to 128 Kbit/sec\(^2\), which is somewhat lower than the spread spectrum radio link. However, at this data rate, it could have been used to transfer 100% of the total contact data to a remote land-based data fusion center (in this case, SACLANTCEN) for monitoring or data fusion processing. In the case of CERBERUS’01 it was used mainly for administrative and management purposes, although it demonstrated the viability of including a land-based processing to this type of multistatic network.

There was a secondary lower bandwidth spread spectrum radio link installed between R.V. ALLIANCE and the HELMSAND, which was responsible for operating echo repeater equipment. This link connected two NATO UNCLASSIFIED computer networks to allow the passage of experimental instructions and environmental data (without encryption).

3.5 Multistatic Data Fusion

At present we identify three levels at which the data from multiple detector-nodes within a multistatic network may be fused. The first level of multistatic data fusion is simply to get the data passed along appropriate data links to some common destination. That is, to collocate the multistatic data from the various detector-nodes. This was successfully accomplished during CERBERUS’01 with the generation of sonar contacts and the exchange of these from ship-to-ship via the contact sharing data link. Each ship obtained a complete copy of the entire network’s contact files, usually in real-time, but subject to the link’s connectivity.

A second level of multistatic data fusion is to visualize the various detector-node data on a common basis, and this was also done during CERBERUS’01. This was done with custom software, which mapped the contact data to a common geographic display based on a commercial Geographic Information System (GIS). This capability was built and provided by SACLANTCEN to all three LFAS-equipped ships. After the contact data from the remote ships and from own ship were available on the local computer, the contacts were mapped geographically according to their arrival time, beam directions and the source and receiver positions. In the case of bistatic configurations, the mapping makes a range calculation according to the proper bistatic equi-time ellipse.

This visualization tool allowed the analysts to view the experiment from the “network” point of view. In real-time the analysts could look at the contacts from various detector-nodes overlaid on the geographic screen at the same time. Figure 8 shows an example output of this visualization tool, which was achieved in real-time during CERBERUS’01. It shows all output contacts from nine detector-nodes (three monostatic, six bistatic), received over 15 minutes, mapped to latitude/longitude space in different colors. In addition, the 3 ships’ trajectories are shown moving north. The visualization tool allows selection of which detector-nodes are displayed together, and how many pings (time history) of contact data are overlaid. Figure 8 shows a lot of contacts, many of which are due to known interference signals. Some regions are clearly seen to have many contacts overlaying, which correspond to areas of high reverberation clutter that are commonly seen by multiple nodes.

\[^2\text{This satellite link can also be configured to operate up to 512 Kbit/sec, if required.}\]
This visualization scheme was attempted in order to facilitate understanding of the performance of the multistatic network during the trial. In particular, it was desired to compare the performance of the individual detector-nodes, for detection and localization of both the submarine target and fixed feature clutter. It was hoped that such a tool would provide real-time insight into both the potentials and the problems that will emerge in the development of multistatic data fusion and tracking algorithms.

In reality, the images that were available for visualization during the trial tended to be quite complex and difficult to interpret in real-time. Extraneous signals from the submarine beacon and the echo repeater obscured the interesting features of the images, and there were some doubts whether the software was performing the proper mapping. Nevertheless, this was a very good first attempt at multistatic data visualization and demonstrates the potential usefulness of the concept in future experiments and operations. The development of these tools continues and it is believed that additional sonar contact clustering schemes will help to reduce the uninteresting interference seen in these geographic representations of the contact data. The CERBERUS’01 multistatic network’s only real-time fusion-nodes were a combination of the consolidation of the data onto a common computer, along with this visualization tool. One of these visualization tools was operating onboard each of the 3 ships. No other multistatic data association or fusion analysis was done in real-time during the experiment.

A third level of multistatic data fusion goes beyond data visualization and is either made through operator analysis or through the application of automatic algorithms. This was not attempted during the CERBERUS’01 sea trial, but has been done subsequently, with some results presented later in this report. This fusion involves the proper combination, association, and fusion of the contact data from different detector-nodes to result in the improved performance possible with a multistatic network. Multistatic network detection statistics and false alarm rates can be calculated and compared with the individual nodes’ performance. In addition, it is recognized that what will be required is a multistatic tracker which will take the entire network’s contact data and output tracks for the multistatic network. Although a multistatic tracking
algorithm was not available to apply to the CERBERUS’01 data in real-time, efforts are underway to develop such algorithms. Preliminary results for this multistatic tracker have been obtained through post-experiment analysis, and are reported on in [3].

4.0 RESULTS

Subsequent analysis of the contact data from the CERBERUS’01 multistatic network was made and the results show the benefit and “value-added” of this concept. Detailed results of this analysis are reported on in [4], and a summary follows. One of the scenarios (Figure 9) included a single stand off source (RV3), with passive bistatic receivers (RV1, RV2) operating close to the target (RV4). The multistatic network in this case was able to improve probability of detection over the monostatic case by a factor of 20, extending the detection range and area coverage. In this scenario, the covertness of the passive bistatic receivers also offers the tactical advantage that the submarine has no knowledge of his detection vulnerability.

![Figure 9: Experimental Run Geometry Executed during CERBERUS’01.](image)

Another scenario (figure 10) that was tested during the trial was a multi-source, multi-receiver network. In this case the multistatic network consisted of 7 detector-nodes (3 monostatic and 4 bistatic). The increased detection opportunities of the multistatic network provided increased numbers of actual submarine detections which, after fusion, improved the overall probability of detection to nearly the maximum level, by far exceeding the best single node performances. In many cases more than a single source-receiver node detected at the same time. This detection redundancy gives opportunities to improve detection confidence and target localization through multistatic cross fixing. This scenario also presents increased complexity to the submarine’s tactical decision making, as there are three sources for which he must either evade ensonification or prosecute.
5.0 CONCLUDING REMARKS

The possibility of overlapping the local sonar display with the remote “acoustic viewpoints” received across the wireless network has been demonstrated, and will be a key to enhancing detection performance through a network-centric concept of operations.

Future work will focus on consolidating the important results obtained, with additional studies on aspects such as range extension (using directional antennas and alternative modulation/frequency schemes), scalability to large networks of autonomous buoys with on-board processing and communications capabilities, dynamic routing and self-reconfiguration using mobile-IP features.

Effective employment of a multistatic sonar network will not only require interoperable systems, CONOPS, and communications, but also effective contact generation schemes and multistatic tracking algorithms to automatically fuse the detection contacts and handle the increased number of false alarms.

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7.0 REFERENCES


