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IEEE Journal of Oceanic Engineering
(Volume: 42, Issue: 2, April 2017)

Defence Research and Development Canada

External Literature (P)
DRDC-RDDC-2016-P116
November 2016

IMPORTANT INFORMATIVE STATEMENTS

Template in use: (2011) CR EL1 Advanced Template_EN 2017-08-30-V01_WW.dotm

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Abstract—**The 2013 Target and Reverberation Experiment (TREX13) sea trial was held just off the coast of Panama City, FL, USA, in May 2013. One of Defence Research and Development Canada's primary objectives was comparing the performance of continuous active sonar (CAS) and pulsed active sonar (PAS) in shallow water, where reverberation and clutter challenge sonar systems. The only option for a moving target during the trial was an echo repeater towed from a ship; however, this posed a serious challenge because before the trial there were no known echo repeater solutions that were compatible with CAS. Existing echo repeaters required short-duration waveforms as used in PAS, and even then they introduced range errors that caused a mismatch in reverberation background and made localization problematic. This paper presents three echo repeater techniques developed for TREX13 and tested on Canadian Forces Auxiliary research vessel *CFAV Quest* during the trial. Experimental results presented in this paper demonstrate detection of the echo repeater by a monostatic CAS system on *R/V Hugh R Sharp*.**

Index Terms—**Continuous active sonar, echo repeater, shallow water, TREX13.**

I. Introduction

CONTINUOUS active sonar (CAS) is an extension of the pulsed active sonar (PAS) technique traditionally used in antisubmarine warfare (ASW) sonar systems. PAS can detect a submarine at most once per ping, and a large search radius requires a long ping repetition interval (PRI) to avoid ambiguous detections. For the example of a monostatic sonar, 1.3 s must be added to the PRI for every kilometer of search radius required (1.3 s = 2 × 1000 m / 1500 m/s). In contrast, CAS has the potential to provide many detections on a single target per ping, regardless of PRI, allowing sonar tracks to be updated at intervals many times shorter than the PRI. Intuitively, tracking algorithms should perform better when provided contacts at rates fast enough to limit target motion between updates. This theory has been backed by preliminary results examining target area-of-uncertainty dependence on track update rate [1]. Furthermore, faster updates increase the probability of catching specular geometries that typically exist for only a brief moment but can result in detections with high signal-to-noise ratio (SNR); these are often referred to as glints. The increased number of detections per ping comes at a cost, however. Echo SNR must generally decrease to achieve faster updates [2], and this tradeoff between SNR and update rate has not been studied to evaluate the effect on sonar performance at the tracking level. The 2013 Target and Reverberation Experiment (TREX13) sea trial was held in May 2013 with one of the primary objectives to investigate the performance of CAS compared to PAS in the shallow-water littoral environment, where clutter and reverberation challenge sonar tracking, and where CAS performance remains unproven [3].

One of the constant challenges of developing ASW technology is the difficulty in obtaining submarine targets for conducting dedicated experimentation. Echo repeaters that simulate targets are often the only substitute for a physical underwater target, especially if target motion is required. Echo repeaters are also important in the preparation and calibration of systems before final validation in an exercise with a submarine.

Echo repeaters typically function by recording the complete incident ping before retransmitting a simulated echo [4]. This imparts a time delay of at least the pulse length, and while this delay may be tolerable for short PAS waveforms, the method is not compatible with CAS. In fact, before the TREX13 trial there were no documented methods of CAS echo repeating. This paper outlines three echo repeater techniques that were developed and implemented by Defence Research and Development Canada (DRDC) to simulate CAS echoes during the TREX13 sea trial. The concepts for the techniques were first introduced in a preliminary paper that was published during the planning phase of TREX13 [3]. The current paper describes the echo repeater techniques in detail and presents images of sonar detections from the echo repeater in each of the modes, demonstrating successful testing.

II. TREX13 Experiments

The TREX13 sea trial was held off Panama City, FL, USA, in May 2013. For the experiments relevant to this paper, University of Delaware's *R/V Hugh R Sharp* was moored and cabled to a transmitter and a receiver, which were effectively colocated with *R/V Sharp* for the purposes of this paper. University of Washington's Applied Physics Laboratory and DRDC operated the transmitter, a model ITC-2015 free-flooded ring transducer. Pennsylvania State University's Applied Research Laboratory operated their five octave research array (FORA) as the receiver [5], [6].

The water depth in the trial area was approximately 20 m. Although this is too shallow for submarine operation, the

Manuscript received February 11, 2016; revised May 12, 2016; accepted July 25, 2016. This work was supported in part by the U.S. Office of Naval Research under Code 32.

Guest Editors: B. Hefner and D. Tang.

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Digital Object Identifier 10.1109/JOE.2016.2595380

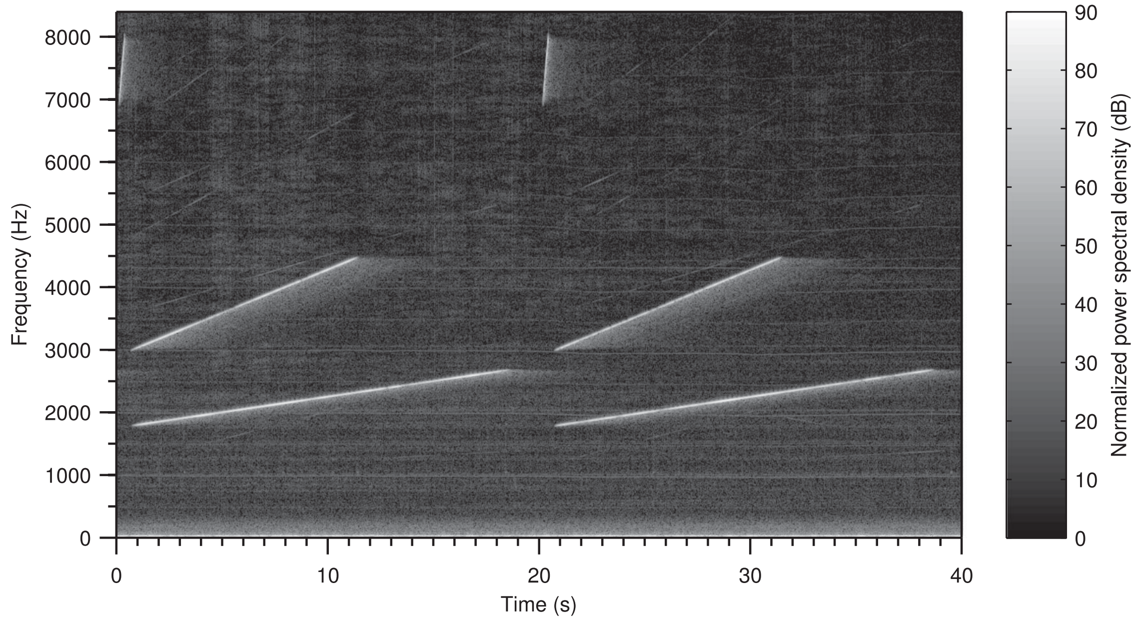

Fig. 1. A spectrogram of two ping cycles recorded on the echo repeater hydrophone. Each 20-s cycle contains the CAS waveform (18-s, 1800–2700-Hz LFM) preceded by a trigger pulse (0.25-s, 7000–8000-Hz LFM). A version of the CAS waveform compressed in time by a factor of 5/3 was also transmitted for one of the modes; this is the 10.8-s waveform observed in the 3000–4500-Hz band.

shallow water offered several advantages such as allowing divers to moor the source and the receiver just above the seabed. The resulting fixed geometry of the array and source was critical for repeating measurements to obtain results with meaningful statistics, and this would not have been possible with a towed array. A CAS echo repeater was the only practical solution for a moving target with high target strength in this extremely shallow environment. DRDC's echo repeater system was towed by *CFAV Quest* at 5 kn along one of two tracks, both originating near *R/V Sharp* with one heading approximately parallel to the shore (southeast) and the other offshore (southwest). A few runs with reverse courses on these tracks were also performed. The echo repeater consisted of a towed hydrophone and transmitter. The signals input to the echo-repeater transmitter and the transmitter operated from *R/V Sharp* were equalized for their respective voltage responses.

The goal of experimentally comparing CAS and PAS performance was achieved by performing 1-h CAS runs, each typically followed by a 1-h PAS run on the same track. The CAS waveform was an 18-s, 1800–2700-Hz linear frequency modulation (LFM) transmitted with a 20-s PRI and source level of 182 dB (re 1 μPa @ 1 m). The dwell time of 2 s was required for echo repeater computations between pings, resulting in a 90% duty cycle. Although this is not technically continuous active sonar, the dramatic increase in duty cycle from PAS allowed a meaningful performance comparison, and for simplicity, the 90% duty cycle will still be referred to as CAS throughout this paper. The PAS duty cycle was only 2.5%, which was achieved with a 0.5-s LFM, with the same 1800–2700-Hz band and 20-s PRI as the CAS waveform. The PAS source level was 197.6 dB (re 1 μPa @ 1 m), which equalized the energy in the CAS and PAS pulses to allow direct performance comparison [3].

A spectrogram of two cycles of the CAS waveform is shown in Fig. 1. The acoustic data used to generate this figure were recorded on the echo repeater hydrophone at 19:05 UTC on May 10 (run 84), at which time the range to the source was approximately 800 m. The CAS waveform in the 1800–2700-Hz band can be observed, as well as a 0.25-s, 7000–8000-Hz LFM that was used to trigger the echo repeater. The waveform in the 3000–4500-Hz band was required for an echo repeater technique introduced in Section III.

Only the essential experimental details have been included here. For the experiments relevant to the echo repeater analysis in this paper, the experimental setup was effectively a monostatic sonar transmitting CAS and PAS pulses with an echo repeater traveling away from the sonar at 5 kn. The focus of this paper now shifts to the echo repeater techniques used in TREX13, and further experimental details can be found in [7].

III. Echo Repeater

CFAV Quest's primary role during TREX13 was to tow an echo repeater system to simulate a moving target.

A traditional echo repeater records an incident, short-duration ping and retransmits it after a brief delay. The recording approach is taken to preserve distortions and transmission loss that occur as the active sonar transmission propagates from the source to the echo repeater.

Delay in a record-then-retransmit type of echo repeater is inherent to allow the complete capture of an incident ping before playing it back through the echo repeater's transmitter. The reason that recording and retransmission do not occur simultaneously is to avoid developing any audio feedback conditions, as in the familiar example of a squealing microphone. There are three problems with delaying the retransmission of a simulated echo from an echo repeater.

1) In the case of a monostatic active sonar system, where the source and the receiver are colocated, the simulated echo appears to be received from a farther range than the actual location of the echo repeater. This not only yields a range error but also causes a mismatch in the reverberation background, which will typically have decayed at the sonar system by the time a simulated echo arrives.
2) In the case of a multistatic active sonar system, multiple receivers are spaced apart in an effort to increase detection opportunities. Simulated echoes arriving at a set of multistatic receivers will all appear to come from different locations and cannot be used to properly triangulate the true location of the simulated target.
3) The implication of the two previous points is that only small retransmission delays (*e.g.*, $\ll 1$ s) are acceptable. CAS employing long-duration waveforms (*e.g.*, > 10 s) therefore requires the echo repeater to retransmit the simulated echo before the complete CAS waveform has been received. This opens the system to the potential for runaway positive acoustic feedback.

The requirement for a low-latency echo repeater compatible with PAS, CAS, and multistatic sonar motivated DRDC to develop advanced echo repeater techniques that avoided the conventional record-then-retransmit approach. The result was DRDC's SmartER prototype towed echo repeater system, which operated for the first time during the TREX13 sea trial. Many echo repeaters simply repeat the signals they record, which effectively simulates a perfect reflection. In reality, a particular reflecting object will have a unique impulse response that deviates from a perfect reflection. The SmartER system was therefore given the capability of convolving the received signal with a predefined impulse response function to simulate a specific target. This capability was tested briefly during TREX13, but the function was bypassed during all of the runs to simulate a perfect reflection, simplifying experimental testing and data analysis.

The prototype echo repeater consisted of a towed hydrophone, a signal processor to generate a simulated echo of the received signal, and an amplifier and towed source to retransmit the simulated echo. The system was built using available assets. There was no attempt at reducing size or weight of components because the deployment platform was a large research vessel that could easily accommodate the system. The hydrophone was an element of a custom-built array of eight hydrophones that was towed approximately 80 m behind *CFAV Quest*. There was difficultly in towing the hydrophone array to the desired depth of 10 m during the trial, and the typical tow depth was approximately 5 m. Beamforming multiple hydrophones was not performed, ultimately because the resulting directivity would have given the echo repeater an aspect-dependent target strength; the simpler omnidirectional configuration was the only practical solution for TREX13. The signal processor was automated, but required experts to monitor the system, vary trigger thresholds as necessary, and manually configure the target strength and the mode of operation in coordination with the transmission schedule from *R/V Sharp*. The source was a model ITC-2010 free-flooded ring with a diameter of 0.42 m. It was mounted to a large tow frame previously built at DRDC. The frame and its tow cable were designed for operating two larger rings at high source level. Although the frame was larger than necessary, it met the requirement for providing a stable tow. The source was towed approximately 5 m behind *CFAV Quest* at a depth of 10 m. The relatively large separation between the source and the hydrophone was chosen to help suppress acoustic feedback. The transmitting voltage response of the ITC-2010 is 130 ± 3 dB (re 1 μPa/V @ 1 m) in the 1800–2700-Hz band of operation. A large amplifier was required to achieve a sufficient source level for simulating echoes from a high target-strength reflector, especially at close range to the sonar source that was operated from *R/V Sharp* at high source level. An Instruments Inc. S11-8 amplifier with a continuous power rating of 4 kW was used to drive the transducer with up to 2000 V.

True continuous active sonar would employ 100% duty cycle; however, as previously mentioned, the prototype system design budgeted two seconds of idle time to rearm the ping generator on *R/V Sharp*, to accommodate the trigger pulse, and to offset any potential latency in the SmartER's reaction to the trigger pulse. This reduced the maximum duty cycle to 90%, or 18 s out of the 20-s PRI.

The SmartER required the use of an out-of-band trigger pulse (as observed in Fig. 1) to synchronize the echo repeater functions.

Three techniques or modes were explored to produce low-latency simulated echoes for the continuous active sonar experiments in TREX13: the ping-pong mode, the dual-band mode, and the tracking-filter mode.

A. Ping-Pong Mode

The nontechnical "ping pong" name was chosen for this mode in which cycles of recording and transmission are alternated. The technique used in this mode is not novel, but the authors were not aware of any previous attempts to implement it for CAS before the TREX13 trial.

In the ping-pong mode, the echo repeater is triggered by an out-of-band signal, which cues it to record in-band acoustic data for a predetermined amount of time. The duration of the recording therefore approaches the PRI for CAS. The echo repeater's retransmit function is disabled during the recording period to prevent feedback. Once the recording period has completed, the echo repeater conditions the recorded acoustic data into a simulated echo. The trigger pulse from the next ping then cues the echo repeater to switch from the recording mode to the transmission mode and then to retransmit the simulated echo. During retransmission, the incident ping is not captured to prevent feedback; however, note that the incident ping produces reverberation, clutter, and other physical echoes at the receiver, thereby providing a realistic background for the simulated echo.

From the perspective of the sonar receiver, the echo repeater retransmits a simulated echo from the previous ping exactly as the current ping becomes incident on the echo repeater, thus replicating a reflection. The simulated echo then propagates to the receiver, where it appears as though an echo from the current

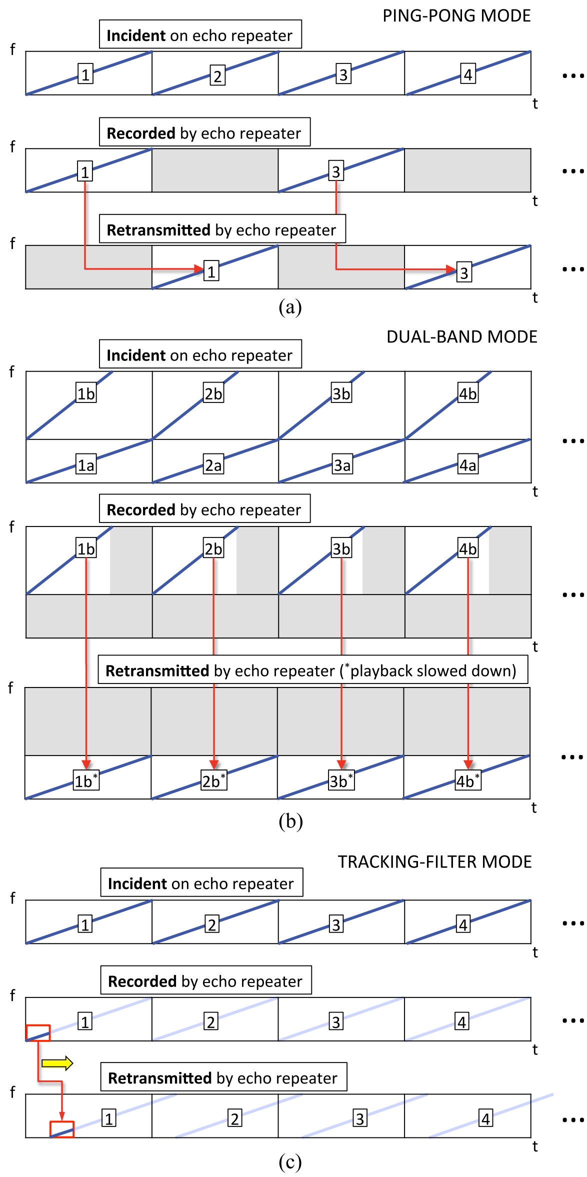

Fig. 2. Depictions of the three echo repeater modes used during the TREX13 sea trial: (a) the ping-pong mode; (b) the dual-band mode; and (c) the tracking-filter mode. The depictions are for illustrative purposes and do not accurately represent the duty cycles, guard bands, or latencies of the real system.

ping has arrived from the exact location of the echo repeater with zero latency, and with the expected reverberation background.

Once the echo repeater finishes retransmission, it switches back to the recording mode, where it receives the next trigger, records, conditions the recording, waits for the next trigger to retransmit, and so on, establishing a cycle in which every second ping is retransmitted by the echo repeater.

Fig. 2(a) depicts how the ping-pong mode functions. It shows the hypothetical spectrogram of four PRIs of a 100% duty cycle CAS LFM incident on the echo repeater in the top panel. The boxed numbers (1–4) are included as timestamps and allow the signal to be tracked in the other panels. The middle panel shows the signal recorded by the echo repeater, with gray shading denoting in-band recording disabled. In this example, the even-numbered signals are not recorded. The bottom panel shows the signal retransmitted by the echo repeater. Every second ping is retransmitted with a delay relative to the incident/recorded signal, but because the delay is equal to the PRI there is an apparent zero delay. For example, the consecutive incident signals labeled “1” and “2” are assumed to be very similar and therefore a physical acoustic reflection is approximated when signal “1” is retransmitted precisely as signal “2” is incident.

The ping-pong mode effectively uses the record-then-retransmit approach with the delay set equal to the PRI. The difference is that every second ping is dropped to avoid feedback while achieving zero apparent latency. The 50% echo repeat rate is in fact the main disadvantage of this approach, but its simplicity and fidelity make it attractive and well suited for many applications.

There are a few constraints for this mode. The ping schedule must use a constant PRI and waveform. The length of the transmitted waveform must be known, otherwise there is a risk of recording and amplifying a noise-only signal. There is also an assumption that the location of the echo repeater is roughly constant for the two consecutive pings in a cycle, ensuring that the ping recorded at the echo repeater undergoes similar propagation as the ping whose arrival triggered the cycle. During TREX13, the echo repeater was towed at speeds lower than 5 kn, so the echo repeater translated less than 52 m during the 20-s PRI. This difference is less than the length of *CFAV Quest* (76 m) and considered negligible for these experiments.

B. Dual-Band Mode

The dual-band mode uses a novel concept and has the potential to provide near-zero-latency simulated echoes for arbitrary waveforms. In this mode, the sonar transmits the original pulse of duration D, in the frequency band $[f_{\text{low}}, f_{\text{high}}]$. A second version of the pulse that has been scaled up out of band is transmitted starting at the same time as the original pulse. Therefore, there are two signals transmitted in two distinct bands, hence the dual-band name. The echo repeater records in the upper band, shifts the signal down, and retransmits in the lower band, thereby avoiding the feedback.

A scaling factor $\alpha\,(\alpha > 1)$ is chosen to scale up the spectrum of the original lower band to form an out-of-band version. Scaling up frequency corresponds to compressing in time as given by the Fourier transform pair $f(\alpha^{-1}t) \leftrightarrow |\alpha|\mathscr{F}(\alpha\omega)$. The scaled waveform has duration D/α and frequency band $[\alpha \cdot f_{\text{low}}, \alpha \cdot f_{\text{high}}]$. As long as $\alpha > f_{\text{high}}/f_{\text{low}}$, the scaled version will be out of the original band, although an adequate guard band must be included to avoid interference between the bands.

In this mode, once the echo repeater triggers, it begins acquiring hydrophone samples in the upper band at the primary sampling rate f_s, and simultaneously begins retransmitting them at a slower secondary sampling rate f_s/α. The faster acquisition rate results in a queue of samples that are played back at the slower rate, which dilates time and scales frequencies down to the lower band. To prevent feedback, the original, lower band is not recorded by the echo repeater; rather, just as in the ping-pong mode, it is required to provide reverberation back at the receiver.

The resulting simulated echo observed at the receiver has traveled half of the propagation distance (source to echo repeater) in the upper band, and half the distance (echo repeater to receiver) in the lower band of interest. This is not a perfect realization of propagation because of the frequency dependency of processes such as attenuation and reflections from the seabed, sea surface, and volume scatterers. Therefore, one assumption of this mode is that the cost for approximating the propagation is outweighed by the benefit of having an echo repeater with the ability to simulate echoes for arbitrary CAS pulses with near-zero latency. The dual-band technique works for PAS as well. Any discrepancy from the nominal, single-band propagation should be similar for both PAS and CAS, so this mode is well suited for a direct comparison of CAS and PAS performance using the same echo repeater mode.

The dual-band mode is depicted in Fig. 2(b). For demonstration purposes there is no guard band included and a scaling factor of $^3/_2$ was used. In the top spectrogram, the CAS signal labeled "1a" is time compressed to form signal "1b," which is $^2/_3$ of the duration of the CAS signal and correspondingly time-frequency scaled out of band. Note that the resulting bandwidth of the upper band is necessarily higher than the lower band, and this technique requires a sonar transmitter with much more bandwidth than required for the original signal. The echo repeater only records the upper band to avoid feedback, as depicted in the middle panel. The bottom panel shows the echo repeater retransmitting the signal back down in the original band by slowing down the playback of the recording by the scaling factor.

A scaling factor of $^5/_3$ was chosen for the TREX13 experiments. This transformed the 18-s, 1800–2700-Hz CAS waveform to a 10.8-s, 3000–4500-Hz LFM. The factor was chosen to include a 300-Hz guard band between the original CAS signal and the upper band. The sonar transmission for the dual-band mode is shown in Fig. 1, which includes the CAS waveform, the scaled waveform in the upper band, and the trigger pulse.

The dual-band mode provides the capability of echo repeating arbitrary CAS waveforms. One of the limitations of this mode is the large bandwidth required to accommodate the upper band signal, which necessarily has more bandwidth than the original, lower band signal. With the addition of a guard band, the bandwidth requirement can easily triple. Furthermore, the power requirement for transmitting two signals simultaneously is not just doubled, but quadrupled. For example, when two different signals of equal average power are added together, the resulting signal will have double the average power. However, the peak amplitudes of the different signals will inevitably align at some points, and the coherent addition of these peaks results in a doubling of the peak amplitude. This 3-dB increase in peak amplitude corresponds to a 6-dB increase in the instantaneous peak power, which is the limiting factor for the power amplifier. The reliance on similar propagation in the two different bands is also a limitation.

C. Tracking-Filter Mode

The tracking-filter mode is another novel approach and sweeps the center frequency of a narrow bandpass filter that is synchronized to the instantaneous frequency of an incident CAS LFM. A small delay results in a mismatch between the narrow recording band and the concurrent frequency transmitted by the echo repeater, thereby suppressing feedback. Again, the trigger pulse is used to cue the echo repeater, in this case synchronizing the frequency-swept narrow band filter. This mode currently works with LFM signals, but could be extended to work with almost any signal in which frequency changes monotonically as a function of time, such as hyperbolic frequency-modulated signals.

The operation of the tracking filter mode is depicted in Fig. 2(c). The filter with continuously swept center frequency has a narrow bandwidth that is analogous to a short time window. In the figure, the concept of a sliding time-bandwidth window is depicted as the red box, which is shown at the start of the CAS LFM and can be imagined tracking along the diagonal line with time, matching the LFM's frequency sweep. The retransmission of the filtered signal is slightly delayed (as depicted by the yellow arrow in the figure) to ensure there will be no acoustic feedback. It should also be noted that, as previously mentioned, the propagation between the echo repeater's receiver and transmitter provides some of the isolation in time, frequency, and amplitude, which is needed to suppress acoustic feedback.

The tracking-filter mode offers low-latency echo repeating for CAS LFM or similar frequency swept waveforms while capturing propagation effects accurately. One disadvantage of this mode is that it is incompatible with PAS because the filtering approach requires long-duration waveforms where the sweep rate is low, resulting in a narrow bandwidth over a relatively long time window. This does not allow direct comparison of CAS and PAS using the same echo repeater technique.

TABLE I
PROS AND CONS OF EACH ECHO REPEATER MODE

Mode	Pros	Cons
Ping pong	• Effectively zero latency* • Supports arbitrary waveforms • Full bandwidth available • PAS & CAS compatible • Simple and low risk	• Actually full cycle latency • 50% echo rate
Dual band	• Near-zero latency • Supports arbitrary waveforms • PAS & CAS compatible	• Pulse energy split between bands • Fraction of bandwidth • Propagation not ideal
Tracking filter	• Near-zero latency • Full bandwidth available	• Supports limited CAS waveforms • Filter complexity

D. Summary of Echo Repeater Modes

Table I provides a summary of the three echo repeater modes. Each mode has its own advantage and disadvantages, and the choice of modes must be application specific. For example, the dual-band or tracking-filter modes might be preferred for

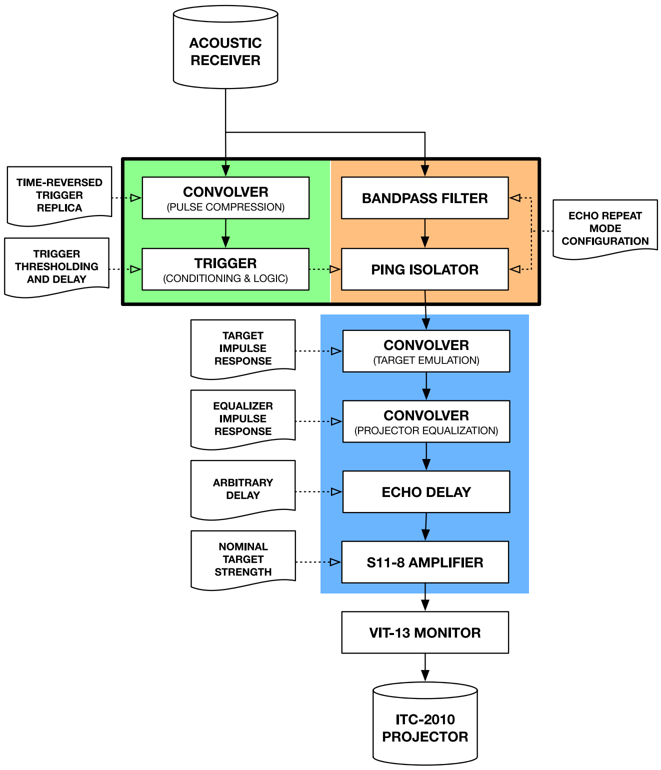

Fig. 3. Diagram of the SmartER system architecture. The green block triggers the echo repeater cycle, the orange block isolates the recorded ping, and the blue block generates a simulated echo from the recording.

tracking studies, while the ping-pong mode might be more suitable for examining individual pings with high fidelity.

E. System Architecture

The architecture of the SmartER system is shown in Fig. 3. The core functions of the system are highlighted within the bold outline, and they are responsible for monitoring the echo repeater's hydrophone and isolating the incoming active sonar ping for retransmission as a simulated echo. The performance of the core functional block is responsible for the functionality of each of the echo repeater modes. Real-time, low-latency operation is required of all components in the system. The system's operation can be grouped into three primary functional tasks: triggering, ping isolation, and generation of simulated echo, which are, respectively, colored green, orange, and blue in the diagram in Fig. 3.

1) Pulse Compressed Trigger: One key to the success of the SmartER is the out-of-band cueing signal that triggers the echo repeater operation (green block in Fig. 3). The transmitting sonar used in TREX13 had a secondary high-frequency band of operation that permitted a 7000–8000-Hz LFM trigger of duration 0.25 s, as previously mentioned. Pulse compression of this LFM with 1000 Hz of bandwidth provided a very robust triggering mechanism with an accuracy of approximately 1 ms and high SNR. Implementation of the matched filter for pulse compression was done through convolution of the received signal with a time-reversed replica of the trigger waveform. A threshold detector was then used to identify triggers.

All of the waveforms transmitted during the echo repeater experiments were preceded by the trigger waveform, and because the trigger was out of band, the trigger function of the echo repeater was always active, even when the echo repeater was transmitting.

2) Ping Isolator: The ping isolator begins its operation once the echo repeater has been triggered (orange block in Fig. 3). It has the task of recording and isolating pings, and aiding in the suppression of feedback. A bandpass filter selects the recording band, which was 1800–2700 Hz for the ping-pong mode, 3000–4500 Hz for the dual-band mode, and a narrow bandpass filter with continuously swept center frequency between 1800 and 2700 Hz for the tracking-filter mode. The three different echo repeater modes are achieved through configuration of the ping isolator.

3) Simulated Echo Generation: The blue region of Fig. 3 shows ping conditioning operations, allowing the simulated echo to deviate from a perfect reflection. The target emulator allows a realistic target impulse response to be applied to the received signal, and the amplifier allows selection of target strength. The frequency response of the echo repeater's transmitter is equalized here, and an arbitrary delay can also be applied to the simulated echo.

Target strengths were varied between 0 and +25 dB for the different runs performed during the trial (target emulator bypassed). The echo repeater transmitter was equalized to a nominal white spectrum. The delay module was used to add 200 ms of latency to the echo repeater system. The addition of a delay was in response to strong echoes observed from the hull of *CFAV Quest* that otherwise would have been received by FORA at the same time as the echo repeater signal due to the low internal latency of the system.

IV. Experimental Test Results

The three echo repeater modes were successfully tested with CAS during the TREX13 sea trial. The ping-pong and dual-band modes were also successfully tested with PAS [8], although only the results for CAS are shown in this paper. A 100-s subset of data recorded near the beginning of three different runs performed in TREX13 is shown in Fig. 4 to demonstrate detection of the echo repeater on FORA.

Fig. 4 shows normalized matched-filter intensity mapped to grayscale as a function of time delay and subping number. The time delay is relative to the direct arrival, which can be seen aligned at 0 s. The subping number plotted on the horizontal axis requires some explanation. The full LFM CAS transmission was divided into 17 segments of equal duration with 50% overlap between segments. This was an arbitrary choice of segments to allow observation of the multiple detections per ping that are possible with CAS. Each segment was used as a matched filter to produce one vertical slice in the plot. The subping number on the horizontal axis in Fig. 4 refers to the individual segments, with 17 subpings per PRI. A total of five PRIs is shown in each panel of Fig. 4. The normalized output of the matched filters shown in grayscale is a measure of SNR, which covers 0–20 dB. The normalizer used a two-pass mean technique, in

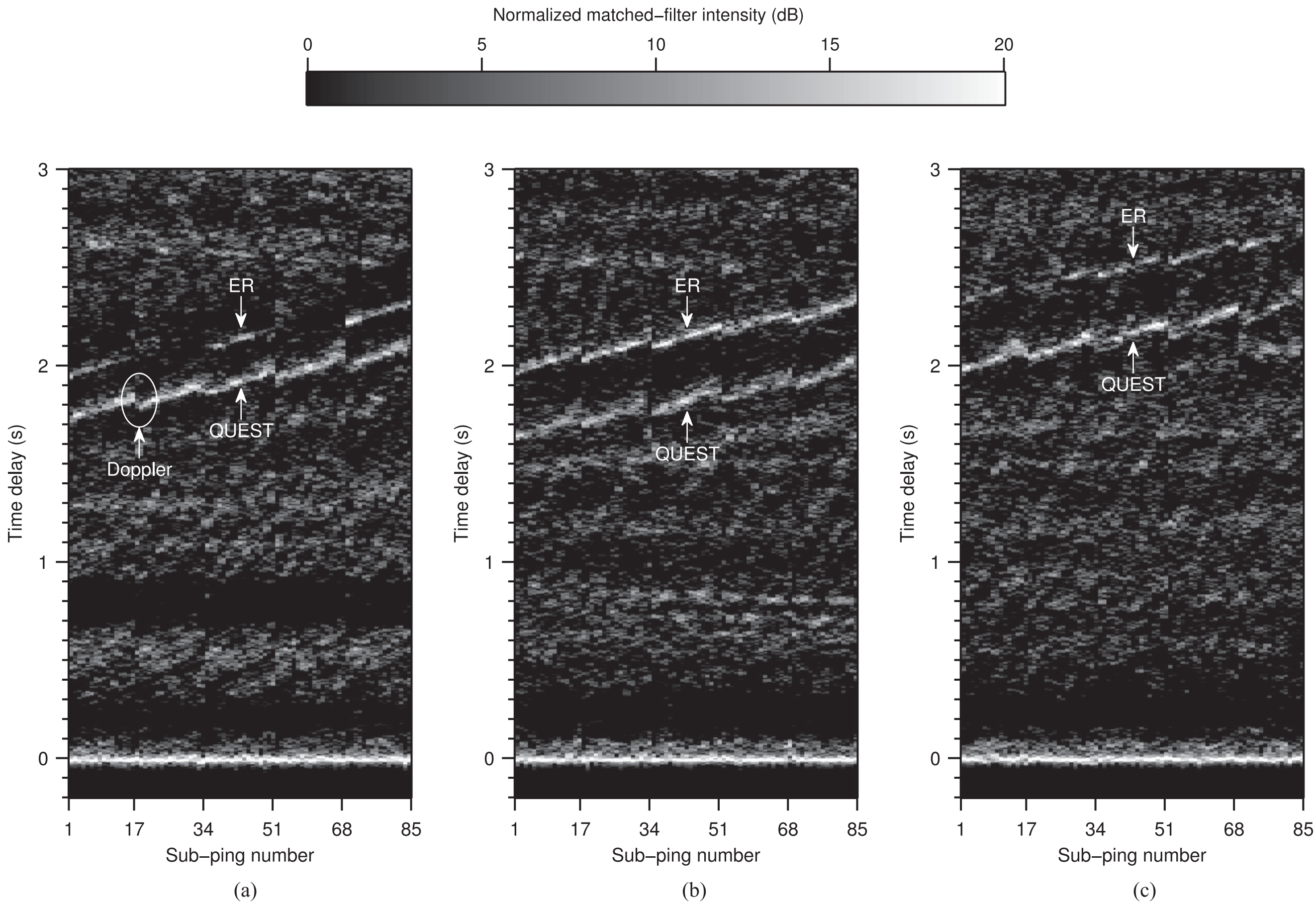

Fig. 4. Normalized matched-filter intensity plotted as grayscale versus time delay and subping number. Each CAS waveform was segmented into 17 subpings which were all used as a matched filter to produce multiple detections per PRI. Five PRIs are shown with the tracks of *CFAV Quest* and the echo repeater beginning at time delays around 2 s and increasing in time delay (range) as *CFAV Quest* opens from the sonar system. Note that relatively small time delays were chosen to ensure high SNR, and the initial time delays for panels (a)–(c) were not chosen to match identically because of noise in adjacent pings that would have obscured the target tracks of interest. The environment for the runs had an approximately constant water depth of 20 m, approximately isospeed sound speed at 1527 m/s, root-mean-square wave heights of 0.10–0.15 m, and a sandy seabed (silty sand to gravelly sand) [7]. (a) The ping-pong mode (run 80). (b) The dual-band mode (run 84). (c) The tracking-filter mode (run 96).

which each sample is divided by a mean value that is computed by first calculating the mean of the data in a 0.5-s window centered on the sample, and then recalculating the mean with the center sample clipped such that it does not exceed 1.25 times the first-pass mean. Diagonal traces of high SNR (white color) corresponding to the echo repeater and *CFAV Quest* can be observed in each of the panels.

The echo repeater was configured with a target strength of 0 dB for the runs analyzed in Fig. 4. A higher target strength of 25 dB was used for earlier runs; however, analysis during the trial revealed that noise, believed to originate from *CFAV Quest*, was being amplified and broadcast by the echo repeater. The noise was observable in the processed FORA data even when the echo repeater was several kilometers away. The gain on the echo repeater was therefore reduced to 0 dB (on May 10). Analysis of the data collected with 0-dB target strength determined that the echo repeater was not being detected at the longer ranges occurring in the last half of each run. In response, the echo repeater target strength was increased to 5 dB and then to 10 dB in later runs.

CFAV Quest's hull proved to be a strong physical target during the trial in addition to the echo repeater's target simulation. *CFAV Quest* detections can be observed as the persistent earlier diagonal track in each of the panels in Fig. 4, opening from an initial time delay of approximately 1.7, 1.6, and 2.0 s in panels (a), (b), and (c), respectively. The tracks of *CFAV Quest* have a stepped appearance, which allow us to visually distinguish the five individual PRIs shown in each panel. The disjoint time delay between PRIs is caused by the Doppler effect [see annotation in Fig. 4(a)] associated with *CFAV Quest*'s 5-kn speed relative to the sonar [9].

The echo repeater track can be observed parallel to *CFAV Quest*'s track in Fig. 4 with an additional time delay of approximately 200–300 ms. The latency relative to *CFAV Quest*'s hull is close to what was expected from the combined latencies of 1) the physical geometry of the echo repeater relative to *CFAV Quest*; 2) the latency added by the delay module; and 3) the internal system latency required for signal processing. Recall that the echo repeater hydrophone was towed about 80 m behind *CFAV Quest*'s stern, with the echo repeater transmitter effectively colocated with the stern (within 5 m). *CFAV Quest* was moving away from the sonar system operated by *R/V Sharp*. With this configuration the sonar transmission was incident on the echo repeater hydrophone approximately 50 ms before it propagated to the stern of *CFAV Quest*. The physical geometry of the echo repeater therefore had an effective negative latency of 50 ms since the echo repeater's hydrophone converts the acoustic signal to an electrical signal which travels effectively instantaneously through the electrical system to the echo repeater transmitter. Also recall that 200 ms of latency was added by the echo repeater's delay module. Combining -50 and 200 ms yields 150 ms, any latency above which is caused by processing in the echo repeater's software or hardware.

Fig. 4(a) shows the echo repeater in the ping-pong mode at approximately 15:10 UTC on May 10 (run 80). The 50% echo repeat rate can be observed, with no echo repeater tracks on the second and fourth cycles (subping numbers 18–34 and 52–68). The latency between *CFAV Quest*'s hull and the echo repeater is approximately 200 ms, indicating approximate 50 ms of internal latency in the echo repeater system.

Fig. 4(b) shows the echo repeater in the dual-band mode at approximately 19:10 UTC on May 10 (run 84). The main advantage of this mode is the 100% echo repeat rate, which is achievable with any waveform type by sacrificing some propagation accuracy. Capturing every cycle is an important feature for research in near-continuous tracking, which is one of the main areas of interest in CAS. Note that the echo repeater has additional latency relative to the ping-pong mode, totaling approximately 300 ms, and indicating internal latency of 150 ms.

Fig. 4(c) shows the echo repeater in the tracking-filter mode at approximately 15:10 UTC on May 12 (run 96). This mode also allows the 100% echo repeat rate. It has all of the propagation effects captured, but is limited to LFM or similar waveforms. It does not work with short pulses, and is therefore incompatible with PAS. The total latency of this mode is similar to the dual-band latency of approximately 300 ms, or 150 ms internal latency.

V. Summary

Three low-latency echo repeater techniques for CAS were developed and implemented by DRDC in the SmartER system. The main challenge was developing concepts to avoid the feedback expected to occur if the echo repeater performed reception and transmission simultaneously. The system was successfully tested in the three modes during the TREX13 trial in May 2013. The ping-pong mode alternated recording and transmitting cycles so that only every second echo was retransmitted by the echo repeater. The dual-band mode transmitted a second version of the waveform in a separate band so that the echo repeater could record and transmit in separate bands. The tracking-filter mode employed a narrow bandpass filter and short delay to form narrow, separate recording and transmitting bands.

Successful echo repeater operation was confirmed by analysis of acoustic data recorded by the FORA receiver. Experimental results for CAS showed detection of the echo repeater simulated echoes. The ping-pong and dual-band methods also work for PAS, not only allowing direct comparison of CAS and PAS performance, but also providing a low-latency echo repeater capability for PAS. The measured internal latencies for the echo repeater modes were approximately 50–150 ms. These latencies are much less than even the short 500-ms PAS pulse used in TREX13, and the prototype system demonstrated great promise for a near-zero-latency echo repeater capability.

Acknowledgment

The authors would like to thank Dr. D. Tang, Dr. T. Hefner, and Dr. K. Williams of the Applied Physics Laboratory, University of Washington (APL-UW, Seattle, WA, USA) who managed and led the TREX13 trial; B. Brand of APL-UW who managed acoustic transmissions; and Dr. J. Preston of the Applied Research Lab, Pennsylvania State University, who managed quality control and data collection for the experiment. They would also like to thank the officers and crew aboard *CFAV Quest* and *R/V Sharp*, and the APL-UW dive team for their support throughout the trial. Finally, the authors would like to thank V. Shepeta and the technical staff at DRDC; J. McInnis, M. Coffin, K. Dunphy, and J. Hood at GeoSpectrum Technologies Inc.; D. Abraham of CausaSci LLC; and D. Grimmett of SPAWAR SSC Pacific.

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Experimental Implementation of an Echo Repeater for Continuous Active Sonar

4. AUTHORS (last name, followed by initials – ranks, titles, etc., not to be used)

Stefan M. Murphy; Jeffrey G.E. Scrutton; Paul C. Hines

5. DATE OF PUBLICATION
(Month and year of publication of document.)

November 2016

6a. NO. OF PAGES
(Total containing information, including Annexes, Appendices, etc.)

9

6b. NO. OF REFS
(Total cited in document.)

9

7. DESCRIPTIVE NOTES (The category of the document, e.g., technical report, technical note or memorandum. If appropriate, enter the type of report, e.g., interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

External Literature (P)

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

DRDC – Atlantic Research Centre
Defence Research and Development Canada
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P.O. Box 1012
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Canada

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DRDC-RDDC-2016-P116

10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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TREX13, anti-submarine warfare, continuous active sonar, echo repeater, shallow water