SIGNAL PROCESSING FOR AN ACTIVE SONAR SYSTEM SUITABLE FOR ADVANCED SENSOR TECHNOLOGY APPLICATIONS AND ENVIRONMENTAL ADAPTATION SCHEMES

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ABSTRACT

An overview of the basic elements of an active sonar system in conjunction with a description of the signal processing chain utilized at the NATO Undersea Research Centre for detection and localization of undersea targets is presented. As the focus of the Navy has shifted to the complex and volatile littoral environments characterized by high background interference, emphasis is given to the capability of advanced sensor technology to resolve left/right ambiguity in the direction of arrival and in broadband adaptation methods to enhance detection performance by incorporating in situ environmental information in the processing chain. This processing was used in a series of sea trials organized and executed by the Centre, a few of which included submarine targets.

1. INTRODUCTION

The operational and scientific communities have recognized the degradation of active sonar system performance in the littoral for two main reasons: background interference (reverberation, clutter, etc) and environmental volatility. The response to these challenges was the introduction of low frequency active systems (LFAS) that are able to suppress reverberation by means of broadband pulse processing and frequency-agile techniques, in conjunction with environmentally adaptive processing, to enable the sonar system to adjust not only to different types of background interference but also to the characteristics of the acoustic channel [1, 2]. The Centre's active sonar system has been upgraded to include broadband capabilities with the procurement of a two-octave modular towed source in conjunction with a new cardioid array with left/right discriminating capability. The processing chain suitable for this system is established to allow the exploitation of broadband technology and the incorporation of in situ environmental information to counteract the effect of complex propagation conditions.
This paper provides an overview of the hardware and software parts of this system, detection results obtained by means of this system, and an example of processing adaptation based on the incorporation of channel time-spread estimates in the background interference normalizer. The paper is organized as follows. In section 2 the sonar system used is briefly described. The active sonar processing chain is discussed in section 3. An example of advanced processing based on environmental adaptation is shown in section 4. The conclusions are summarized in section 5.

2. LOW FREQUENCY ACTIVE SONAR

In its simplest configuration, a towed LFAS system consists of a towed sound source and a towed receiver array. When the source and the receiver are towed by the same vessel, we talk about a *monostatic* sonar. When the source and the receiver are not collocated, then we talk about *bistatic* or *multistatic* sonar configurations [3]. This paper is concerned with monostatic systems.
The NURC towed LFAS system includes two sound sources that can be towed and operate simultaneously: the *low frequency source* is utilized in the 800-1800Hz band; the *medium frequency source* is utilized in the 2000-3500Hz band (may operate up to 5000Hz). In LFAS applications the transmission is usually azimuthally omnidirectional, with beamwidth in the vertical plane from 3 to 30 degrees [4]. The two main types of signals utilized are continuous wave (CW) and frequency modulated (FM) pulses. CW pulses are characterized by good Doppler frequency resolution but poor range resolution and poor background reverberation suppression. FM pulses are characterized by poor Doppler resolution but high range resolution and reverberation suppression [4, 5]. Other waveforms with different properties exist, like Newhall, Pseudo Random Noise and Costas pulses [6, 7, 8]. In this paper only linearly frequency modulated (LFM) pulses are considered.
Receiving arrays are linear assembles of hydrophones designed to increment signal-to-noise ratio (SNR) and directionality [4, 9]. Traditional towed line arrays suffer from ambiguous returns in which the sonar operator is unable to ascertain whether a target is to port (left) or to starboard (right). Although operational methods exist for overcoming this problem, they are time-consuming and usually cannot be applied to a single ping. There are different sensor-based solutions to resolve port/starboard ambiguity: directional transmitters that use different pulses to port and starboard; twin line arrays with two parallel line arrays spaced at approximately a quarter of a wavelength of the highest frequency; arrays of directional hydrophones. This last category includes a special kind of towed array, called *triplet* or *cardioid array*. These towed arrays use a line of triplets instead of a line of single hydrophones (see fig. 1). Each triplet consists of three closely-spaced omnidirectional hydrophones mounted at the corners of an equilateral triangle perpendicular to the axis of the array. Estimation of the array twist, which is important for correct hydrophone positioning, is obtained by means of roll sensors evenly distributed along the array. The NURC array has 126 triplets (for a total of 378 hydrophones)

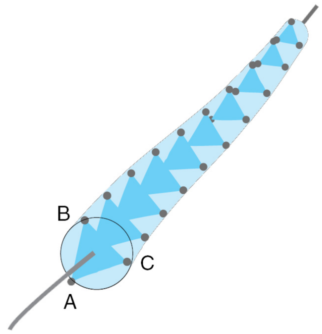

Figure 1: Pictorial representation of a cardioid array.

with sampling frequency of 12800Hz. The acoustic module is about 35 meter long and consists of two sub-arrays in a nested configuration, designed for two specific frequency ranges (the nominal upper ends of the operating frequency are 1810 Hz and 3620 Hz, respectively).

3. ACTIVE SONAR PROCESSING CHAIN

The sonar processing chain is the series of operations to be performed on the sonar data to go from raw acoustic data reception to detection output. The main steps of the NURC active sonar processing chain are illustrated in fig. 2. Hydrophone data are initially band-pass filtered. Filtered data are then base-banded and decimated to reduce the computational load. Decimated data are beamformed to assess the direction of arrival of the echoes. Beamforming is the most time-consuming processing step, at least for cardioid beamforming. Typically more than one hundred beams are formed, which are then passed to the matched filter (MF) to increase the signal-to-noise ratio. MF outputs are then normalized to remove the background interference. The processing steps listed so far are standard and are part of any active sonar processing chain. Nonetheless the implementation of single modules can vary depending on the particular application.

The next steps are designed and implemented at NURC to improve sonar performance and to obtain metrics useful for sonar performance evaluation. The normalizer is followed by the Page test detector which has to take into account target spreading due to sound propagation (multipath) and target scattering. Detections are clustered to form sonar objects in conjunction with information about the target range, azimuth and size. Finally, objects are processed to create three detection outputs: the beam collapse detection output, the SNR (as local measure of performance), and the Receiver Operating Characteristics (ROC) curve (as global measure of performance [10]). In the next sections the main processing steps are described in more detail, starting from the beamformer.

3.1 Beamforming

One way of solving the port/starboard ambiguity problem is a special kind of beamforming, called *cardioid beamforming* [11]. The beam pattern obtained from cardioid beamforming corresponds to the beam pattern for a normal line array [9] weighted by the cardioid-shaped beam pattern obtained by combining the data of the three hydrophones in the triplet. This two-step processing is illustrated in fig. 3 for a steering direction of 45 degrees. On the left panel, the red line represents the response of the *cardioid hydrophone*, which behaves like a directional hydrophone, and the blue line is the line array beamformer response, characterized by the ambiguous beam at 315 degrees. The final result is shown in the right panel, which is the result of the multiplication of the cardioid response by the line array response. The port/starboard suppression is best at broadside and becomes less toward endfire [12].

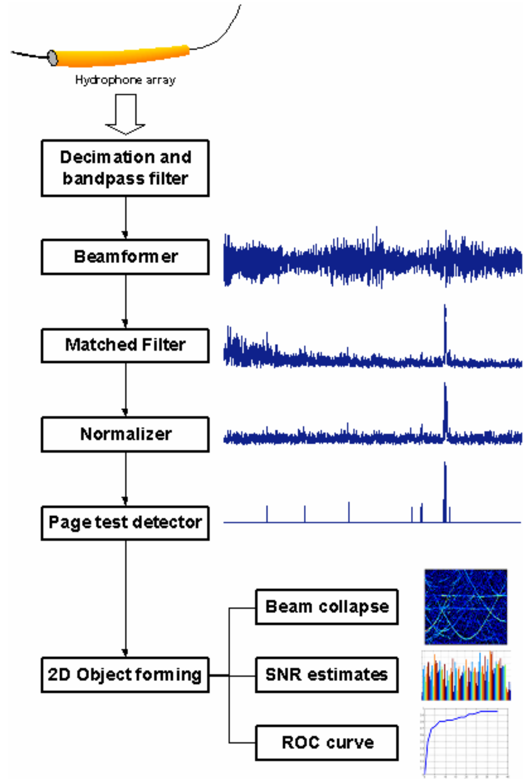

Figure 2: The NURC active sonar processing chain.

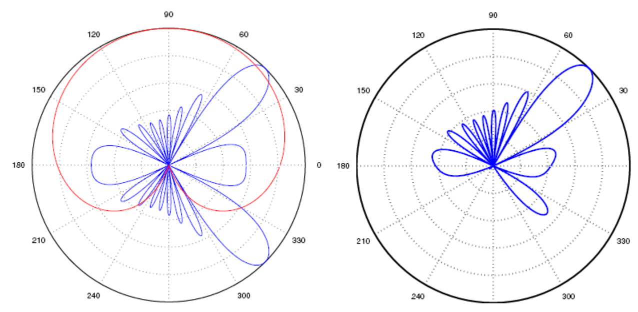

Figure 3: The two steps of cardioid beamforming.

3.2 Matched filter

The matched filter correlates the received echo with a replica of the transmitted signal. Both synthetic replicas or real replicas can be used for correlation in the matched filter. Synthetic replicas are easy to generate but may be significantly

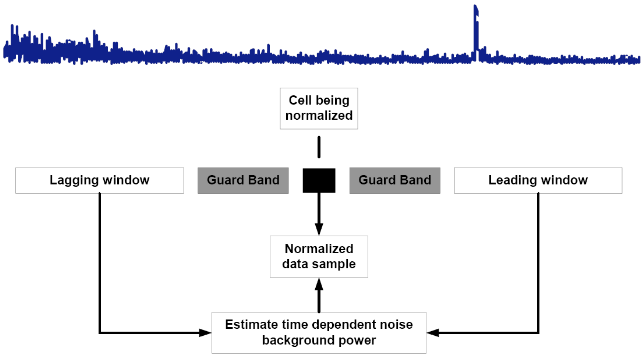

Figure 4: Flow diagram of the split window normalizer.

different from the actual transmitted signal, due to source and environmental characteristics.

3.3 Normalization

Sonar MF output time series are usually characterized by space and time variability of reverberation and background noise. This variability produces a test statistic without a known distribution, therefore it is not possible to apply directly a threshold for a desired false alarm rate. For this reason, the variability of the background has to be estimated and removed before detection. This process is often referred to as *normalization*. The average reverberation and background noise power can be estimated using data adjacent to the cell to be normalized. The main idea behind the so-called *split-window normalizer* is the generation of a sliding window with a central part that consists of two guard bands around the point to be normalized (see fig. 4). The mean reverberation and background noise power is calculated based on the leading and lagging parts of the main window without taking into account the two guard bands around the central point. The samples in the guard bands are excluded from the calculation to avoid a spill of the target's energy into the background calculation and, therefore, bias in the noise estimate. The magnitude of the central point is normalized with the mean noise power. This process is repeated for each point of the MF output as the window slides over the entire time series [13]. This normalizer is called the *mean normalizer*, as it calculates the mean power of the background noise. Variations on the normalizer may be used. A frequently adopted alternative is the *trimmed mean normalizer* that calculates the local mean reverberation and background noise power after discarding some of the largest and some of the smallest value samples of each sliding window [14].

3.4 The Page Test Detector

In shallow water environments, propagation to the target, reflection off the target and propagation to the receiver spread an active sonar transmitted signal in time and frequency [5]. An optimal detector would coherently combine the standard matched filter output according to the multipath structure and the target reflection properties. Since in real applications this information is not available, sub-optimum detectors have to be searched for. It is shown in [15] that integrating the magnitude-squared matched filter output (i.e. incoherent combination) can improve detection performance in

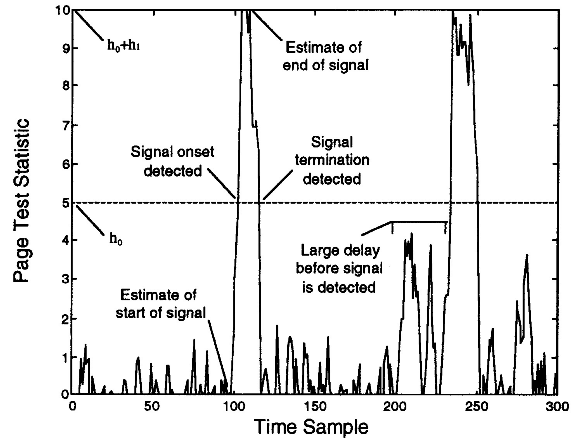

Figure 5: Example of the operation of the Page test in detecting signals of varying duration in noise: the test statistic is shown as a function of time sample (picture from [18]).

time-spread channels. The Page test [16] is used here as the energy detector which integrates different segments that belong to the same echo [17]. Besides signal detection, this test indicates the start-stop times of a received signal in a normalized MF output time series. The Page test is the optimal detector in the sense of minimizing the worst-case average delay before detection while constraining the average time between false alarms. However it does not necessarily maximise the probability of detecting a finite duration signal, as the optimum detector would require the knowledge of the data probability density function. An example of the operation of the Page test is shown in fig. 5.

3.5 Contacts and Object Forming

We define a *contact* to be any detection generated by the Page test. Even if the Page test tries to integrate the energy that belongs to the same target, integration may not be complete and multiple contacts may be associated to the same target echo. This problem arises especially for broadband pulses, characterized by high range resolution. For this reason nearby contacts, which likely belong to the same target, are clustered in time and angle to form *sonar objects*. The closing morphological filter (dilation followed by erosion), derived from binary image processing theory [19], is used for this purpose and to fill holes within clusters. As a result of clustering, a fine bearing estimation can also be obtained as the weighted average of bearing values of the cells belonging to an object. Acoustic information is stored to the so called *contact files*, together with all the relevant non acoustic information, such as: date and time; source position and depth; receiver position, depth, heading, rolls; sound speed; towing vessel navigation data; steering directions; transmitted signal parameters.

An important property of the contact files is their size. All the redundant information is discarded and the file size can be significantly smaller than the raw acoustic files. As an example, one minute worth of data recorded by the cardioid array is about 1GB, while the typical size of a contact file is 25KB, hence the data reduction is of the order of 40000. The low data rate allows transmission over communication networks,

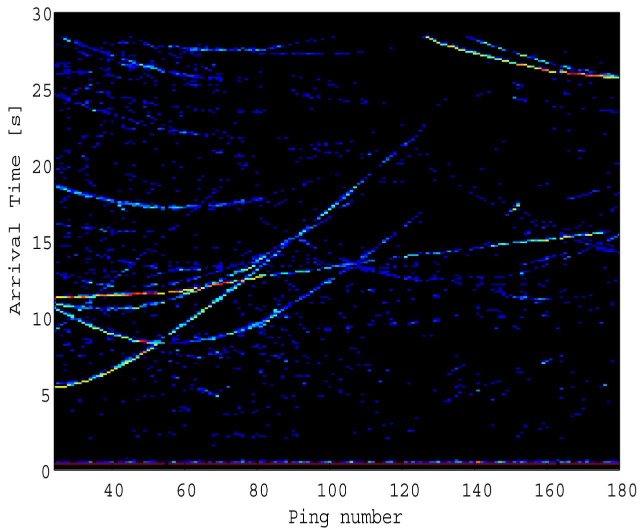

Figure 6: Example of beam collapse plot.

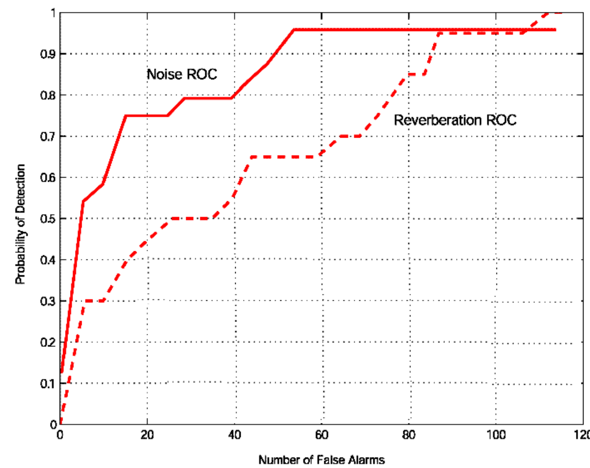

Figure 7: ROC curves used for detection performance comparison between a noise-limited and a reverberation-limited scenario.

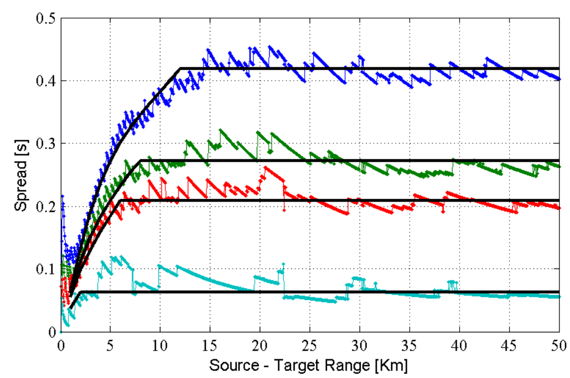

Figure 8: Time spreading for 2-way propagation: analytical (black lines) and simulated (color lines).

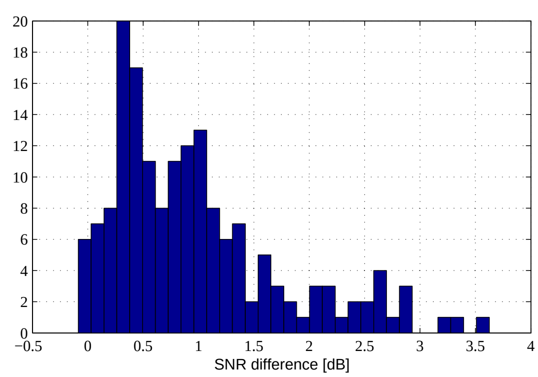

Figure 9: Distribution of SNR increase due to the use of the adaptive normalizer.

which is a key requirement in multistatic operations where the different units involved may want to exchange the detection data via radio or satellite links [20]. Similarly, these files can be transmitted to cooperating underwater platforms through low data rate acoustic transmissions.

3.6 Displays and Performance Analysis

Sonar contacts are used for data visualization and sonar performance evaluation. By selecting the maximum output of the object matrix for each range over a selection of beams and by repeating this procedure for each ping, the *beam collapse* plot is produced. This detection output is useful for real time visual tracking of strong echoes during the run. An example of a beam collapse plot is shown in fig. 6, where the SNR is color-coded. The horizontal axis is ping (transmission) number, the vertical axis is echo arrival time. The straight track crossing the plot from left to right, starting around 11 sec and ending around 15 sec, corresponds to the target. The other tracks are generated by strong clutter points. The SNR measurements obtained from the object matrix are a local detection performance measurement, which are suitable for ping-to-ping performance comparison. SNR values are used also for sonar performance model validation through comparisons between calculated values and estimated values produced by the model. Another measure of performance is a modified version of the ROC curve that plots the probability of detection versus the number of false alarms per ping. This provides additional information on the absolute number of strong clutter points for each detection scenario. Figure 7 is an example of sonar performance analysis by means of ROC curves. The two curves refer to the same sonar system operating either in reverberation-limited or noise-limited conditions. The reduced probability of detection in the reverberation-limited case underlines the challenges active systems face in shallow water conditions.

4. ENVIRONMENTAL ADAPTATION

An example of detection performance enhancement based on environmental adaptation is given in this section. The idea is to adjust the size of the normalization guard band (as defined

in section 3.3) according to the channel time spread estimate. Closed-form expressions for time channel spread have been derived for isovelocity water by using ray invariants and acoustic flux [21]. According to this theory, it is possible to predict the two-way channel impulse response as a function of sound speed in the water, the water depth and the geoacoustic bottom properties. In [22] the analytical formulae have been validated by numerical simulations using a sound propagation ray tracing model. The results are shown in fig. 8, where the black lines are the analytical calculations and the color lines are the model predictions. Different colors correspond to different signal-to-noise ratios, as for decreasing SNR's, the effective time spreading decreases. As predicted by both the analytical solution and numeric simulations, two regimes are present: at shorter ranges, time spreading linearly increases with range; at longer ranges, time spreading is almost constant. This knowledge can be used to tune the normalizer to the particular environmental conditions in order to take into account the actual echo time spreading due to the channel. The adaptive normalizer has been tested on real data. The performance improvement, with respect to standard normalizers, is measured in terms of target SNR increase. The benefit of using the adaptive normalizer is shown in fig. 9, which is the histogram of SNR increases for a number of transmissions: the adaptive normalizer leads to an average SNR increase of the order of 1 dB and with peaks of up to 3.5 dB.
Other adaptation strategies aim at optimal tuning of some of the key sonar parameters such as the source and receiver depths and the transmitted waveform. The tuning is driven by predictions made by a suitable sonar performance model [23].

5. CONCLUSIONS

A modern experimental sonar system suitable for active detection in the littoral is presented. This system consists of two broadband sources and a cardioid (triplet) receive array with port/starboard discrimination capability. The standard processing chain associated with such a system is improved to include directional beamforming, Page test detection and object forming to accommodate detection and localization. An example of detection performance enhancement obtained through an environmentally adaptive scheme, according to which the parameters of the normalization parameters are optimized based on the channel spread, is offered.

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