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Passive acoustic signal processing capabilities

Initial survey of existing algorithms and deficiencies

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Abstract

An initial survey of the passive underwater acoustic signal processing capabilities available at Defence Research and Development Canada (DRDC) was conducted. The focus of this survey was methods and algorithms for passive sonar detection, classification, localization, and tracking (DCLT) to enable research for the Canadian Arctic Underwater Sentinel Experiment (CAUSE). The information in this review was primarily gathered through discussions with other scientists, engineers, and computer scientists, rather than an exhaustive literature review. As a result of this survey, several gaps in DCLT processing capability were identified that should be addressed during the CAUSE project. Seven main areas for research and development were identified that have the potential to significantly enhance the signal processing capabilities for the CAUSE project. Much of this work will be conducted by a contractor; however, some research will continue to be carried out by DRDC scientists, and in collaboration with academic and international partners.

Résumé

Ce document décrit les résultats d'une étude préliminaire portant sur les capacités actuelles de Recherche et développement pour la défense Canada (RDDC) en traitement du signal dans le domaine de l'acoustique sous-marine passive. L'étude a couvert les méthodes et algorithmes de détection, classification, localisation et poursuite (DCLP) pour les sonars passifs dans le cadre du projet de recherche expérimentale d'une sentinelle sous-marine pour l'Arctique canadien (RESSAC). L'information fut obtenue en consultant des scientifiques, des ingénieurs et des informaticiens plutôt qu'en faisant une revue exhaustive de la littérature. L'étude a permis d'identifier plusieurs lacunes en DCLP qui devraient être comblées au cours du projet RESSAC. Elle met en évidence sept principaux secteurs de recherche et développement ayant le potentiel d'améliorer sensiblement les capacités de traitement du signal pour le projet RESSAC. La plus grande partie de ces travaux seront effectués par un entrepreneur, mais des recherches continueront d'être menées par des scientifiques de RDDC et par l'entremise d'une collaboration avec des partenaires universitaires et internationaux.

Table of Contents

1 Introduction

The objective of the Canadian Arctic Underwater Sentinel Experiment (CAUSE) is to investigate and demonstrate wide-area underwater/under-ice surveillance in the Canadian Arctic [1], primarily using passive acoustics. These project objectives will be addressed through technology demonstrations and the provision of advice to the Department of National Defence (DND) and the Canadian Armed Forces (CAF), so that the CAF are better prepared to operate in the changing Arctic environment and maintain a persistent surveillance capability at Canada's northern approaches [1].

In order to enable a persistent surveillance capability in the Arctic there is a requirement to detect acoustic Signals Of Interest (SOIs). These SOIs include acoustic signatures generated by anthropogenic objects including submarines, surface ships, and Unmanned Underwater Vehicles. To facilitate detection of SOIs, two different types of acoustic sensors—designed to be deployed for extended periods of time in the Arctic—are being developed under the CAUSE project: a mile-long seabed surveillance array and a drifting Vertical Line Array (VLA). These two sensor types represent vastly different scales in the amount of data collected and available processing power, and thus different signal processing challenges.

The seabed array will be cabled back to shore in order to stream acoustic data from 96 hydrophones in real-time. Data collected by the seabed array can be used to advance the development of detection, classification, localization, and tracking (DCLT) algorithms and tools using acoustic signals from targets of opportunity in conjunction with ships' Automatic Identification System (AIS) data. The array is currently being designed and built with an anticipated deployment in 2019. Once deployed, large volumes of data will be collected, which will need to be processed quickly and efficiently. Fortunately, since data is being streamed to a central processing facility, there will be a significant amount of computer processing power available for DCLT processing.

In contrast, the drifting VLA system will be required to perform onboard DCLT. The VLA system is currently being designed, but is expected to be 500 m long with an acoustic array containing 48 to 96 hydrophones. The design goal is to produce a long-life (at least a year) system that will have the potential to perform long-range under-ice surveillance [2]. To meet this requirement, embedded DCLT processing must be conducted efficiently onboard the drifting VLA system, with just summary reports sent via low data-rate radio communications when an SOI has been detected.

This report captures the results of a preliminary investigation conducted by the author to determine the current state of the passive acoustic signal processing capabilities available at DRDC – Atlantic Research Centre that might be of benefit to the CAUSE project (Section 2). In addition, areas in which DRDC has limited capability, and/or further research is required, are identified in Section 3.

2 Survey of Existing Passive Signal Processing Algorithms

This section summarizes the results of the author's initial review of passive acoustic signal processing capabilities that may be of benefit to the CAUSE project. The following information was primarily gathered through discussions with other scientists, engineers, and computer scientists. It should be noted that this is not the result of an exhaustive literature review. DRDC – Atlantic Research Centre has conducted significant amounts of research on passive acoustic signal processing in the past, most of which is not detailed here. The following is merely an account of capabilities that are currently in use, or have been within the past ~5 years.

2.1 System Test Bed

The System Test Bed (STB) [3] is a flexible computing environment developed by DRDC – Atlantic Research Centre that has been in continuous development and use for more than twenty years. It contains a set of software components that provide sensor interfacing, signal processing, data management and recording, data fusion, and operator-machine interfacing [3]. For the purposes of this document, the focus will be on the signal processing aspects of the STB, although other components of the STB are certainly useful for the CAUSE project.

The following summarizes a discussion the author had with Gary Inglis about the passive acoustic signal processing capabilities of the STB.

- *Detection*. The STB currently contains 'good' detectors for tonals and swath signals. In typical operation many detectors are configured with different parameters (frequency band, FFT length, integration time, etc.) and run in parallel in order to ensure detection across multiple frequencies. Currently, there is no transient detector—aside from performing ping interception—integrated in the STB. From further discussion with other Defence Scientists, there are plans to integrate the Acoustic Sentinel [4] detector (see Section 2.2.1) with the STB, after which it should be possible to configure the Sentinel detector to perform broadband transient processing; however, some research would be necessary to determine optimized detector parameters for transient signals.
- *Classification*. Other than the aural classifier (discussed in Section 2.4), there is no automated classifier implemented in STB. Although the aural classifier is implemented in STB, it has not been used other than in a research capacity, and further testing would be necessary to use it in the more operational context in which STB is often employed. Gary mentioned that there was some past research on a neural network classifier integrated into the STB, but the contractor controlled the code so it has not been maintained, nor is it possible to modify.
- *Localization*. The STB has limited localization ability, designed for two or more sensors. Currently, the localization is all operator-assisted; that is, the operator must manually choose the data that is passed to the localizer. The ideal case is for this process to be automated by having the results of an automatic detector feed directly into the localization module. Additionally, the STB will only be able to provide a bearing to a target on the seabed array, rather than an actual localization estimate.

- *Tracking*. Gary indicated that STB has no tracker implemented which is suitable for processing passive sonar signals. There are several tracker algorithms available in the STB which can be used for active sonar, including those currently under development for the Integrated Multistatic Active-Sonar Technology (IMAST) trial, and the ITAC tracker (see Section 2.4 for more details on ITAC).

Also of note, the STB has no real ability to do embedded processing since there are issues with memory management. Thus, the STB is only a viable option for processing the data from the seabed array, and cannot be implemented on the final DAMS solution. Nonetheless, the same signal processing algorithms and concepts may be implemented separately in the STB and on the embedded system used by the DAMS, but will likely need to be configured differently in order to optimize the processing/memory management for each application. Despite this limitation for the final DAMS solution, STB has been proposed as an interim capability during the DAMS development. The STB will likely be installed on a laptop which will be placed in a waterproof housing of the DAMS buoy in order to test the DAMS concept during the 2019 CAUSE demonstration trial.

2.2 Underwater Surveillance and Communications Group

The Underwater Surveillance and Communications (USC) group has a long history (although the group's name does not) of performing passive acoustic surveillance, both in temperate and Arctic waters.

The USC group has recently been involved in at least three projects which have resulted in signal processing capabilities that will be useful for the CAUSE project. These projects include the Rapidly Deployable Systems (RDS) project [5], the Northern Watch Technology Demonstration Project [6], and development of the Distributed Undersea Sensor Network (DUSN) under the Force ASW project. Passive signal processing for SOIs was advanced under each of these projects, as described in the remainder of this section.

2.2.1 Rapidly Deployable Systems Project

DRDC's participation in the RDS project began in the mid-1990s [5], resulting in many hardware and software developments. The software developments included signal processing algorithms to perform array element localization (AEL), measurements of the water column and bottom properties, detection of sources with the array in 'sleep' mode, and localizing both narrowband and broadband sources in bearing, range, and depth. Detections were accomplished using the Acoustic Sentinel detector (modern version described in Section 2.2.3) running on an embedded system autonomously in real-time. No automated classification algorithms were developed under the RDS project; however, several acoustic localization/tracking algorithms were developed. These include Matched Correlation Processing (MCP), Matched Field Processing (MFP), backpropagation, and Lloyd Mirror processing. MCP can be used to localize broadband sources in a full 3D environment—the speed of this method is limited by the search grid's step sizes in range, depth and bearing, as well as the number of hydrophones in the array [5]. MFP processing can be used for either tonal or broadband signals [5]; limitations of this method depend on the acoustic propagation model used, as well as the stability of the oceanographic conditions. In the past, Arctic oceanographic conditions were considered very stable, but are likely to become increasingly unstable as more Arctic ice melts, thereby limiting the suitability of the MFP method. The backpropagation algorithm was designed to localize a source using data from a vertical line array by using the principle of reciprocity to propagate the measured field out in range and depth—the point where the field focuses is the estimated acoustic source location. Backpropagation may be used for either a narrowband or broadband source [5]. Finally, the Lloyd Mirror processing technique is used to estimate the track and depth of a narrowband, nearby source in shallow water [5].

Many of the algorithms developed as part of the RDS project focused on localizing/tracking targets close to a sensor. This is in contrast to many of the CAUSE objectives, which rely on performing DCLT processing of targets at large distances from the sensing system. As such, the suitability of, in particular, RDS' localization and tracking algorithms must be carefully evaluated before significant effort is expended on further development of these algorithms.

2.2.2 Northern Watch Technology Demonstration Project

The objective of the Northern Watch project was to demonstrate surveillance capabilities at an Arctic chokepoint (i.e., persistent local-area surveillance) [6]. During the Northern Watch project a Processing and Display System (PDS) was developed to process the seabed array data, generate sonar displays, and provide 'derived' content to fuse with data from other sensors. The PDS was developed using the STB. This system provided the following signal processing functionality:

- audio analysis;
- channel analysis;
- beamforming analysis;
- broadband analysis;
- DEMON analysis;
- narrow-band analysis;
- signal detection and localizations from broadband, DEMON, and narrow-band data;
- range prediction;
- acoustic data visualization; and
- tactical visualization including nautical chart overlays, range prediction overlays, track overlays, and line of bearing overlays [6].

Localization was accomplished during the 2015 Northern Watch demonstration trial by using bearing information from multiple acoustic sensors to generate a cross-fix localization. Of note, a human operator was required to be 'in the loop' for much of the signal processing done during the Northern Watch project; that is, minimal automation was employed by the signal processing algorithms. With respect to automation, the final project report [6] states, "It is a short fall of the [Northern Watch] project that in the end almost no [Underwater Sensor System] signal processing development was included and only the most basic detection and cross-fix algorithms were developed."

2.2.3 Distributed Undersea Sensor Network Nodes

The DUSN nodes are the most current iteration of autonomous systems developed by the USC group for performing local area surveillance. Automated detection and tracking/bearing estimation are performed onboard the DUSN nodes.

Detection is accomplished using either the time- or frequency-domain Acoustic Sentinel detector [4]. The time-domain Acoustic Sentinel detector algorithm compares the ratios of a short time exponentially averaged signal with a longer time-averaged value—a detection is triggered when this ratio exceeds a pre-defined threshold. Similarly, the frequency-domain Acoustic Sentinel detector applies a 'fast' and 'slow' exponential filter for each FFT bin and the ratio of these filters for each frequency bin is compared against a detection threshold [4].

There are two available tracking/bearing algorithms in the DUSN nodes. The first is a Minimum Variance Distortionless Response (MVDR) algorithm which provides the bearing to one or more targets. The second algorithm is a Phase Gradient estimation method which can estimate the bearing and elevation angles to a single target (future developments will likely add the ability to track multiple targets) emitting a broadband acoustic signature [4].

2.3 Software Tools for Analysis and Research

DRDC maintains a software suite referred to as Software Tools for Analysis and Research (STAR). The STAR software is designed to be flexible, reusable, with low processing-load, such that its algorithms are suitable for implementation in both workstations and low-power embedded systems [7, 8]. The signal processing components of STAR that may be useful to the CAUSE project are contained in the Signal Processing Packages (SPPACS) and STAR-IDL software tools. SPPACS algorithms are written in C/C++, which efficiently perform standard signal and/or sonar processing tasks [7]. The STAR-IDL group of software were developed to support general research and analysis by providing scientific grade analysis tools that allow for efficient analysis of a data set. Furthermore, the STAR-IDL algorithms integrate seamlessly with those in SPPACS [7].

STAR contains many of the components required for DCLT processing of passive sonar:

- *Detection*. STAR contains a detector which is capable of detecting the SOIs for the CAUSE project (both tonal and transient signals). For example, the author has found the band-limited energy detector [9] to be very useful for detection of marine mammal calls (i.e., broadband transients). The detector is similar in concept to the Sentinel detector discussed in Section 2.2.3, but includes additional/alternate signal processing options. For example, the band-limited detector can be applied to other time series than just an energy time series; for example, entropy and higher-order power law time series [8].
- *Classification*. DRDC's aural classifier (further detail in Section 2.4) has been integrated in the STAR software.
- *Localization*. There are multiple beamforming algorithms available. Localization algorithms are also available, although little documentation is included for these tools.
- *Tracking*. Some passive acoustic tracking capability exists in STAR. This includes the STAR-IDL Bearing Tracker. Other tracking algorithms are available which have previously been applied to active sonar—it is worth investigating these further to determine their suitability for passive sonar tracking.
- In addition to the DCLT algorithms, the STAR software contains many algorithms to handle data pre-processing and visualization.

Further information on the algorithms in the list above may be obtained in the documentation associated with any recent STAR software release.

Modification and application of the STAR software can be done internally at DRDC, but is more commonly performed by a contractor with a license for the STAR software. There is typically a standing offer/task authorization contract in place to support STAR software development, and data analysis employing the STAR tools. Most recently, Akoostix Inc. / Geospectrum Technologies Inc. have held the STAR standing offer.

2.4 Aural Classifier

The aural classifier was developed at DRDC – Atlantic Research Centre based on anecdotal evidence that sonar operators can aurally distinguish between active sonar returns from target and clutter objects [10]. To date, the aural classifier has only been tested for active sonar, marine mammal vocalizations, and torpedo acoustic signatures; it has not been tested yet on SOIs for the CAUSE project. In particular, careful thought is needed in order to determine if the classifier is suitable, and how best to implement it, for continuous tonal signals as the aural classifier has only been applied to transient signals in the past.

Previous effort has been made to integrate the aural classifier's algorithms with the STB [11, 12], providing a distinct advantage relative to other potential classifiers. Significantly, two modules were integrated into the ITAC-STB system: the 'Aural Feature Extractor' and the 'Aural Classifier.' The 'Aural Feature Extractor' performs all necessary filtering of the acoustic time series and extracts the perceptual features for each contact. The 'Aural Classifier' module compares the perceptual features for each contact with those in a pre-processed training set, and generates a classification decision and probability of class association for each contact [11]. It is worth noting that more work is required to fully integrate the aural classifier into the STB, since a bridging technique was employed to reuse the existing aural classifier IDL code [11]; efficiencies may be gained in processing by fully porting the aural classifier code to another language (e.g. C/C++). In fact, a full port of the aural classifier code would be necessary if it were to be used by the final version of DAMS in order to facilitate the embedded processing required by DAMS.

3 CAUSE Signal Processing Approach

This section briefly addresses the signal processing research approach proposed for the CAUSE project. The first part of this section provides an overview of the key research areas for passive acoustic signal processing which were identified as a result of the survey of current capabilities. Many of the topics listed will be essential for developing a signal processing approach for DCLT for both the seabed array and the drifting VLA system. Therefore, a scalable solution would be ideal; alternatively separate solutions tailored for the different processing scales may be developed. The last part of this section details the implementation approach that will likely be taken; including the fact that much of the CAUSE signal processing research effort will be addressed through a Task Authorization contract.

3.1 Key Research Areas to be Addressed

The following list briefly identifies the key signal processing research topics which should be addressed in the CAUSE project:

- *Automation of the DCLT processing chain*. Significant research effort should be directed towards automating the DCLT processing chain. The requirement for onboard processing for the DAMS and the large volumes of data generated by the seabed array make this research area critical for the success of the CAUSE signal processing effort. Ideally, there must be no requirement for operator-assisted tasks (e.g., an operator selecting detections to be passed to the STB localizer). Machine learning methods should be investigated.
- *Detection of broadband transient signals*. Recent research efforts have primarily been directed towards the development of tonal signal detectors (as with the suite of STB detectors, and the Sentinel detector). Development of broadband transient detectors may improve the probability of detecting a submarine, and aid in classification. This is an especially important topic since the tonal signals emitted by a modern submarine are usually at such low sound pressure level that they are difficult to detect using conventional techniques.
- *Signal classification*. Signal classification is an area that requires significant development, since DRDC has little capability to currently do this for SOIs. The aural classifier seems to be the only automated classifier at DRDC which has potential to be used to classify SOIs. Research should be done to identify other potential classifiers, and compare their effectiveness to that of the aural classifier. If the aural classifier is used for the CAUSE project, the Bayesian classifier currently employed should be replaced with a more advanced classifier architecture. Furthermore, we must consider how much of the classification process ought to be done by an off-board system, as providing a complete classifier onboard an autonomous systems risks the security of the acoustic intelligence used to provide a classification decision. A possible solution is to calculate the classification features, produce the appropriate linear combination of features to generate a ‘data point’ in ‘feature space,’ and transmit the ‘data point’ back to a secure location. The final classification decision would be generated by mapping the data point onto a pre-defined decision space. In this way, the sensitive acoustic intelligence information would be removed from the off-board system, as it is primarily contained in the curves separating the regions of the decision space. Another advantage of this method is that very little bandwidth would be required to transmit the ‘data point.’

- *Tracking*. Some localization algorithms have already been developed, but there is no automated tracking algorithm available at DRDC which has been tested on SOIs for the CAUSE project.
- *Association of detections*. In order to facilitate, classification, localization and tracking it would be useful to associate discrete detections with the appropriate acoustic source. This is required for both a single sensor, and multi-sensor approach. It becomes particularly important to achieve correct detection association when fusing information from multiple receivers to perform cross-fix localizations. Detection association is not a simple matter of grouping detections by common frequencies, since the frequency of the received signal may be altered due to Doppler Shift [6] and, in some cases, acoustic propagation effects. Some recent effort has been expended at DRDC to improve the association stage; however, there is still significant research and development left to be done to perform automated detection association.
- *Integrated approach*. An interesting, and possibly fruitful, topic to explore is an integrated approach to DCLT. Rather than the typical linear flow of information along the DCLT processing chain, information from latter processing steps in the signal processing chain could be used to refine estimates from previous steps. Refer to Figure 1 for conceptual representation of this integrated approach.

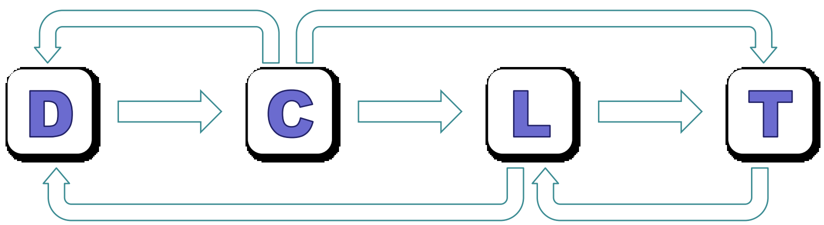

Figure 1: *Conceptual representation of how information could flow between the DCLT processing steps. Note that this is not just a linear flow of information from the detector, to the classifier, then the localizer, and finally the tracker, rather it passes information back and forth between earlier and later processing stages.*

A good example of this integrated approach is the work done to develop an Integrated Tracker and Aural Classifier (ITAC) system. The ITAC concept uses classification information to improve target tracking, specifically at the contact-track association stage [11].

- *Dataset development.* A common data set(s) is/are required for development, testing, and comparison of DCLT algorithms and approaches. It will be beneficial to have both unclassified and classified data sets. An unclassified data set will facilitate easy development of algorithms, publication, and collaboration; however, a secret data set is required for realism. Existing data sets, from DRDC trials or ADAC's library, can be used to build appropriate data sets. The final data set(s) should include data collected under a variety of conditions (e.g., acoustic propagation characteristics, ambient noise, and sensor types), and include a range of signal-to-noise ratios (SNRs). Including data from an assortment of recording conditions will facilitate the development of robust DCLT algorithms, rather than algorithms tuned to a specific environment or recorder type.

3.2 Implementation Approach

The approach to implementing the identified signal processing research will be addressed using three different methods:

- *Contracting.* A large Task Authorization contract will be the primary vehicle for performing this research. The contractor will develop new passive signal processing algorithms, as well as modify/improve existing DRDC algorithms. Modification of existing algorithms, for example, may include translating from their current scientific programming language (e.g., MATLAB or IDL), to another programming language for more efficient data processing (e.g., PYTHON or C). In addition, the contract will produce acoustic/non-acoustic data sets for development and testing of DCLT algorithms.
- *NSERC Collaborative Research Grant*. We hope to establish a Natural Sciences and Engineering Research Council (NSERC) Collaborative Research Grant with Dr. David Barclay of the Dalhousie Oceanography Department. Dr. Barclay is an expert in underwater acoustic noise and propagation modelling. This grant will be used to facilitate research relevant to DCLT in the Arctic, as well as to train graduate students (potential future hires) in underwater acoustics. JASCO Applied Sciences has been identified as a suitable industry partner for the grant.
- *In-house research*. Research will also be conducted at DRDC, potentially in collaboration with other partners. The focus of the in-house research will likely be broadband transient detection and classification and exploring options for an integrated DCLT approach.

4 Conclusion

An initial survey of the passive acoustic signal processing capabilities available at DRDC was conducted. As a result of this survey several gaps in DCLT processing capability were identified that should be addressed during the CAUSE project. Seven main areas for research and development were identified; these signal processing research priorities include: automation of the DCLT processing chain, detection of broadband acoustic transient signals, signal classification, development of tracking algorithms, association of detections, investigation of employing a holistic/integrated approach for DCLT processing, and development of both unclassified and secret data sets to support testing and validation of DCLT processing methods. Much of this work will be conducted by a contractor; however, some research will continue to be carried out by DRDC scientists, and in collaboration with academic and international partners.

In order to facilitate ongoing development, either in-house or by a contractor, it would be incredibly useful to develop and maintain a repository for DCLT algorithms used by the Underwater Sensing section. A survey, like the one presented here, would be an easy task if all algorithms were maintained in a central location. This requirement has been brought to light through conversations with Derek Clark. Derek has offered to help set up a central repository (with additional support as necessary), and maintain the version control software that will enable such a repository. A properly maintained and documented repository will also make it much easier in the future to identify gaps in capability, and the best way forward to fill those gaps.

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An initial survey of the passive acoustic signal processing capabilities available at Defence Research and Development Canada (DRDC) was conducted. The focus of this survey was methods and algorithms for passive sonar detection, classification, localization, and tracking (DCLT) to enable research for the Canadian Arctic Sentinel Experiment (CAUSE). The information in this review was primarily gathered through discussions with other scientists, engineers, and computer scientists, rather than an exhaustive literature review. As a result of this survey, several gaps in DCLT processing capability were identified that should be addressed during the CAUSE project. Seven main areas for research and development were identified that have the potential to significantly enhance the signal processing capabilities for the CAUSE project. Much of this work will be conducted by a contractor; however, some research will continue to be carried out by DRDC scientists, and in collaboration with academic and international partners.

Ce document décrit les résultats d’une étude préliminaire portant sur les capacités actuelles de Recherche et développement pour la défense Canada (RDDC) en traitement du signal dans le domaine de l’acoustique sous-marine passive. L’étude a couvert les méthodes et algorithmes de détection, classification, localisation et poursuite (DCLP) pour les sonars passifs dans le cadre du projet de recherche expérimentale d’une sentinelle sous-marine pour l’Arctique canadien (RESSAC). L’information fut obtenue en consultant des scientifiques, des ingénieurs et des informaticiens plutôt qu’en faisant une revue exhaustive de la littérature. L’étude a permis d’identifier plusieurs lacunes en DCLP qui devraient être comblées au cours du projet RESSAC. Elle met en évidence sept principaux secteurs de recherche et développement ayant le potentiel d’améliorer sensiblement les capacités de traitement du signal pour le projet RESSAC. La plus grande partie de ces travaux seront effectués par un entrepreneur, mais des recherches continueront d’être menées par des scientifiques de RDDC et par l’entremise d’une collaboration avec des partenaires universitaires et internationaux.

13. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g., Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Passive sonar; signal processing; detection; classification; localization; tracking; CAUSE