PERFORMANCE OF THE SHOELACE WAVEFORM FOR HIGH DUTY CYCLE MULTISTATIC SONAR

Doug Grimmett[a]

[a]Naval Information Warfare Center Pacific, San Diego, CA, 92152

Abstract: *High duty cycle (HDC) sonar operations that use continuous (or near continuous) acoustic transmissions offers potential improvements over pulsed active sonar by providing an order-of-magnitude or more increase in the number of detection opportunities with a faster revisit rate for improved target localization and holding. If multiple transmit sources (as in multistatic sonr) are used without separately assigned frequency bands or time schedule interleaving, mutual interference is likely. This interference can lead to missed detections and/or ambiguous localization solutions. Some advanced waveforms have been proposed, which are designed to provide mutual orthogonality, but they come with increased processing load/complexity and come with other constraints. This paper describes a simple HDC waveform, termed the "Shoelace" waveform, which transmits both up-swept LFM and down-swept LFM waveforms simultaneously, and repeatedly. This approach reduces, but does not eliminate the mutual interference effect of the two signals on each other, but it still has the potential to provide an overall increase in multistatic performance by increasing the number of HDC detection opportunities, exploiting acoustic channel variability, reducing revisit rate, and improved tracking/localization performance.*

Keywords: *High Duty Cycle, Continuous Active Sonar, Multistatics, LFM*

BACKGROUND

High duty cycle (HDC) sonar operations that employ continuous (or near continuous) acoustic transmissions offer potential improvements over pulsed active sonar by providing an order-of-magnitude or more increase in the number of detection opportunities [1]. For a continuously repeating Linear Frequency Modulated (LFM) waveforms, this is achieved by breaking the waveform's processing interval/bandwidth down into smaller pieces. This may come at the cost of a reduction in received signal excess level per individual detection but can still provide better performance at the output of a tracker, with improved target holding and localization [2].

In multistatic active sonar, multiple acoustic receivers and transmitters operate together as a network. With multiple sources transmitting continuously, mutual interference is likely, and this must be mitigated. Using identical waveforms for multiple sources will yield ambiguity about detection contact localization. Using different waveforms will not suffer the ambiguities but may still cause mutual interference via echo obscuration. Some advanced waveforms have been proposed [3], which are designed to provide mutual orthogonality, but they come with increased processing load/complexity and come with other operational constraints.

This paper describes a simple HDC waveform, termed the "Shoelace" waveform, which transmits both up-swept LFM and down-swept LFM waveforms simultaneously, and repeatedly with close to or equal to 100% duty cycle. This approach minimizes but does not eliminate the mutual acoustic interference of the two signals on each other but can still provide an overall increase in multistatic performance, by providing additional detections opportunities above standard HDC single LFM waveforms.

The first section of this paper describes the LCAS'15 at-sea experiment, which provided the Shoelace waveform data used in this study. The next two sections describe the processing method and detection performance obtained. Finally, conclusions are then provided.

THE LCAS'15 EXPERIMENT

The Littoral Continuous Active Sonar 2015 (LCAS'15) at-sea experiment was conducted in October 2015 in the shallow, coastal waters off the peninsula of Portovenere, Italy. A monostatic sonar was operating from the ship R.V. ALLIANCE, and transmitted HDC waveforms and received echo data with a port/starboard-discriminating horizontal towed array. A 45-minute run ("MN05") was dedicated to transmitting a Shoelace waveform. The run geometry is shown in Fig. 1. The ALLIANCE was transiting along the 110-meter contour in south easterly direction, at a speed of about 4 kts, with its sonar gear deployed at a depth of 60 m. A surrogate target Echo-Repeater (E/R) system was deployed by C.R.V LEONARD, holding station at a fixed location slightly upslope from the ALLIANCE track. ALLIANCE was closing the E/R, with the closest-point-of-approach (CPA) of about 4 km occurring at the end of the run. Data was recorded in real-time, and detailed processing and analysis of the Shoelace waveform was done post-trial.

The experiment was conducted by the NATO Centre for Maritime Research and Experimentation (CMRE) together with collaborators from NATO CMRE, Australia, Canada, Italy, New Zealand, Norway, U.K. and the U.S.A.

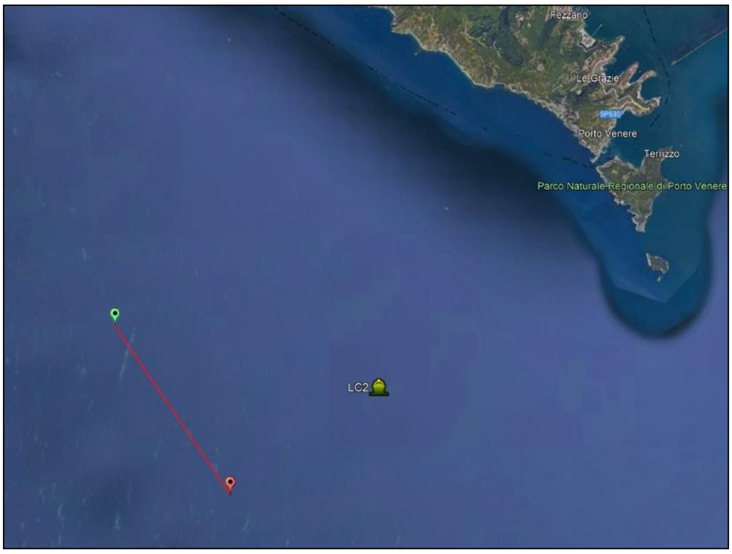

Fig.1: The LCAS'15 geometry for the Shoelace run. The location of the simulated (E/R) target is shown in yellow and the monostatic sonar track is shown in red.

THE SHOELACE WAVEFORM PROCESSING

Fig 2. shows a timeseries (top) and spectrogram (bottom) of the Shoelace waveform transmitted during the LCAS'15 sea trial. Three cycles of the waveform are shown, as received on the beam pointing at the (E/R) target. The transmitted waveform is contained within 800 Hz, with the UP LFM sweeping from 1800 to 2600 Hz while the DOWN LFM is simultaneously sweeping from 2600 to 1800 Hz. The ping repetition interval (T_{pri}) was 20 sec, consisting of the sweep transmit duration (T_c) of 18 sec, followed by a 2 sec gap before retransmission. Reverberation and other interferences are observed in the image.

Active sonar processing includes the application of a matched filter, by correlating a replica of the transmitted waveform with the received data. For HDC LFM waveforms, it standard practice to implement a bank of multiple matched filters to process a set of sub-portions of the LFM transmission cycle. The sub-portions (i.e., sub-bands) will be a smaller processing time (T_p) and processing bandwidth (B_p). For this analysis, we have chosen the sub-bands to have T_p=1 sec, with corresponding B_p=44.4 Hz. These are overlapped in time/frequency by 50%, and the resulting processor includes a bank of 35 (18 plus 17 overlapped) matched filters. The same sub-bands are used for processing the UP LFM as for the DOWN LFM; only the sweep slope is reversed in the replicas.

Since echo times (and subsequent ranging computations) are relative to the direct blast, each sub-band is time-aligned using the sub-band direct blast arrivals. In the case of a single LFM (not the Shoelace) waveform, there is a clear window for detection, without interference, until the next direct blast arrives T_{pri} seconds later. However, in the case of the Shoelace waveform, for any of the processed sub-bands, the opposing direction (DOWN on UP or UP on DOWN) direct blast energy will enter into the other's field-of-view and interfere with detection for a period of time. This effect is shown annotated in the figure.

Fig. 3 (top) shows the 35 timeseries outputs (over 20 sec) of matched filter processing for a single HDC cycle (stacked, top to bottom, then left to right). In this case, the replicas used were for the UP LFM. The timeseries have been time aligned by each sub-band's

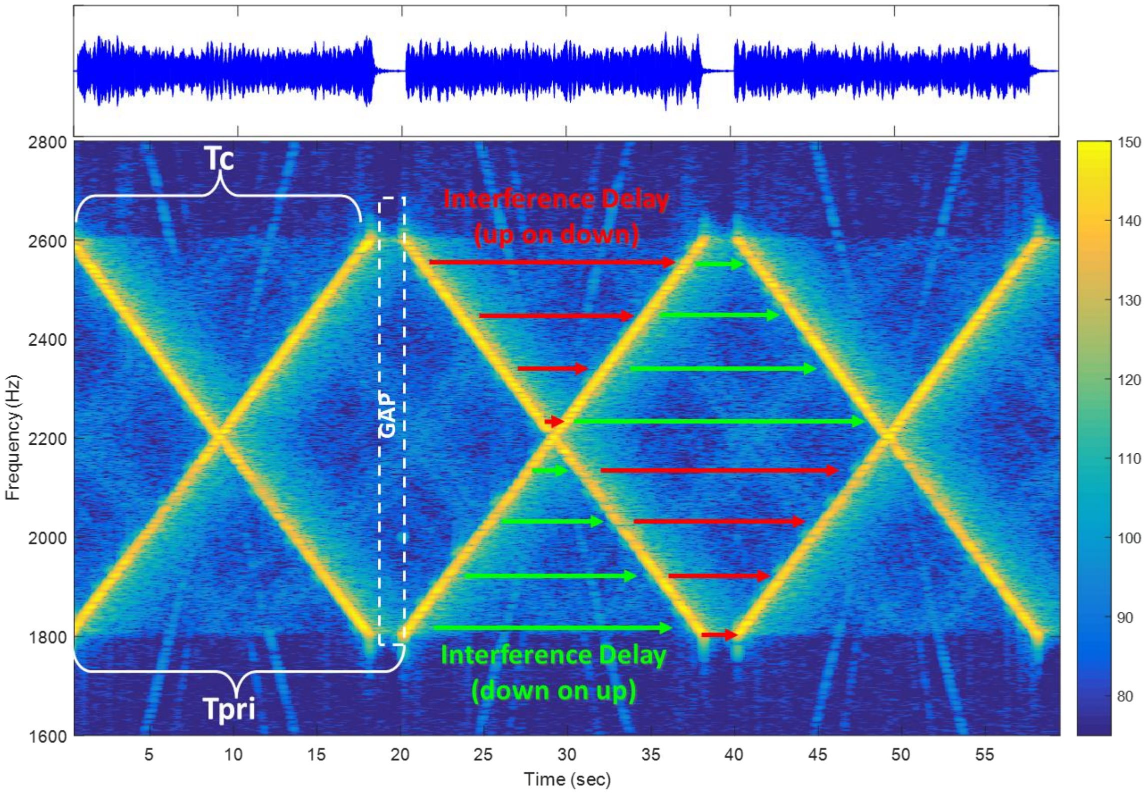

Fig.2: Spectrogram of the Shoelace waveform with descriptive annotation.

direct blast arrival time (at 0 sec), and extend over the single-cycle field-of-view of 20 sec. The E/R detections are seen (contained within green lines) at the time delay of about 8 sec in many of the individual scans. The interference induced from the DOWN LFM is also seen crossing through the field-of-view twice over the HDC cycle (within the red lines) and masking detections whenever it overlaps with the target echo time window However, we see that outside of those interference instances, detection is still possible.

Fig. 3 (bottom) shows the corresponding detection output of a standard split-window normalizer for the data. Here we see that normalizer effectively preserves target echoes when they are present, and it effectively screens the interference portion of the timeseries, without generating any processing artifacts.

The data was processed for the entirety of the 45 min run for both the UP and DOWN LFM waveforms, which included beamforming, sub-band matched filtering, split-window normalization, clustering and detection (contact-forming). Fig. 4. shows a display of the extracted contact data for the UP (left panel) and DOWN (right panel) LFM. The vertical axis is the elapsed time of the run (slow-time), the horizontal axis is the echo delay-time (relative to the received sub-band direct-blast), with color representing the contacts' bearing (obtained via beamforming and fine bearing estimation algorithms). Only half of the cycle time (10 sec), bearings to the port side, and contacts above 12.5 dB SNR are shown here. Note the large density of false alarms and the structure of the bottom-generated reverberation and clutter. The displays for the UP versus the DOWN waveform look very similar at this scale, but we will show later that their measurements statistics vary. Although the target echoes from the E/R are present in these displays, they are not easily apparent. They can be seen as curves of blueish points progressing from about 9 sec to 6 sec time delay over the course of the run.

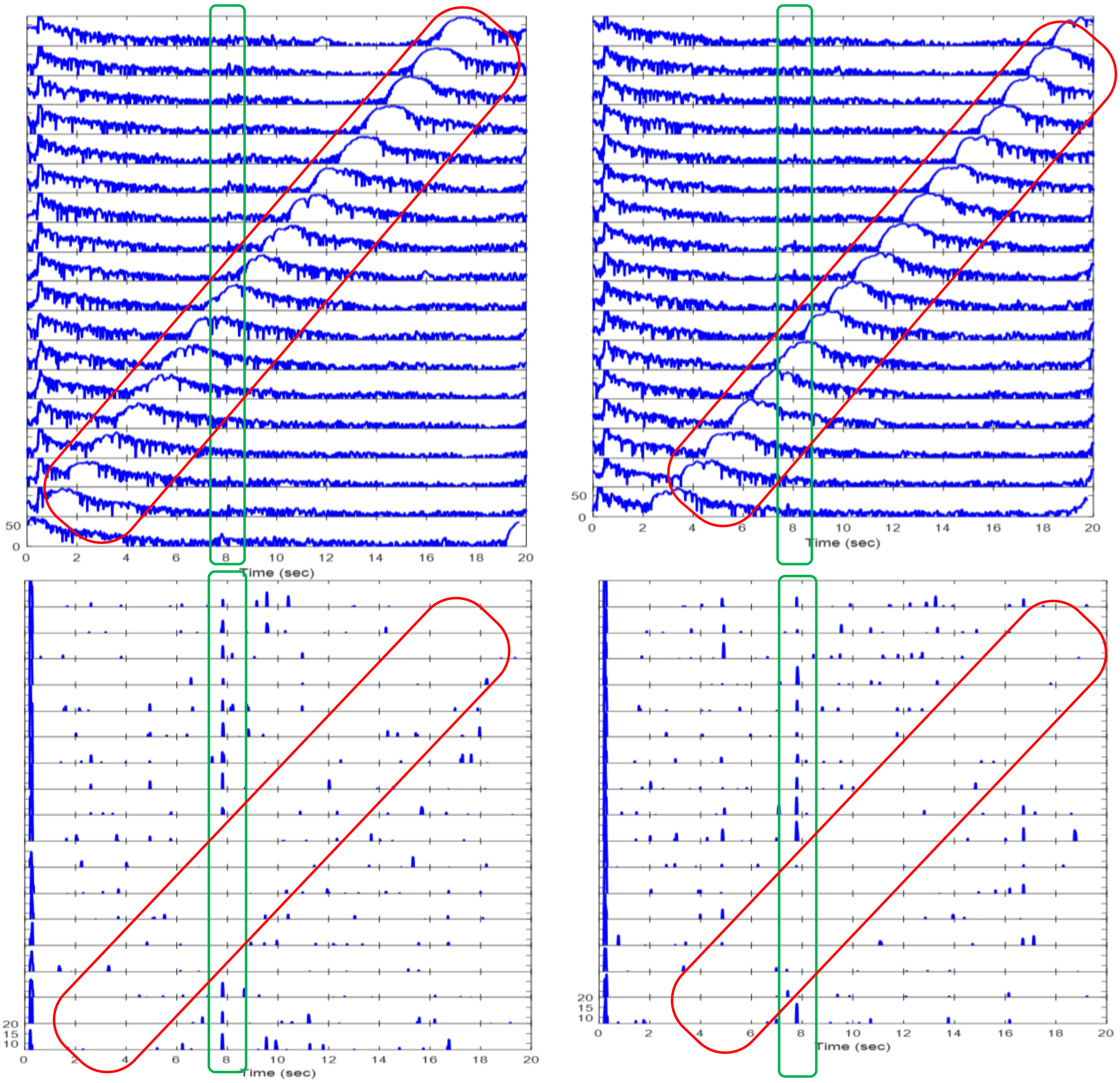

Fig. 3: One cycle of 35 scans (sub-bands) of the Shoelace UP waveform; matched filter output (top), normalized output (bottom); sequence from top-to-bottom, then left-to-right.

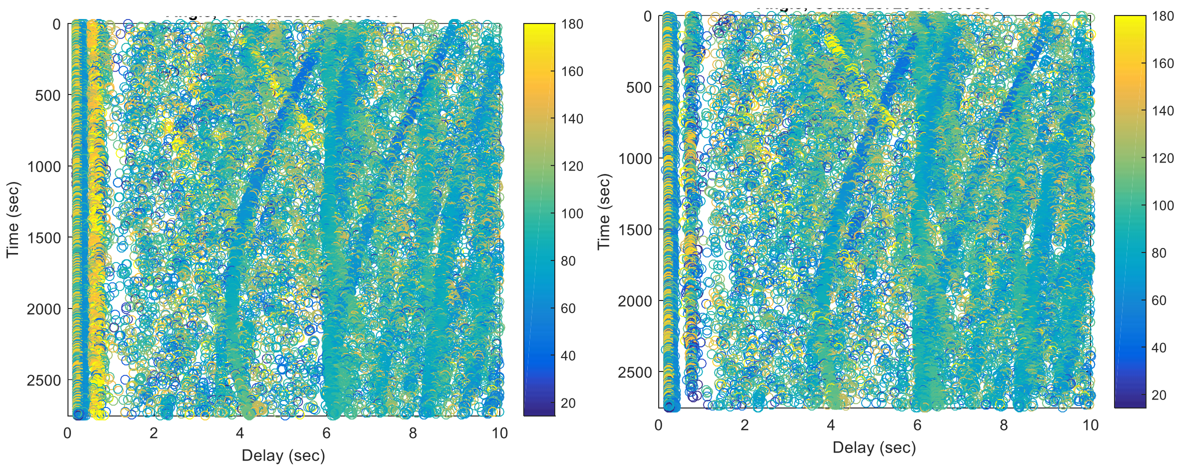

Fig.4: Extracted detection contacts; Shoelace UP (left) and DOWN (right); color indicates contact bearing.

After some analysis, and utilizing ground truth information, we tagged what are believed to be actual E/R echoes from the total set of contacts, for both UP and DOWN LFMs; these are shown overlaid in left panel of Fig. 5. The echo delay times for the UP LFM are observed to be slightly less that those for the DN LFM at the beginning of the run (> 8 sec), and then they ultimately merge into the similar time delay at CPA (~6.2 sec). In the figure's right panel, a zoomed view is presented, and we clearly see the time-delay bias errors for small bandwidth signals [4], and their differences between the UP (to the left) and DN (to the right) processing. Detections are seen in clusters, within the 35 scans/opportunities, and in between these (every other cycle), there are no target detections. This is due to the operational mode of the E/R system, which was set to record the direct blast signal from one cycle and then retransmit only during the successive cycle, causing the gap in clusters.

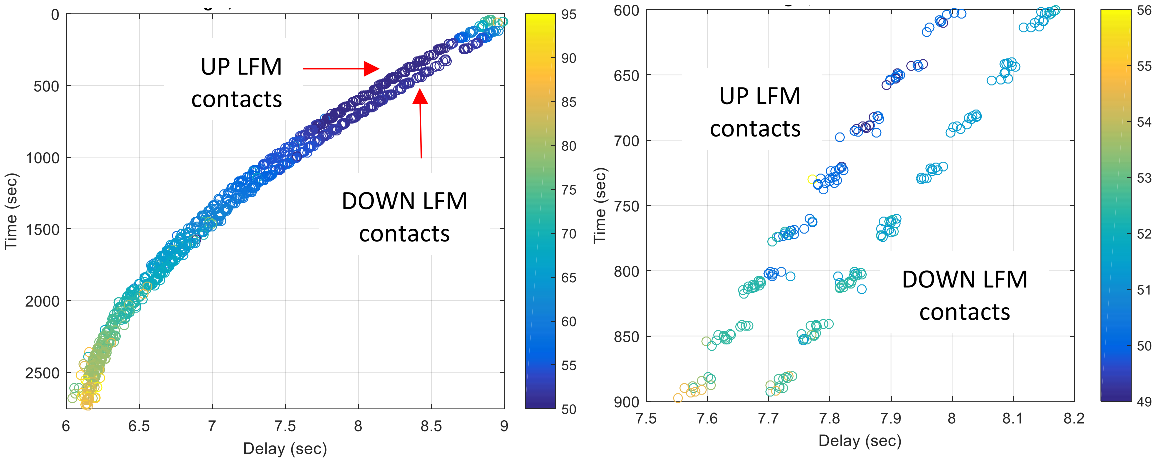

Fig. 5. Extracted target-originated detection contacts for UP and DOWN waveforms, overlaid; full run duration (left); zoomed view (right); color indicates contact bearing.

PEFORMANCE OF THE SHOELACE WAVEFORM

One of the motivations of using the Shoelace waveform is to increase the number of detection opportunities as well as the diversity of those opportunities, by enabling two waveforms to be transmitted simultaneously (either by the same source in a monostatic configuration, or by different bistatic sources). Of course, there is not complete orthogonality between the UP and the DOWN LFM, and due to the mutual interference, the number of valid detection opportunities can never be doubled.

However, by choosing small sub-bands in the HDC processing, the mutual interference obscuration time can be reduced. The time breadth of the interference/obscuration zone for a sub-band is of minimum of duration of $2T_p$ (at the output of the matched filter due to uncorrelated signals). The maximum expected percentage gain of increased detection opportunities, G_{opp}, (of Shoelace vs. single LFM) can be estimated by

$$G_{opp} = \left(1 - 2\frac{2T_p}{T_c}\right) \cdot 100\ . \qquad (1)$$

The obscuration zone can be greater than $2T_{p,}$ in the case of heavy reverberation conditions or other factors, and this appears to be the case in the LCAS'15 data set. In Fig. 3. we see obscuration zones withs about 4-sec durations for the 1-sec sub-band used. It is also seen that detections were made in 23 of 35 sub-band opportunities (66%), the others being obscured by interference in two groups of about six contiguous scans each. Assuming equivalent performance (on average) of the DOWN signal, we estimate in this case 33% more detections opportunities are available using the Shoelace (UP and DOWN) waveform that for a single UP or DOWN LFM waveform. In less reverberant conditions this could rise to a maximum of about 80% more detection opportunities.

Another advantage of this waveform is that the increased detection opportunities have more detection diversity, which can enhance performance. At any given scan time, the sub-bands for the UP and the DOWN signals are different. For example, at the beginning of a Shoelace waveform cycle, the UP waveform will at the lowest frequency sub-band while the DOWN waveform will be at the highest frequency sub-band. As time evolves they will cross when at the Shoelace center-frequency, and will finally end up in the sub-band that the other waveform started in. This provides the processor the advantages of frequency and temporal diversity that is present in the acoustic channel.

Fig. 6 shows the results of analysis performed on the detection data of the LCAS'15 Shoelace run. The panel in the top left shows the overall status of detections made. Of the total detections made by both UP and DOWN processing, about half were made by the UP and the other half by the DOWN. Of the total detections, slightly less than half were made

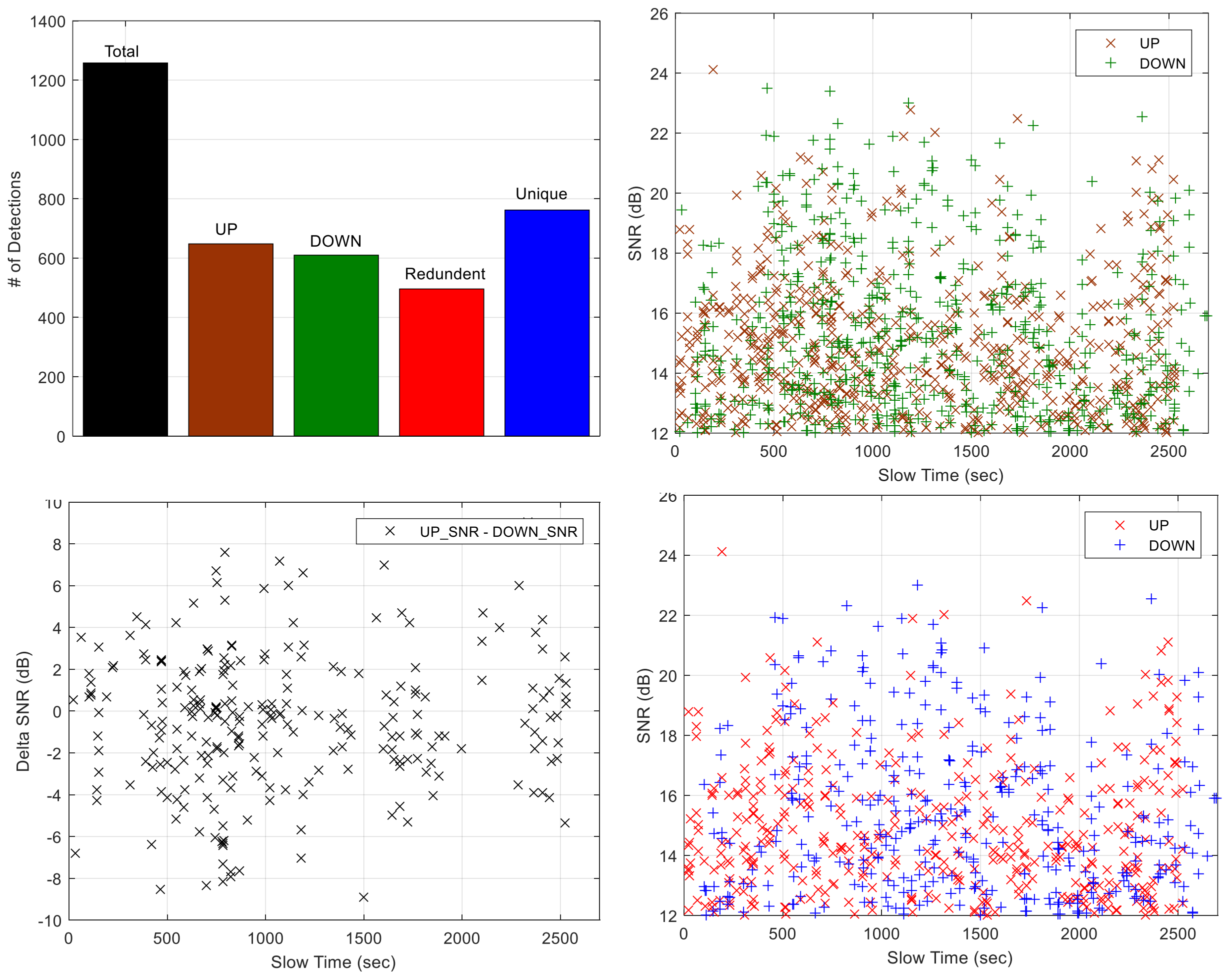

Fig.6. Detection SNR for Shoelace waveforms. Detection type breakdown (top left); UP vs. DOWN detections (top right); SNR differences for redundant (simultaneous UP & DOWN) detections (bottom left), and unique (UP or DOWN) detections (bottom right).

whilst the inverse waveform (e.g. for a DOWN detection the corresponding UP detection, and vice versa) was also redundantly detected. And of all detections slightly more than half were "uniquely" detected, meaning that at that time when the UP detected, the DOWN was not detected, and vice versa. The other three panels show the detection SNRs for these cases. In the top right panel, the plot shows SNRs for UP and DOWN detections as a function of time. The bottom left panel shows the SNR differences when redundant detections were made on both the UP and the DOWN signals (UP SNR minus DOWN SNR) simultaneously. In many cases there are differences greater than 3 dB. The bottom right panel shows the SNR of all the "unique" detections as a function of time and color-coded UP or DOWN. These plots show a wide temporal/spectral variability in detection SNR, which suggests that better detection and tracking performance by taking advantage of their detection diversity.

SUMMARY AND CONCLUSIONS

The Shoelace HDC waveform has the potential to provide an increase in the number and update rate of target detections by providing an increase in detection opportunities. This may be particularly effective in highly variable acoustic channels that exhibit a lot of temporal and spectral fluctuations. The LCAS'15 data provided a first opportunity to evaluate this waveform. More mutual interference (in terms of obscuration time window) than expected was observed in the data set. Nevertheless, an impressive increase in detections and their detection diversity was observed, and this is expected to contribute to further increases in performance when data fusion and tracking algorithms are applied. In particular, the range-bias errors of small bandwidth LFM (sub-bands) are opposing, and can be combined and corrected within a tracking algorithm [4]. The tracking performance of the waveform will be a focus of further, future work.

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REFERENCES

[1] **D. Grimmett, R. Plate**, High Duty Cycle Sonar Performance as a Function of Processing Time-Bandwidth for LCAS'15 Data, Editor, *in Proc. of the 5th International Conference on Underwater Acoustics*, Skiathos, Greece, July 2019.

[2] **D. J. Grimmett,** Target AOU Growth Containment using LFM High Duty Cycle Sonar Editor, *in Proc. of the 2nd International Conference on Underwater Acoustics,* Rhodes, Greece, June, 2014.

[3] **D. Hague,** J. R. Buck, An experimental evaluation of the generalized sinusoidal frequency modulated waveform for active sonar systems, *The Journal of the Acoustical Society of America* **145**, 3741 (2019)

[4] **D. J. Grimmett,** Target Doppler Estimation and Range Bias Compensation using LFM High Duty Cycle Sonar, *in Proceedings of the 2nd International Conference on Underwater Acoustics*, Rhodes, Greece, June, 2014.