Experimental Comparison of High Duty Cycle and Pulsed Active Sonars in a Littoral Environment

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LONG-TERM GOALS

To determine if near-continuous target detection obtained from using high duty cycle sonar provides improved performance over conventional pulsed active sonar, in a littoral environment.

OBJECTIVES

Military sonars must detect, localize, classify, and track submarine threats from distances safely outside their circle of attack. However, conventional pulsed active sonars (PAS) have duty cycles on the order of one percent which means that 99% of the time, the track is out of date.   In contrast, high duty cycle sonars (HDC) have duty cycles approaching 100% which enable near-continuous updates to the track. If one can overcome technical challenges such as the high dynamic range required by the receiver, then HDC should significantly improve tracking performance in the free-field environment that one encounters (approximately) in the deep ocean; however, improvements in tracking performance in shallow water are not assured since both targets and clutter will be tracked continuously and HDC may increase false tracks to an unacceptably high level – essentially continuously tracking the clutter. Theoretical predictions of performance are challenging since the reverberation background for shallow water HDC has not been accurately modeled. To compare performance of HDC with conventional PAS in the littorals, a set of experiments were conducted as part of the Target and Reverberation Experiment (TREX) in spring 2013. This was the first scientifically controlled experiment conducted in the littorals to compare the environmental effects on these two approaches to active sonar. In this project the data from TREX will be analyzed to provide a quantitative comparison of the impact of the environment on the two techniques.

APPROACH

This project will be carried out primarily by the PI, Dr. Paul C. Hines at Dalhousie University's Dept. of Electrical and Computer Engineering. Additional research support will be provided by senior undergraduate research assistants and/or graduate students.   TREX was conducted in approximately 20 m of water approximately 1 nmi off the coast of Panama City, FL. During TREX, comparative measurements of tracking and classification were made using HDC and PAS signals in a littoral

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environment[1]. This was the first scientifically controlled experiment conducted in the littorals to compare the environmental effects on these two approaches to active sonar. A series of metrics (eg. number of detections, matched-filter gain, false alarm rates, track purity, track latency, etc.) will be used to quantify detection, classification, localization, and tracking (DCLT) performance using the two sonar methods. The data are greatly enhanced by supporting environmental measurements made by DRDC and other TREX participants [1].

In the primary experiment, RV SHARP was fixed in a four-point mooring with an active sonar consisting of an ITC 2015 transmitter and the FORA horizontal line array receiver. CFAV QUEST towed an echo-repeater (the SmartER) to act as a surrogate target along one of two 5 nmi long tracks, each of which started at the safe-standoff distance from SHARP (see Figure 1). Track 1 (referred to as the *reverberation track*) ran parallel to the shore at approximately 129°T; track 2 (referred to as the *clutter track*) ran offshore at approximately 240°T. The speed of advance for all runs was nominally 5 knots (on gas turbine to reduce self noise). Both the HDC and PAS pulses were linear FM (LFM) swept from 1800-2700 Hz with a pulse repetition rate of 20 seconds. The PAS pulse length was 0.5 s (2.5% duty cycle) whereas the HDC pulse was 18 s (90% duty cycle). The experiment was designed so that both pulses contained equal energy whenever possible; the HDC source level was 182 dB re 1μPa@1 m and the PAS was 197.6 dB re 1μPa@1 m.

Figure 1: Map of the TREX site showing QUEST GPS (blue lines) marking the run evolution for some of the reverberation and clutter track runs (see text for more detail).

In most active sonar experiments, the sonar and/or the target are moving so that one cannot cleanly isolate the impact of platform motion from that of environmental variability. During TREX however, a 15 m long air-filled hose was anchored to the seabed approximately 3 km away from RV SHARP. This passive acoustic target system (PATS) had minimal surface expression, thereby drastically reducing its motion. This fixed-fixed geometry provided an opportunity to examine the effect of the acoustic channel on signal coherence. Additional details on the experiment are provided in [2].

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[1] Note that comparison of HDC and PAS is just one of several experimental objectives of TREX. Please refer to Ref. [1] for an overview of the experimental goals.

WORK COMPLETED

The focus of the effort during FY 2015 has been to examine the effect of surface roughness on signal coherence for short and long sonar pulses.[2] Since the source, receiver, and the PATS were fixed in place, and the sound speed profile (not shown) was relatively stable during the period of the experimental runs examined in this paper, it is reasonable to assume that the primary environmental variable is the sea surface. Surface wave height was measured directly using an APL-UW wave buoy, and measured indirectly using CFAV QUEST's downward-looking X-band TSK WM-2 wave-height meter. It can also be inferred from measurements from two annemometers located on the mast of CFAV QUEST. These data are summarized in Figure 2 for a 144 hour period that encompassed all 17 runs. The start of each of the runs is marked by arrow heads placed along the -20 kn grid line; solid arrow heads mark the HDC runs and unfilled ones mark the PAS runs. After examining these three sources of environmental data, the wave buoy data was chosen to be the metric used as a measure of surface roughness. The radar measurement provides a useful backup but can return spurius results for certain combinations of ship heading and wave direction-this is likely the cause of the excessive wave heights reported by the radar near hour markers 24 and 72. Although wind measurements were taken at much more frequent intervals than the wave buoy (one measurement per minute compared to one per half hour), the time lag between wind speed magnitude (and direction) and surface roughness is problematic for experimental runs lasting only an hour. Finally, the wave buoy provided high quality data on wave frequency and direction which should correlate with signal coherence.
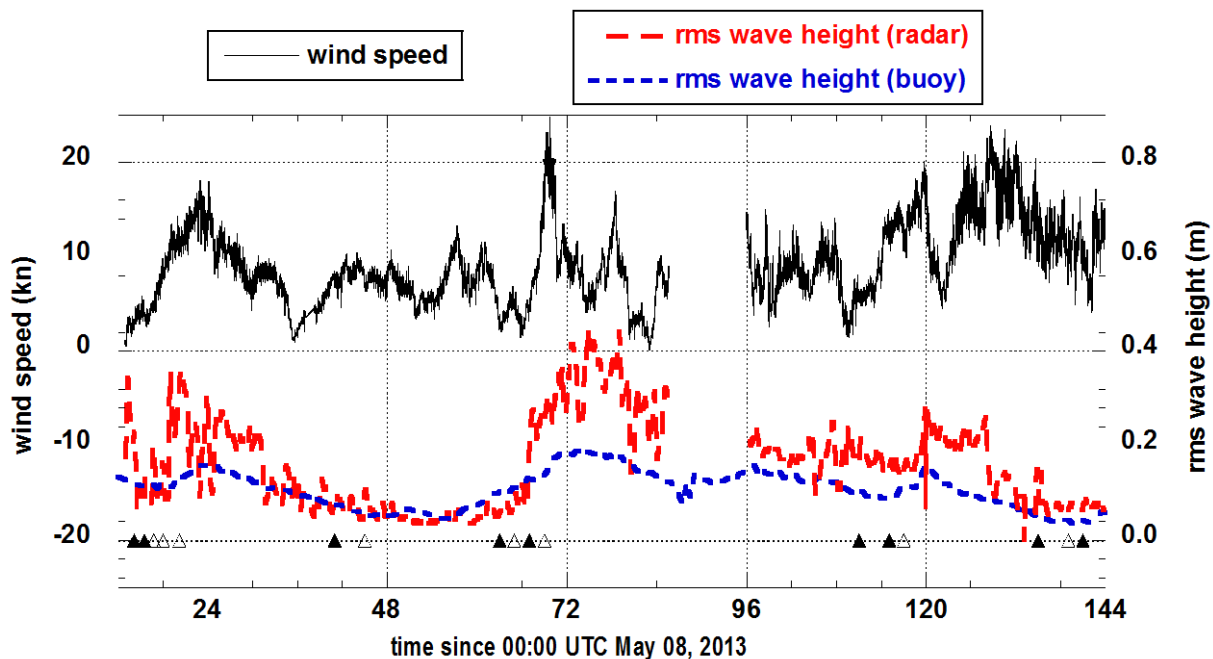

Figure 2. Wave height in rms meters measured by one of the APL-UW wave buoys (blue short dash) and CFAV QUEST's downward-looking X-band TSK WM-2 wave-height meter (red long dash) and wind speed in kn (solid black line), for a 144 hour period starting at 00:00 UTC on 8 May 2013. Both vertical axes begin below zero to provide separation between the curves. See text for further details.

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[2] DRDC's free-falling cone penetrometer was used to estimate seabed composition along the tracks. A summary of the results are contained in [4] and will be used to support propagation modeling in the coming year.

To quantitatively compare the relative performance of HDC and PAS requires that environmental conditions were stable between HDC-PAS run pairs. Several techniques were considered to enable this, each with advantages and disadvantages. One could transmit HDC and PAS signals concurrently using contiguous frequency bands; however, since we employed broadband LFM pulses there was a risk that propagation effects might be different in the two bands; alternatively one could transmit HDC and PAS signals concurrently in the same band but with different replicas – for example, using an upswept HDC and a down-swept PAS LFM. In this case however, should any clipping on the direct blast occur during the higher-power PAS transmission it would contaminate the entire HDC return. In the end, since this was the first attempt at the measurement, a scientifically conservative approach was employed. Separate HDC and PAS runs were done in close succession to minimize changes in the weather (and corresponding changes in surface roughness) while also reducing the likelihood of experimental and signal processing errors. Although this worked fairly well, the coastal spring weather conditions and variable boat traffic did mean that conditions between runs were not identical.
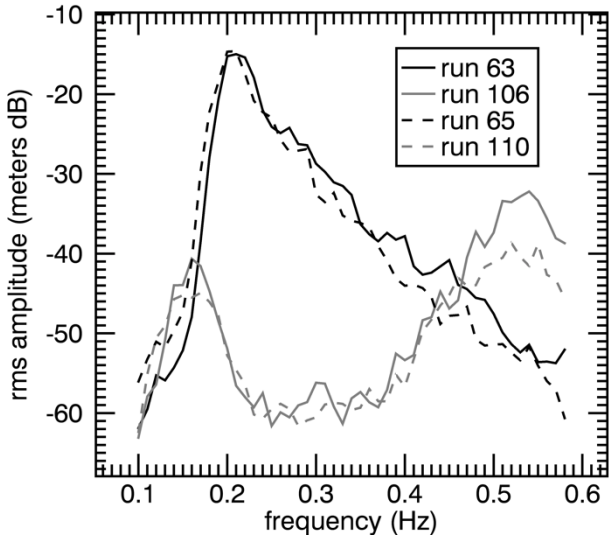

Figure 3. Two-dimensional wave height spectra of four HDC-PAS run pairs (63-65 and 106-110). Spectra for HDC runs are shown using continuous (i.e. solid) lines and spectra for PAS runs with pulsed (i.e. dashed) lines.

Table I: HDC-PAS run pairs and surface wave height from analysis of wave buoy data.

HDC run	rms (m)	PAS run	rms (m)
63	1.027	65	1.009
73	0.547	77	0.424
80	0.651	82	0.767
84	0.976	86	0.998
100	0.695	102	0.826
106	0.245	110	0.252

To match run-pairs, the wave height spectra measured using the APL-UW wave buoy were compared for the runs. Figure 3 shows the wave height spectra for HDC run 63 and PAS run 65 at the start of the measurements and HDC run 106 and PAS run 110 near the end of the measurement window. These results are encouraging in that the amplitude and frequency dependence are similar for the run pairs, but also because the run pairs show some variability, indicating that different roughness conditions occured throughout the experiments. Next, the two-dimensional wave frequency spectra obtained from the wave buoy were also used to select HDC-PAS run pair matches. This is important since the *direction* as well as the *magnitude* of ocean waves will have an impact on acoustic signal coherence. Figure 4 shows the directional spectra for run pair 63 and 65. In both cases the two-dimensional spectra indicate that the waves are propagating on shore from the southwest. Table I shows the subset of HDC-PAS run pairs selected for the analysis based on similarities of sea surface conditions.
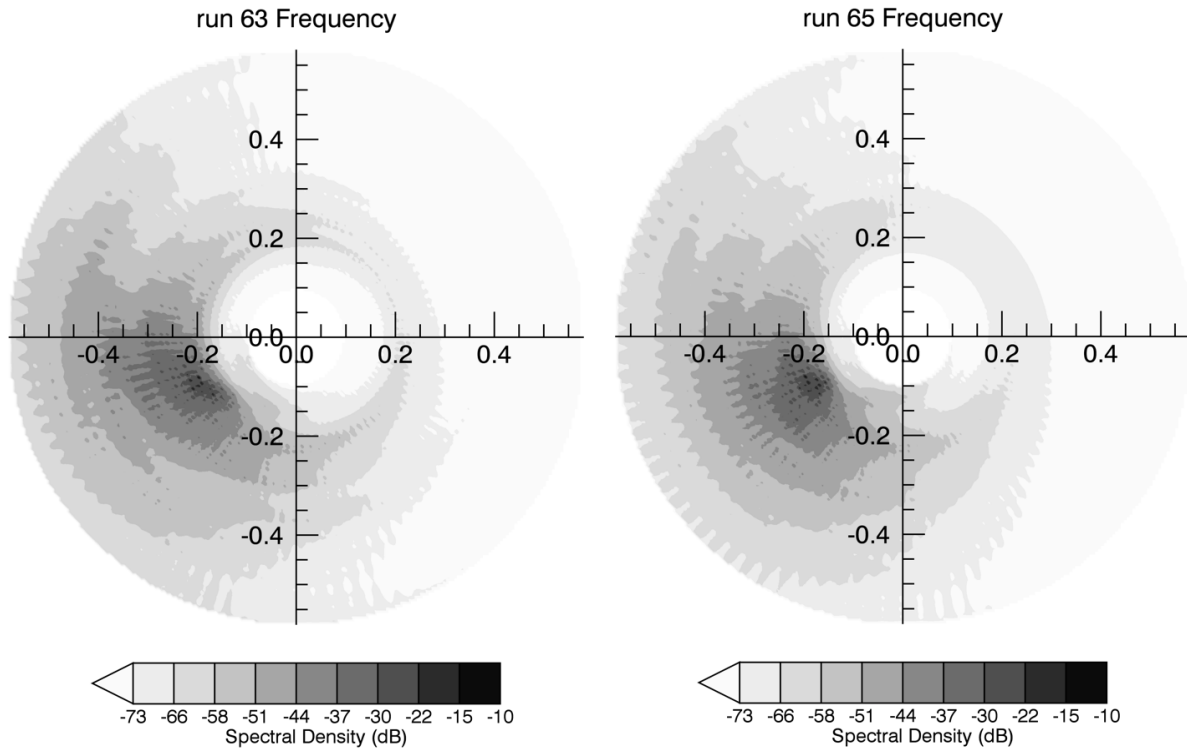
Figure 4. *Three-dimensional wave frequency spectra plots are produced as polar intensity plots. Frequency increases with distance from the origin, and the polar angle indicates wave direction relative to true north, with the top of the plot being true north. In this run pair, the dominant swell can be seen at approximately 0.2 Hz, and originating from the southwest. Note that the buoy did not record data at less than 0.1 Hz or greater than 0.58 Hz which gives these plots their distinct donut shape.*

On PAS runs 77 and 102, the mean echo levels from the PATS received on FORA were several dB lower than the other runs listed in Table I. The drop in level is inconsistent with surface roughness conditions. The most likely cause is fluctuations in the source level, possibly due to overloading the source amplifier. An *in situ* calibration of the source was performed by examining the direct arrival on FORA. Since the hydrophones closest to the ITC source clipped during the PAS runs, a single unclipped FORA hydrophone (located furthest from the ITC) was used for calibration for all runs. Since the ITC source and FORA hydrophone were separated by several water depths, the mean level of the direct arrival for each run was plotted against *rms* wave height during the run to ensure the received level of the direct arrival was uncorrelated with surface roughness. These data are shown in Figure 5. A linear curve fit to the data (not shown) returned a Pearson's correlation of $R = 0.04$ which corresponds to negligible correlation. This suggests that the 7 dB variation in level of the direct arrival level during the 12 runs is primarily due to source level fluctuations. To correct for ping-to-ping fluctuations in the source level, the direct signal arrival for each ping was plotted against the corresponding echo from PATS received on FORA. These data are given by the black dots shown in Figure 6. The mean levels for a run, for the direct arrival level and the PATS echo level are given by the larger (red) circles. Error bars are set at one standard deviation. A linear fit to the individual pings is given by the solid line which has a slope of $m = 0.8$. The departure from a slope of $m = 1$ is likely due to the effect of surface roughness on correlation. The equation given in the figure is used to correct for source fluctuations and normalize the mean echo levels in subsequent plots.
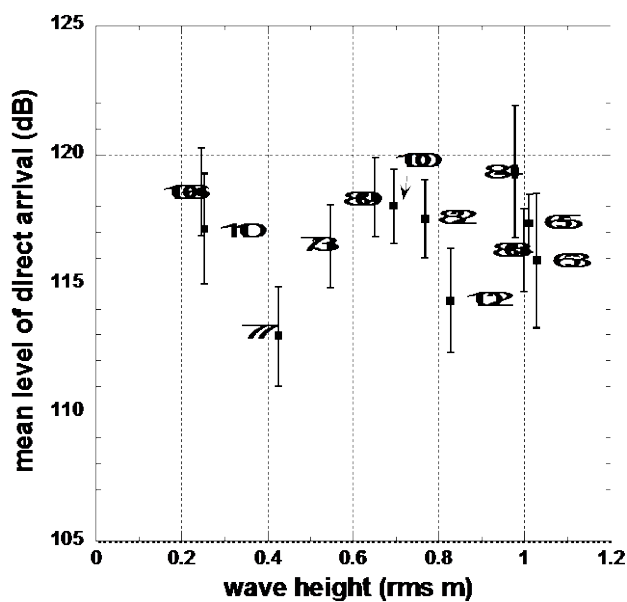
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Figure 5. Plot of mean level of direct arrival vs. rms surface wave height. Error bars are ±1 st. dev. Run number is listed beside each run.
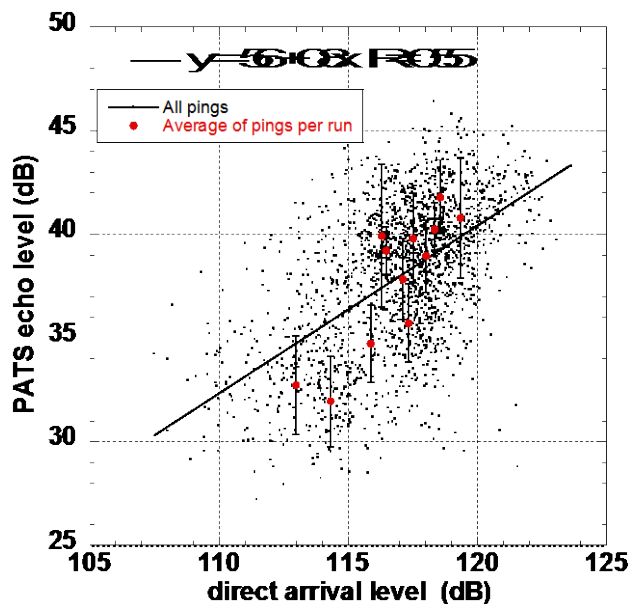

Figure 6. Plot of PATS echo level vs. direct arrival for each of the pings from all runs listed in Table I.
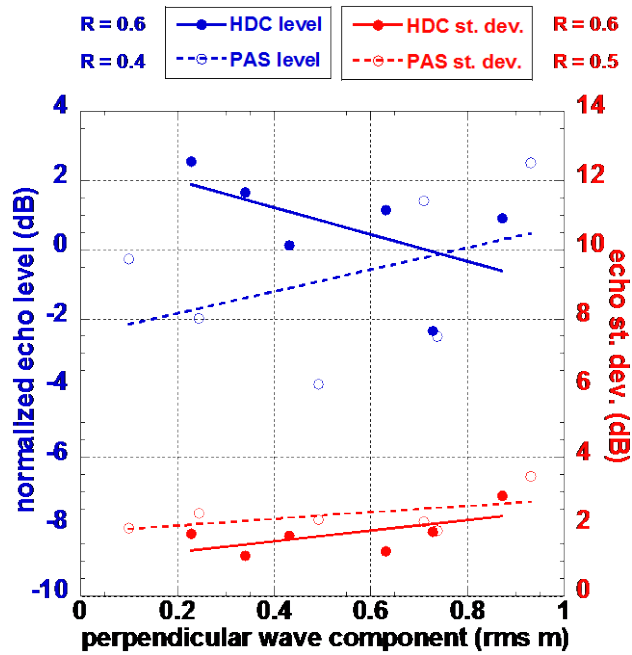
RESULTS

Figure 7a. Normalized mean level and standard deviation of echoes from PATS as a function of the surface roughness component traveling perpendicular to the FORA array beam directed at PATS.
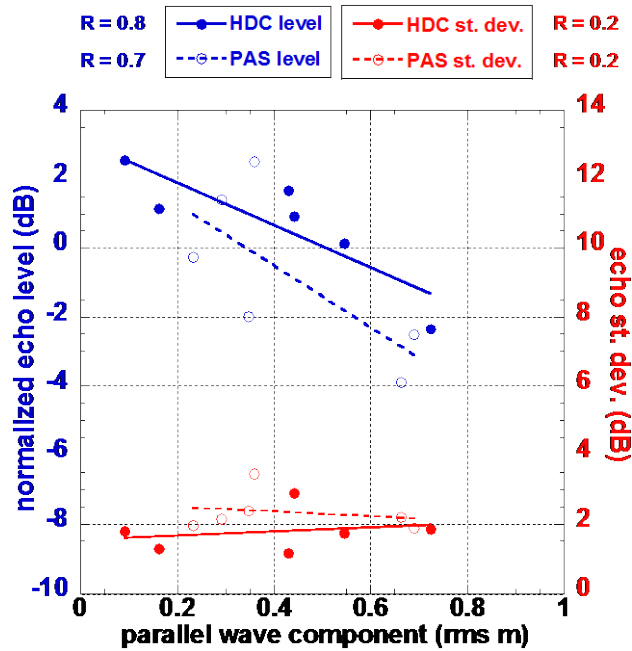

Figure 7b. Normalized mean level and standard deviation of echoes from PATS as a function of the surface roughness component traveling parallel to the FORA array beam directed at PATS.

In order to examine the effect of surface roughness on signal coherence the following approach was taken. The normalized mean echo level and the variance were computed for each of the runs listed in Table I. Then the two-dimensional wave height spectra were integrated and separated into the two components that are perpendicular to, or parallel to, the FORA beam. This was done based on heuristic arguments that surface roughness along these orthogonal coordinates may have significantly different impacts on signal coherence. The mean and standard deviation data for the HDC and PAS runs are plotted separately as a function of the perpendicular component of rms waveheight (Figure 7a) and the parallel component of rms waveheight (Figure 7b). The blue text, data, and vertical axes refer to the echo level results and the red text, data, and vertical axes refer to the standard deviation results. Although there are a limited number of data points, a least squares fit was done for each of the eight sets of data contained in the plots in Figure 7. The resulting equations are not all that instructive and have been omitted; but the Pearson's correlation value R and the sign of the slope are worthy of discussion. The mean echo level and the standard deviation results will be discussed separately in that order.

The echo levels of both HDC and PAS are strongly correlated with the *parallel* component of surface roughness ($R = 0.8$ and $R = 0.9$, respectively), and decrease with increasing waveheight. This is expected since scattering off a rougher surface will lead to a poorer match of the acoustic wave with its replica signal. Interpreting the echo levels in terms of the perpendicular component of roughness is not as straight forward. The echo level decreases with increasing roughness for CAS as expected; but the echo level *increases* with roughness for PAS and this is counter-intuitive. Although there is low-moderate correlation for PAS ($R = 0.4$), it is likely that the lack of data is causing this counter-intuitive result. Analysis of the effect of surface-waves propagating perpendicular to and parallel to the acoustic beam should provide further insight on the relative correlation of HDC and PAS signals. The final observation to make about the echo levels is that the mean HDC echo level is approximately 2 dB higher than the mean PAS echo level. This is surprising, given the much longer time-bandwidth product for HDC; one explanation is that it is statiscally insignificant given the variance on the data but it is certainly worthy of mention.

Turning now to the standard deviation results, three things stand out: first, the Pearson correlation is significantly higher for the perpendicular component of surface roughess than for the parallel component. The reason for this is not immediately obvious but does suggest that the other observations should be focused on the data in 7a. With that in mind, we note that the standard deviation increases with increasing roughness for PAS and HDC, and it is higher for PAS than for HDC–the first, because rougher seas should lead to greater ping-to-ping variability in the coherence, and the second since the much longer time duration of the HDC pulses will provide some time-averaging of the matched-filter gain during a ping which would reduce the ping-to-ping fluctuations. This latter effect leads to a standard deviation of PAS is about 0.6 dB greater than HDC. This could be an unanticipated advantage of HDC since it should reduce random detection threshold exceedences and therefore lower false alarm rates. Although the difference is less than 1 dB, one must bear in mind that measurements were limited to fairly benign seas because safety requirements meant that R/V SHARP had to disconnect the sonar and release from its mooring in rough weather. More detailed analysis is required before firm conclusions can be drawn.

IMPACT/APPLICATIONS

Automated DCLT in support of anti-submarine warfare (ASW) is critically important to the US Navy; its importance will continue to increase as shrinking defense budgets translate to fewer ASW ships and smaller crew sizes.   DCLT is particularly challenging in littorals where clutter (active sonar echoes from non-targets) causes unacceptable false alarm rates in classifiers and overloads automated tracking algorithms by generating too many false tracks. Furthermore, High Duty Cycle sonar is rapidly becoming a high profile topic as both the US and Canada integrate this technology into their respective fleets. HDC offers some exciting possibilities in ASW but its performance in high clutter (eg. littoral) environments has not been scientifically verified, and is by no means assured. The analysis proposed here will provide a scientifically controlled side-by-side comparison of HDC and PAS performance for DCLT in a littoral environment. As well as increasing our knowledge base on the subject, it will provide a dataset which will anticipate future questions from the operational community as HDC is employed. Predicting uncertainly in transmission loss and reverberation based on environmental variability will enable exploitation of environmental knowledge to identify the best window of opportunity to execute military operations and provide tactical guidance for optimal deployment of ASW sonars and supporting environmental measurements.

RELATED PROJECTS

A multi-national joint research project (MN-JRP) lead by the Centre for Maritime Research and Experimentation (formerly NURC) has been approved and the first field trial is scheduled for September-October 2015. This project has leveraged the knowledge and lessons learned from the TREX experiment (and the subsequent data analysis) to conduct dedicated shallow water HDC experimentation, in an operationally-relevant environment, to further assess HDC ASW performance in the littorals. The PI as well as several other members of the TREX experiment are involved in the development of this project. This MN-JRP will study the efficacy of HDC in shallow water for target detection, localization, tracking, and classification compared to the conventional PAS baseline. Particular attention will be paid to quantifying the impact of the shallow water environment on HDC performance. The MN-JRP is built around the concept of performing one or two ASW experiments with the NRV Alliance and a diesel-electric submarine target. While experimentation dedicated to HDC data collection is planned, the MN-JRP will also seek to exploit NATO exercises where possible.

This grant also benefits from DRDC Atlantic's Force ASW Program which is using the TREX data to support its work in classification and tracking. The PI is collaborating closely with the DRDC team working on the TREX analysis.

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4. Paul C Hines, Stefan M. Murphy, Keaton Hicks, and Nicholas Taylor, "Measurements of Signal Coherence for High and Low Duty Cycle Sonars in a Shallow Water Channel," Proceedings of IEEE Oceans15, Genoa, Italy, May 2015.

PUBLICATIONS

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