Sub-band processing of continuous active sonar signals in shallow water

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***Abstract*— Continuous active sonar (CAS) is a special case of active sonar where the ping duration approaches the ping repetition interval. Sub-band processing is a method of breaking up the long-duration CAS transmission to achieve faster processing update rates than pulsed active sonar (PAS). This paper compares experimental signal-to-reverberation ratio (SRR) measured for CAS and PAS echoes. The processing bandwidth was varied, and the processing integration time was proportional to the bandwidth because linear frequency modulated (LFM) pulses were employed. The data were collected during back-to-back CAS and PAS runs during the TREX13 sea trial, which was conducted in shallow, 20-m water near the shore of Florida, USA. Sub-band processing was applied to the CAS data as well as to the PAS data to allow comparison, although for PAS the increased updates are not at equal intervals over the ping cycle as in CAS. Increasing the number of sub-bands increases the update rate, but the corresponding decrease in bandwidth is expected to reduce SRR. Examining the trade off between update rate and SRR is an important first step in understanding how CAS performs in the littoral environment.**

Keywords—continuous active sonar; shallow water; littoral; coherence; signal-to-reverberation ratio; TREX13

I. Introduction

The concept of continuous active sonar (CAS) is generating interest in the anti-submarine warfare (ASW) community, largely due to the potential for rapid detection updates [1]. This dramatically decreases surveillance gap times compared to conventional pulsed active sonar (PAS). The faster updates can be accomplished by breaking a long-duration CAS waveform into smaller sub-bands and using each sub-band as a matched filter. This sub-band approach works for simple frequency-modulated (FM) waveforms that have monotonically swept frequency, such as the linear FM (LFM) considered in this paper. Increasing the number of sub-bands increases the number of detection opportunities per ping repetition interval (PRI); however, the lower energy and bandwidth of the sub-bands can result in lower signal-to-noise ratio (SNR) and signal-to-reverberation ratio (SRR), respectively, than if the CAS echo was matched filtered using a replica of the full waveform [2]. There is a therefore a trade-off between update rate and echo quality.

The relationship between the size of sub-bands and resulting SNR or SRR is complicated by the potential for coherence loss with large time-bandwidth product waveforms, such as those typically used in CAS. For example, different frequencies in a wideband signal can undergo different propagation, and different portions of a long-duration pulse can also propagate differently if the environment changes over the pulse duration [3]. This results in a mismatch between the transmitted and received signals, and a subsequent lower matched-filter gain than the theoretical maximum. This is referred to as coherence loss. Coherence loss is difficult to predict but is expected to be greater in complex propagation environments such as those found in shallow-water littorals [3]. The study of how CAS performs and the effect of sub-band processing is therefore of particular interest in these shallow-water regions.

Shallow-water experiments with CAS were conducted during the Target and Reverberation Experiment 2013 (TREX13) sea trial that was held in May 2013 [1,2,4]. During the experiments considered in this paper, both CAS and PAS pulses were transmitted for comparison. A stationary target was present, as well as an echo repeater towed by Canadian Forces Auxiliary Vessel (CFAV) QUEST. The echoes from these targets were located in the processed data. The analysis in this study was limited to the reverberation-limited region, which is of great importance in the littorals. The SRR achieved by CAS and PAS were compared using both full-band and sub-band processing.

II. Experiments

The TREX13 sea trial was held within 8 km of shore in Panama City, Florida. The water depth was quite shallow at approximately 20 m in the area of trial operations. The source was an ITC-2015 and the receiver was the Five Octave Research Array (FORA) of Pennsylvania State University's Applied Research Laboratory. Both source and receiver were mounted approximately 2 m above the sea floor and cabled to Research Vessel (RV) SHARP, which was moored in close proximity.

Two particular 1-h runs on May 10, 2013 were considered, although there were many other experiments performed during the trial [5]. The weather during both of these runs was calm with very little sea-surface roughness. The first run, during 15:00–16:00 UTC, was a CAS run, where an 18-s LFM swept over 1800–2700 Hz was transmitted with a PRI of 20 s. The

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duty cycle was not truly continuous to allow operation of an echo repeater, which was towed by CFAV QUEST. QUEST started near the location of SHARP and FORA at the beginning of the run and travelled at 5 kn on a heading of 240° along what was referred to as the 'clutter track'. Following the CAS run, QUEST returned to the starting point near SHARP and repeated the track over 17:00–18:00 UTC, this time transmitting the PAS pulse, a 0.5 s LFM over the same band with the same PRI. The only difference was that the source level was increased by 15.6 dB during the PAS run so that the energy of the CAS and PAS pulses was equal (see Table I). This equality was chosen so that the theoretical maximum SNR and SRR were the same for CAS and PAS echoes.

The echo repeater towed by QUEST switched between recording and transmitting operations based on a 7000–8000 Hz LFM trigger pulse that was transmitted immediately before each PAS and CAS transmission. The echo repeater operated in an alternating mode, sometimes referred to as the "ping-pong" mode [6], for the two runs described above. When the echo repeater was triggered, it would record for approximately 20 s in the CAS mode and approximately 2 s in the PAS mode to ensure the entire incident signal was captured. On the next trigger, *i.e.*, when the start of the next pulse was incident on the echo repeater, the echo repeater would begin transmitting the previous recording, this time without recording the incident signal. Isolating the transmission and recording operations in this way avoided feedback that would otherwise occur in the echo repeater system. The result was that it appeared as though an echo was being reflected from an object at the same range as the echo repeater with no latency, albeit on every second ping.

The echo repeater was designed to operate with very low latency and simulate echoes with the appropriate time delay. During the experiments it became evident that the hull of QUEST also provided a strong echo, and it was therefore necessary to inject delay in the echo repeater to provide time separation between the echo repeater and hull of QUEST to make echo analysis possible. The added time delay was approximately 0.3 s.

An air-filled hose, the Passive Acoustic Target System (PATS) was also deployed as a target at a range of 2.83 km from SHARP at a bearing of 114°. This was a valuable addition to the experiment because the fixed source, fixed receiver, and fixed target provided a static geometry. The only difference between PATS echoes was therefore caused by changes in the environment, so the PATS offered a good benchmark for echo statistics.

TABLE I. WAVEFORMS

Name	*Type*	*Duration*	*Source Level*	*Frequency Band*
PAS	LFM	0.5 s	197.6 dB[a]	1800–2700 Hz
CAS	LFM	18.0 s	182 dB[a]	1800–2700 Hz

[a] re 1 μPa @ 1 m (source levels selected for equal energy)

III. DATA PROCESSING

The goal of the data processing was to apply matched filters, identify target echoes, and obtain the SRR of those target echoes over the duration of the experimental runs. This allowed comparison of SRR for CAS and PAS runs when processed using the full bandwidth. In order to investigate faster updates, CAS data were processed in sub-bands in addition to the full band, and PAS data were processed with the same bands to allow a direct comparison.

The first step was beamforming the data from the FORA triplet sensors for each of the runs. The triplet-beamformed data from the PAS run was then matched filtered, or correlated with the corresponding full-band PAS replica. A split-window normalizer was then used to form an estimate of SRR at each sample, and samples above an 8 dB threshold were clustered in time and beam to form detections. The detections corresponding to echoes from the PATS air hose were automatically identified by the bearing and time delay relative to the direct blast. This was fairly straightforward due to the high SRR of the PATS echoes and the stability of their time delays due to the static configuration; however, manual verification of each echo was still performed to ensure that the large number of false alarms encountered did not result in a misidentification. After this stage, the SRR values of the PATS echoes for the PAS run were available for the full-band processing case.

Sub-band processing was then performed on the PAS data using the replicas described in Table II. In addition to the full, 900-Hz bandwidth, bandwidths of 450 Hz, 225 Hz, and 112.5 Hz were used. These sub-bands were formed by extracting appropriate, non-overlapping snippets from the full-band PAS replicas. The snippets were shaded with 20% Tukey windows (*i.e.*, $\alpha = 0.2$) to form the final sub-band replica. The duration of the sub-bands was proportional to the bandwidth, a property of the LFM waveform. Note that for PAS, the increased sub-band updates occur at equal intervals within the short 0.5-s duration of the PAS pulse. This does not have the same effect as CAS, where the updates are at regular intervals over the ping cycle (or most of it in this case), offering the desirable effect of decreasing gaps in surveillance. The identification of the sub-band detections from the PATS was completely automated using the time delay of the previously identified full-band detections. The large number of sub-band detections made any manual verification impractical. Following this step, the SRR values of PATS echoes were available for both full- and sub-band processing for the PAS run, noting that the sub-bands were treated individually throughout the processing; that is, they were not averaged incoherently as some sub-band processing methods might.

Next, the same processing was repeated for the CAS run using the CAS full- and sub-band replicas. Although using an 18-s matched-filter replica is perhaps less common, its implementation is no different than with a short replica as in PAS. This concluded processing for the PATS air hose.

TABLE II. SUB-BAND FREQUENCY RANGES

Band (Hz)	Number of sub-bands			
	1	*2*	*4*	*8*
1	1800–2700[b]	1800–2250	1800–2025	1800–1912.5
2		2250–2700	2025–2250	1912.5–2025
3			2250–2475	2025–2137.5
4			2475–2700	2137.5–2250
5				2250–2362.5
6				2362.5–2457
7				2457–2587.5
8				2587.5–2700

b. Full band

Further treatment was required for identifying echoes from QUEST's hull and the echo repeater. The procedure was the same as that outlined above, but rather than simply using a replica of the transmission, the replica was corrected to match the theoretical Doppler distortion caused by QUEST's 5-kn relative velocity. The CAS waveform used in TREX13 is much more sensitive to Doppler mismatch than the PAS waveform [4], therefore employing a Doppler-corrected replica ensured that a CAS-PAS comparison could be done without bias from Doppler mismatch. The echoes from QUEST and the echo repeater generally had lower SRR and also had varying time delay due to QUEST's advance during the run. These factors added complexity to the analysis and more care was required during manual verification of the full-band echoes. The sub-band identification of echoes was again done automatically based on the full-band identifications.

The following section presents the SRR of the echoes identified through the data processing outlined above.

IV. RESULTS

The SRR values averaged for the sub-band echoes of the PATS, QUEST, and echo repeater are summarized as a function of processing bandwidth in the plots in Figure 1a, b, and c, respectively. The blue curve denotes CAS and the red curve denotes PAS. Averaging across sub-bands with the same bandwidth was performed to obtain a single mean value for each bandwidth. The PATS target was stationary and within the reverberation-limited range, which was conservatively estimated to be 4 km during the two runs. As QUEST travelled away from SHARP, its range transitioned from reverberation-limited to noise-limited. Only echoes with FORA-to-QUEST ranges below 4 km were considered to simplify analysis in this paper. The SRR values in Figure 1 are therefore mean values over the entire run for PATS, while only roughly the first half of the run was used for the QUEST and echo repeater averages.

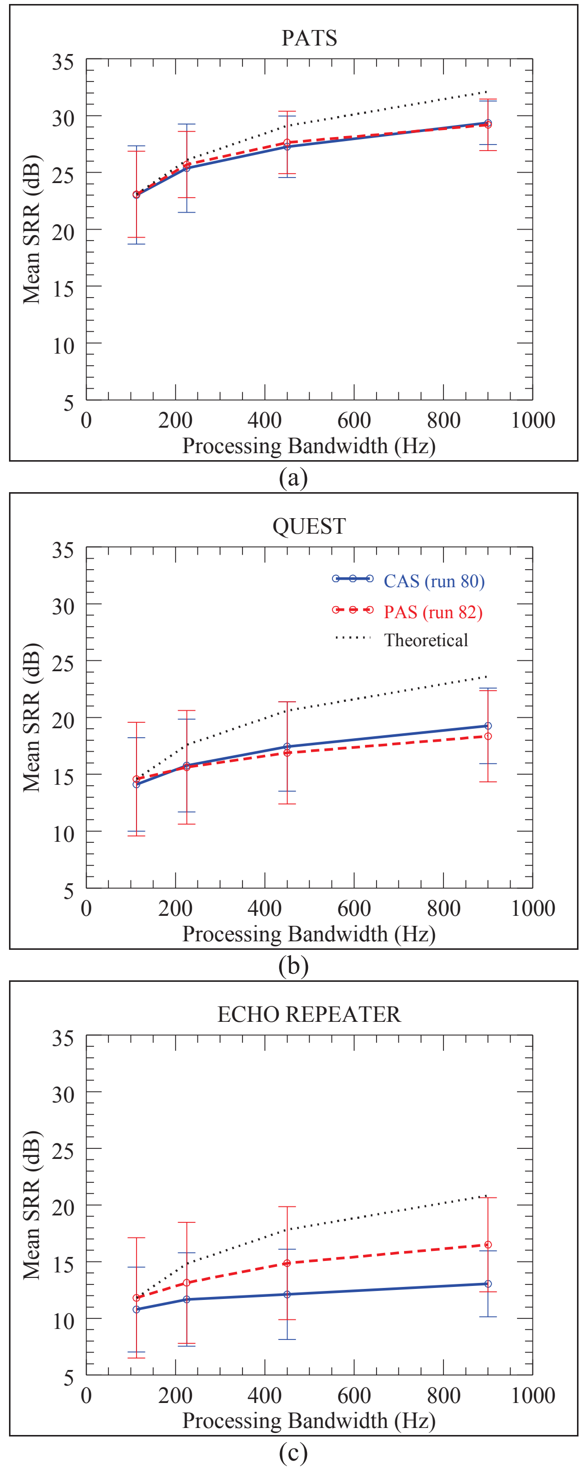

Fig. 1. SRR versus bandwidth, averaged over pings and sub-bands for (a) PATS, (b) QUEST, (c) echo repeater. CAS in blue (solid), PAS in red (dashed), and theoretical in black (dotted). Vertical bars denote one standard deviation from the mean. Means and standard deviations were calculated from SRR values in dB based on evidence of approximate log-normal SRR distributions.

TABLE III. NUMBER OF PATS ECHOES

Number of echoes	Number of sub-bands			
	1	*2*	*4*	*8*
CAS	176	352	704	1408
PAS	178	354	710	1406

TABLE IV. NUMBER OF QUEST ECHOES

Number of echoes	Number of sub-bands			
	1	*2*	*4*	*8*
CAS	63	122	236	430
PAS	62	115	222	418

TABLE V. NUMBER OF ECHO REPEATER ECHOES

Number of echoes	Number of sub-bands			
	1	*2*	*4*	*8*
CAS	31	54	89	150
PAS	32	63	119	222

The number of echoes used in each of the averages plotted in Figure 1 for PATS, QUEST, and the echo repeater are presented in Table III, Table IV, and Table V, respectively. Note that fewer echoes were detected for QUEST and the echo repeater because only about half of the run was analyzed to constrain these moving targets to the reverberation-limited region. Also, the SRR was lower than for PATS, resulting in some missed detections, especially at smaller sub-bands where SRR decreased further. The echo repeater had even fewer echoes because a simulated echo was produced for only 50% of the pings with the mode used in the analyzed runs.

The black dotted line in Figure 1 is the theoretical SRR:

$$\mathrm{SRR}_{theor}(B) = \mathrm{SRR}_{PAS}(B_{min}) + 10\log_{10}(B/B_{min}), \quad (1)$$

where B is the bandwidth. This equation is based on a simple assumption that SRR is proportional to bandwidth and independent of pulse duration and energy for the reverberation limited case. The SRR at the smallest bandwidth, $B_{min} = 112.5$ Hz, for the PAS case was used as the reference because it should have the least coherence loss.

The first observation is that for the PATS echoes, CAS and PAS achieve nearly identical SRR at all processing bandwidths. As expected, the lowest SRR occurs at the lowest processing bandwidth for this reverberation-limited case. However, the theoretical 3-dB increase in SRR for every doubling of processing bandwidth is not quite achieved. This is presumably due to coherence loss at higher bandwidths. In this case, the implication is that the 18-s integration time of the CAS pulse was not a limiting factor in this experiment. This is perhaps due to the extremely calm surface conditions during the runs, which could have resulted in effectively stationary conditions over the 18-s CAS transmission.

Similar results can be observed for QUEST and the echo repeater, although in the case of the echo repeater the PAS average is 3–4 dB higher than the CAS average at higher bandwidth. The reason for this is not known, but it is potentially an effect of the echo repeater system since the PATS and QUEST are both physical targets and showed little discrepancy between PAS and CAS.

V. SUMMARY

The SRR of PAS and CAS echoes measured during two experimental runs during TREX13 was very similar for the four processing bandwidths considered in this paper. SRR was observed to increase with processing bandwidth, although below the rate expected from a theoretical linear relationship. This suggests that both CAS and PAS echoes exhibited more coherence loss at higher bandwidth, independent of pulse length. It is therefore speculated that the calm weather conditions during these runs provided an environment that exhibited little change over the duration of the 18-s CAS pulse. There were many more datasets collected during TREX13 [5], and further analysis is required to investigate how sub-band processing affects the ultimate performance of a sonar system.

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