DOPPLER ESTIMATES FOR LARGE TIME-BANDWIDTH PRODUCTS USING LINEAR FM ACTIVE SONAR PULSES

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Abstract: *Doppler sensitive active sonar waveforms have the potential to distinguish target echo returns from stationary compact clutter and to improve target tracking by providing the tracker with an estimate of the Doppler range rate. Linearly Frequency Modulated (LFM) active sonar waveforms are typically assumed to be Doppler insensitive. However, for LFM pulses with a high Time-Bandwidth product (TB), this assumption is no longer valid and Doppler sensitivity can be exploited for target velocity estimation. On the other hand, a potential drawback is caused by a low acoustic channel coherence since, in this case, increasing the TB can decrease the matched filter gain. A sea trial was carried out by the Littoral Continuous Active Sonar (LCAS) Multi-National Joint Research Project (MN-JRP) in the gulf of Taranto in October of 2016. Two LFM active sonar waveforms were simultaneously transmitted to detect an artificial target (echo repeater). Over a ping repetition interval of 20 seconds, the first LFM waveform was one second in duration and ranged from 2.7-3.5 kHz (low TB Pulse Active Sonar - PAS). The second LFM waveform was 20 seconds in duration, ranging from 1.8-2.6 kHz (high TB Continuous Active Sonar - CAS). Our results demonstrate a gain in signal to reverberation ratio using LFM Doppler processing. In addition, we show that the estimate of the Doppler range rate obtained by this technique can be used in echo classification and tracking.*

Keywords: *Continuous Active Sonar, Wideband, Doppler, echo repeater, littoral environment, high duty cycle sonar, signal to reverberation ratio, continuous LFM*

1. INTRODUCTION

Interest in increasing the duty cycle of traditional pulse active sonar (PAS) to a continuous active sonar (CAS) mode has arisen recently for anti-submarine warfare (ASW) applications including littoral scenarios [1]. In PAS systems, a sonar signal is transmitted for a short duration followed by a long listening duration (upper frequency band of Fig. 1). In CAS systems, a sonar signal is transmitted continuously while simultaneously listening for echoes (lower frequency band of Fig. 1). CAS offers the potential advantage of increasing the target update rate through sub-band processing [1-3] to improve tracking performance [4]. On the other hand, a potential drawback is caused by a low acoustic channel coherence since, in this case, increasing the TB can decrease the matched filter gain [1-3].

Active sonar systems correlate received acoustic signals with a replica of the transmitted signal. The theoretical matched filter response, R, for a given time mismatch, $\Delta\tau$, and Doppler mismatch, $\dot{r}$, of a LFM pulse with bandwidth B, duration T, and centre frequency f_o was originally derived by Kramer [5] and is reproduced here as Eq. (1).

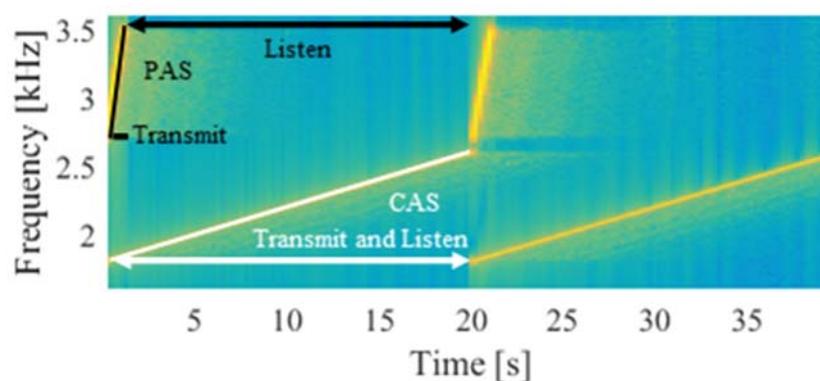$$|R| = \frac{1}{2U}\sqrt{\left[C\left(\frac{A}{U}+U\right)-C\left(\frac{A}{U}-U\right)\right]^2 + \left[S\left(\frac{A}{U}+U\right)-S\left(\frac{A}{U}-U\right)\right]^2}, \tag{1}$$

where C and S are the Fresnel integrals [6],

$$U = T\sqrt{\frac{B}{T}\left|\frac{2\dot{r}}{c}\right|\left(1-\frac{\dot{r}}{c}\right)} \cong \sqrt{BT\frac{2\dot{r}}{c}}, \tag{2}$$

c is the speed of sound, and

$$A = T\left(f_o\frac{2\dot{r}}{c}-\frac{B}{T}\Delta\tau\right). \tag{3}$$

Fig. 1: Spectrogram of an example LFM PAS (1 second long from 2.7-3.5 kHz, black labels) and LFM CAS (20 seconds long from 1.8-2.6 kHz, white labels) signals with a ping repetition interval of 20 seconds.
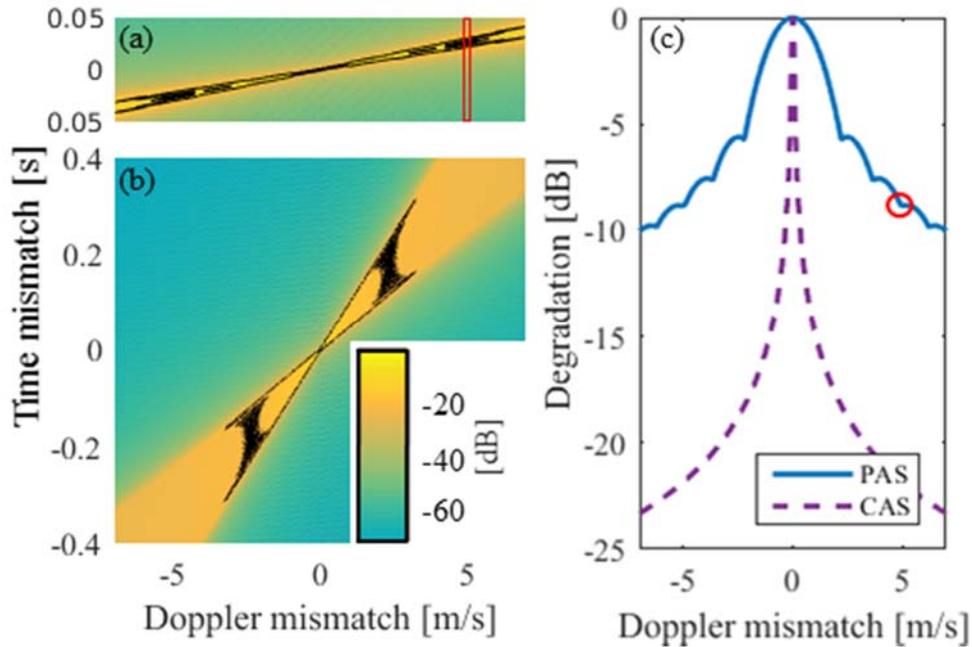
Fig. 2: (a) PAS and (b) CAS theoretical matched filter degradation for Doppler-time mismatch. The black lines in (a) and (b) represent the -10 dB and -20 dB contour lines respectively. (c) Theoretical matched filter degradation of uncompensated Doppler for PAS (solid blue) and CAS (dashed purple). Red circle indicates the maximum from the red rectangle in (a).

The squared theoretical matched filter degradation for the full band PAS and CAS signals in Fig. 1 are shown in Fig. 2a and Fig. 2b respectively as calculated by Eq. (1). The maxima of Fig. 2a and Fig. 2b for each Doppler mismatch are shown by the blue (PAS) and purple (CAS) plots in Fig. 2c respectively. The red circle in Fig. 2c indicates the maximum of the region outlined by the red rectangle in Fig. 2a. Fig. 2c shows that the CAS signal is significantly more sensitive to target Doppler mismatch. Note the sharp degradation of the CAS signal with increasing Doppler mismatch; the CAS signal has a -3 dB point of approximately 0.1 m/s compared to approximately 1.6 m/s for the PAS signal.

To compensate for relative target motion, the replica can be time-scaled by a factor of $1-\delta_v$, where δ_v is given by,

$$\delta_v = 2\dot{r}/c \,. \tag{4}$$

LFM PAS is typically assumed to be Doppler insensitive, however Fig. 2c shows that this assumption is not valid for LFM signals with large Time-Bandwidth (TB) products. In an operational environment, the target Doppler is unknown, necessitating a bank of time scaled replicas that span the range of possible target speeds. Previously, CAS has been used to estimate Doppler by exploiting the frequency dependence of the slope of the ambiguity function [7]. In this paper, we will correlate the received acoustic signal with a bank of matched

filters in order to maximize the matched filter output and to obtain a direct measurement of the target Doppler speed.

2. EXPERIMENT AND DATA ANALYSIS

In October 2016, the Littoral CAS (LCAS) Multi-National Joint Research Project (MN-JRP) held a sea trial off the coast of Taranto (Italy) to compare the detection capability of LFM PAS with LFM CAS. The NRV ALLIANCE attempted to detect an echo repeater acting as an artificial target towed by CRV LEONARDO.

On October 22, the NRV ALLIANCE towed a sonar source that transmitted a LFM PAS signal (from 2.7-3.5 kHz over 1 s with a source level of 214 dB re 1 µPa @ 1 m) and a LFM CAS signal (from 1.8-2.6 kHz over 20 s with a source level of 201 dB re 1 µPa @ 1 m) with a ping repetition interval of 20 s, as shown in Fig. 1. Each pulse had the same total energy in the water per ping. The source was towed at a depth of approximately 70 m. NRV ALLIANCE also deployed a towed array with 64 triplet hydrophones at a depth of approximately 80 m. The CRV LEONARDO towed an echo repeater at a depth of approximately 70 m with a target strength of 15 dB.

The CRV LEONARDO sailed downslope and antiparallel to NRV ALLIANCE with a closest point of approach of approximately 6.2 km, as shown in Fig. 3a. Both vessels travelled at approximately 3 knots (~1.5 m/s). Fig. 3a also shows the bathymetry of the operational area, acquired using an *EM 302 KONGSBERG* 30 kHz multibeam echo sounder.

The sound speed profiles were measured at 06:36UTC and 16:33UTC on October 22 using a *Sea-bird Electronics 9plus* conductivity, temperature, and depth (CTD) sensor and are shown in Fig. 3b. The measured sound speed resulted in a downward refracting sound speed profile with a 35 m deep mixed layer.
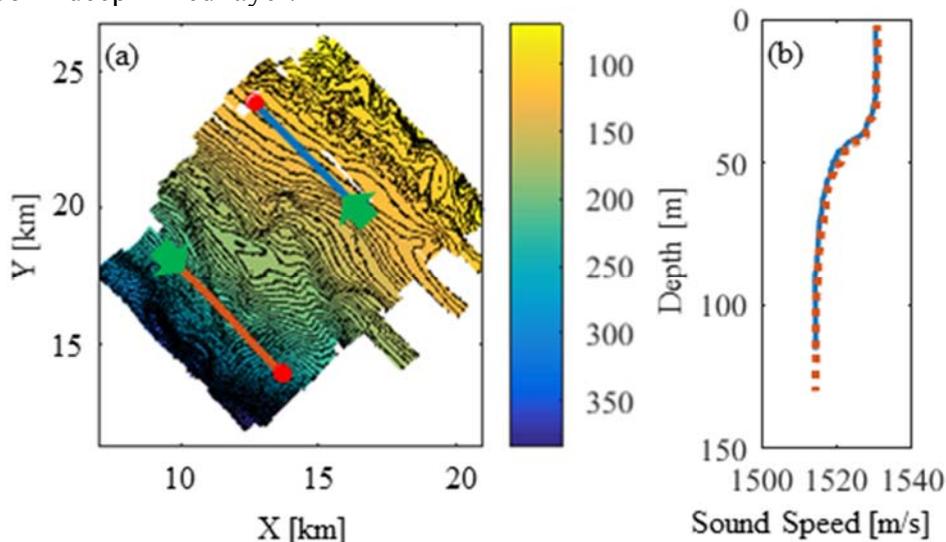

Fig. 3: (a) NRV ALLIANCE (blue) and CRV LEONARDO (red) trajectory from green arrow to red point. Background shows bathymetry of operational area. (b) Sound speed profile measured at 06:36UTC (blue) and 16:33UTC (dashed red) on October 22.

Note that source, receiver and echo repeater were all below the thermocline. The sound speed as measured by moored *Sea-bird Electronics SBE37* CTD sensors at depths of 5, 20, 30, 35, 40, 50 and 60 meters and at a sample rate of 1 Hz varied by less than 1.4 m/s at each depth for the duration of the run.

The sea conditions were sea state 3, with waves coming from the south and a dominant wave power spectral density of approximately 0.5 m²/Hz at 0.16 Hz, measured using a *Datawell oceanographic instruments MKIII* moored directional wave rider.

The hydrophone data acquired during the run were first beamformed into 64 cosine spaced beams. Next, the data were analysed in two different ways: the first using standard LFM processing, where the beamformed output was matched filtered with a replica of the transmitted waveform; and the second using LFM Doppler processing, where the beamformed output was matched filtered with a bank of time scaled (Doppler shifted) replicas of the transmitted waveform. The Signal to Reverberation Ratio (SRR) was then estimated using a sliding window median filter with a length of 600 meters (normalisation). A detection threshold of 6 dB was applied, followed by a clustering phase. The maximum SRR was selected for the cluster within ± 1 km and ± 2 beams of the expected target location. The Doppler bank (i.e. velocity estimation) that provided the peak matched filter output was also recorded for LFM Doppler processing.
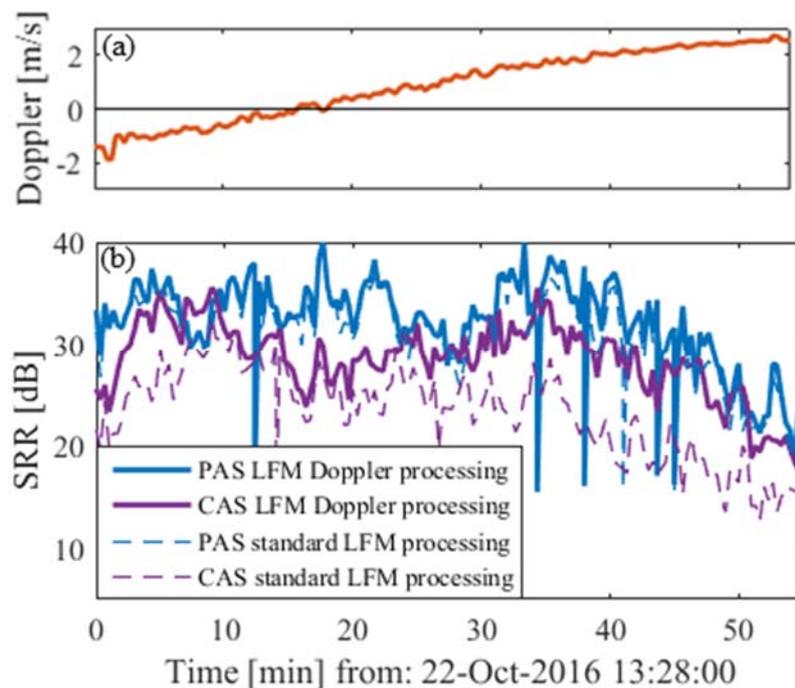

Fig. 4: (a) Derivative of bistatic range with respect to time (Doppler) as calculated using GPS measurements. (b) SRR from artificial target (echo repeater) for PAS (blue) and CAS (purple) with LFM Doppler processing (solid lines) and standard LFM processing (dashed lines).

3. EXPERIMENTAL RESULTS

The SRR levels from the artificial target for coherently processed CAS and PAS pulses are shown in Fig. 4 with and without LFM Doppler processing. Note that the increase in SRR from standard LFM processing to LFM Doppler processing is as much as 13 dB for CAS and 5 dB for PAS. This difference is attributed to the higher Doppler sensitivity of the LFM CAS waveform. Also note that LFM PAS has higher echo returns than LFM CAS. This is likely due to the channel coherence time being longer than 1 s but less than 20 s, and/or movement in the source, towed array, and/or echo repeater [8].

Figure 5b shows the expected gain from LFM Doppler processing compared to standard LFM processing for the LFM CAS waveform (solid purple), calculated using the expected Doppler shown in Fig. 4a and the theoretical degradation shown in Fig. 2c. Fig. 5b also shows the measured gain from LFM Doppler processing (blue) and a 5 min long sliding median window of the measured gain shown by the dashed purple line. The gains are significant (~8 dB at 2 m/s) - but are smaller than expected. This can also be attributed to reduced channel coherence and/or movement in the source, receiver, and/or echo repeater. Fig. 5a shows how the measured Doppler values (blue) compare to the expected Doppler (orange). The bars represent a qualitative uncertainty that is inversely proportional to the echo SRR as the error in the Doppler measurement is expected to decrease with increasing SRR. The bars are also inversely proportional to the waveform TB which can be explained by the sharpness of the plots in Fig. 2c. The uncertainty in the Doppler measurement is low enough that it can be used as a classification feature to distinguish a target echo return from stationary compact clutter and may also be useful as a tracker input.
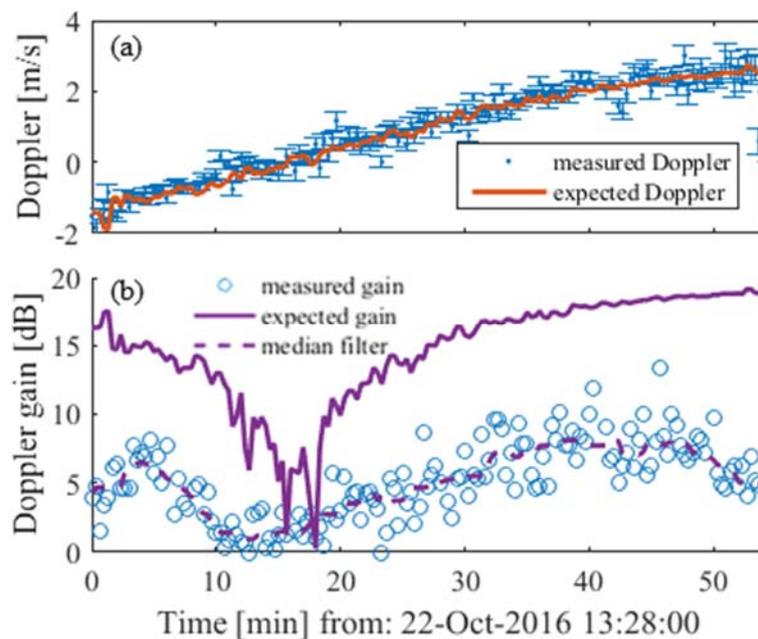

Fig. 5: CAS waveform (a) derivative of bistatic range with respect to time (orange), Doppler speed with peak SRR for each ping (blue), bars are inversely proportional to the echo SRR; (b) expected gain from LFM Doppler processing (solid purple), the measured gain from LFM Doppler processing (blue), and a 5 min long sliding median filter of the measured gain (dashed purple).
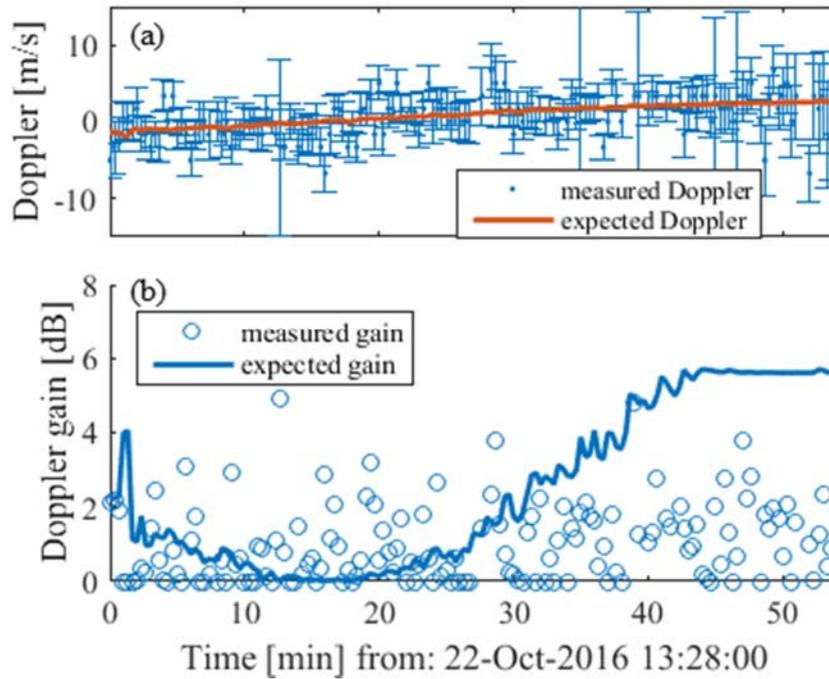
Fig. 6: PAS waveform (a) derivative of bistatic range with respect to time (orange), Doppler speed with peak SRR for each ping (blue), bars are inversely proportional to the echo SRR; (b) expected gain from LFM Doppler processing (blue line) and the measured gain from LFM Doppler processing (blue points).

Fig. 6 shows the same analysis for the PAS pulse. The gain from LFM Doppler processing on PAS is significantly lower than on CAS. As expected, the uncertainty of the Doppler measurement is high enough that the echo return cannot be distinguished from compact clutter within the uncertainty of the measurement.

4. CONCLUSIONS

A LFM pulse with a large TB was experimentally shown to be Doppler sensitive. LFM Doppler processing of echoes from CAS signals was demonstrated to improve matched filter levels by approximately 8 dB at a Doppler speed of 2 m/s. The Doppler estimate provided by the LFM Doppler processing allows for classification when compared to stationary compact clutter and gives additional information to a tracker. Future work involves testing if the Doppler estimates can reduce false alarms and improve tracking.

5. ACKNOWLEDGEMENTS

REFERENCES

[1] **P.C. Hines**, Experimental comparison of continuous active and pulsed active sonars in littoral waters, In *Proc. 1st International Conference and Exhibition on Underwater Acoustics*, Corfu, Greece, pp. 51-58, 2013.

[2] **S.M. Murphy P.C. Hines**, Sub-band processing of continuous active sonar signals in shallow water, In *Oceans 2015 - Genova*, Genova, Italy, pp. 1-4, 2015.

[3] **R. Plate and D. Grimmett**, High Duty Cycle (HDC) sonar processing interval and bandwidth effects for the TREX'13 dataset, In *Oceans 2015 - Genova*, Genova, Italy, pp. 1-10, 2015.

[4] **D. Grimmett**, Target AOU Growth Containment using LFM High Duty Cycle Sonar, In *Proc. Of the 2nd International Conference on Underwater Acoustics*, Rhodes, Greece, pp. 839-846, 2014.

[5] **S.A. Kramer**, Doppler and Acceleration Tolerances of High-Gain, Wideband Linear FM Correlation Sonars, *Proceedings of the IEEE*, 55 (5), pp. 627-636, 1967.

[6] **J. Boersma**, Computation of Fresnel Integrals, *Math. Comp.,* 14, pp. 380, 1960.

[7] **D. Grimmett**, Target Doppler Estimation and Range Bias Compensation Using LFM High Duty Cycle Sonar, In *Proc. Of the 2nd International Conference on Underwater Acoustics*, Rhodes, Greece, pp. 831-838, 2014.

[8] **P.A van Walree**, Propagation and Scattering Effects in Underwater Acoustic Communication Channels, IEEE J. of Oceanic Engineering, 38 (4), pp. 614-631, 2013.