PERFORMANCE ANALYSIS OF CODED WAVEFORM SONAR

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Abstract — A significant property of coded waveforms is their covertness ability under water. In addition to that, coded waveform sonars are resilient against acoustic countermeasure decoys and jammers. Also, these types of sonars provide an infrastructure which can evolve to a sonar sensor network. The advantages of coded waveform sonars increase their popularity in modern sonar systems. The purpose of this study is to analyze coded waveform active sonar performance of a submarine and submarine targets. Different operating frequencies, target ranges and different pulse types like classical continuous wave (CW) and frequency modulation (FM) are utilized during this study. A comparative analysis of coded waveforms is performed for binary phase Barker code and polyphase Frank code. Transmitter, receiver structures and channel modelling are included in the simulations. Deep water scenarios where a submarine is facing against both stationary and high speed targets are considered for this analysis. Multiple sonars operating in a dense environment are found to be useful for the utilization of coded waveform sonars as well as reducing the multipath effects of underwater medium. Finally, Monte Carlo simulation is used to evaluate Coded waveform performance against CW and FM pulses for probability of detection and false alarm rates under different circumstances mentioned above. Hardware requirements and cost effectiveness of coded waveform sonars are examined. Implementation and applicability challenges are also discussed in the conclusion. So, in addition to performance based evaluation, the simulation results are also considered to evaluate if this method is convenient under different circumstances despite the practical difficulties in its implementation.

1 Introduction and History of Active Sonars

The first sonars were single tone CW sonars whose primary goal is to detect range and bearing of a target. The required SNR for long range targets without poor range resolution imposed by long pulses forced development of pulse compression techniques. FM pulses are utilized in sonar system for this purpose. Although FM pulses provide good range resolution, their Doppler performance is not as satisfactory as CW sonar. Since Doppler information is an important tool to characterize and track a target, most systems use CW and FM pulses in a combined fashion. Binary phase coded pseudo random noise (PRN) waveforms like Barker Codes are initially proposed to combine advantages of CW and FM systems. The advantages of Barker codes are their simplicity, but the pulse compression ratio is lower than in the linear FM (LFM) case and the compression is very sensitive to frequency changes due to the Doppler effect for high speed target cases. Polyphase codes like Frank and Zadoff-Chu besides Costas frequency hopped signals are recently introduced which are worth considering in coded waveform sonar systems. AF (Ambiguity functions) of CW, LFM and PRN pulses are theoretically illustrated in Figure 1, where δf_0 is denoted in frequency (1/T) and t is denoted in time (1/ B). Elliptical area constituted by CW pulse enhances Doppler resolution where LFM forms Doppler sensitive slopped elliptical area that is limited within slope mismatch [1]. In theoretical comparison, PRN waveform has lower ambiguity which ensures better resolution.

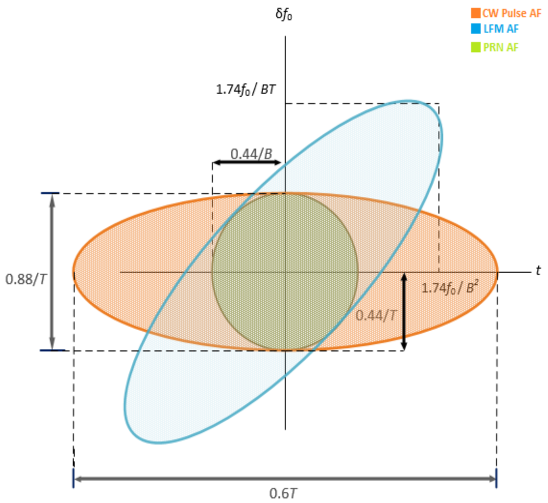

Fig. 1. Ambiguity Function (AF) of CW, FM and PRN waveforms

Due to covertness, resistance against multipath and ability to be used in Code Division Multiple Access (CDMA) underwater networks make phase coded waveforms good candidates for modern sonar systems. However, despite their advantages, phase coded waveforms are not unimodular and the energy has to be normalized so that the power amplifier can properly transmit the signal without distorting [5].

Expanding naval interest in operations in littoral regions has resulted in renewed interest in advanced waveform designs for Low Frequency Active (LFA) sonars. Some other techniques in recent studies propose the following signal structures for LFA sonar [5]:

- Long M-sequences with reduced power
- Hyperbolic FM
- Costas Frequency Hopped Signals
- Costas based signal with LFM sub-pulses
- The cyclic algorithm new (CAN) based signals

The alternatives indicated above, are claimed to provide good Doppler and range resolution simultaneously.

These waveforms also give chance to more advanced receiver designs such as instrumental variables (IV) receiver.

2 Approach and Method

In real systems, transmitter generates the electrical drive signal, amplifies it, and excites the transducer with this signal. Transducer converts the electrical signal at its input into an acoustic one. The acoustic signal propagates out into the medium to the reflecting surface and back. When the transducer receives the reflected signal, it is converted back to electrical form at its terminals. Received electrical signal is pre-amplified, filtered and, digitized at the receiver. Then, match filtering of the received signal with a reference signal, which is the expected received signal from an ideal reflector, is done in processor unit. The transmitted signal is used as the reference [2].

In this study, an end-to-end sonar simulation system is constructed using MATLAB Phased Array System Toolbox. Signal generation, transmitter array model, target model, receiver array model, Doppler matched filter processing and constant false alarm rate (CFAR) detector is constructed in MATLAB while Bellhop Channel model is simulated using Acoustic Toolbox [3].

To execute different case scenarios, target-source and external parameters which are given in Table 1, are used in Sonar Simulation Model.

Table 1. Case Scenario Parameters

	Case 1 *submarine detecting another submarine*	**Case 2** *torpedo detecting a submarine*	**Case 3** *submarine detecting a surface ship*
Target	Submarine	Submarine	Surface Ship
Source	Submarine	Torpedo	Submarine
Target Range	5 km	5 km	4 km
Target Depth	400 m	400 m	10 m
Target Strength	10dB	10dB	10dB
Source Depth	100 m	100 m	500 m
Target Doppler	5 m/s	5 m/s	5 m/s
Conformal Array Radius (source)	2.5 m	0.25 m	2.5 m
Pulse Width	80 ms	80 ms	80 ms
Sound Profile	Munk	Munk	Munk
Ambient Noise	55 dB	50 dB	55 dB
Frequency	8 kHz	20 kHz	8 kHz
Number of Monte Carlo runs	100	100	100

Performance analysis is implemented by Sonar Simulation Model, which is illustrated in Figure 2, consists of:

- Signal generation module which is used for generation of FM, CW and phase coded signals
- Transmitter array for both submarine and torpedo sonars which is modelled as a conformal array
- Bellhop channel model that is used to generate rays for Munk sound profile
- Ambient noise model
- Target models
- Receiver array models which include sensor properties
- Doppler matched filter processing module which produces the maximum instantaneous SNR at its output when filter matches target speed.
- CFAR module that aims to detect targets and eliminates false alarms.

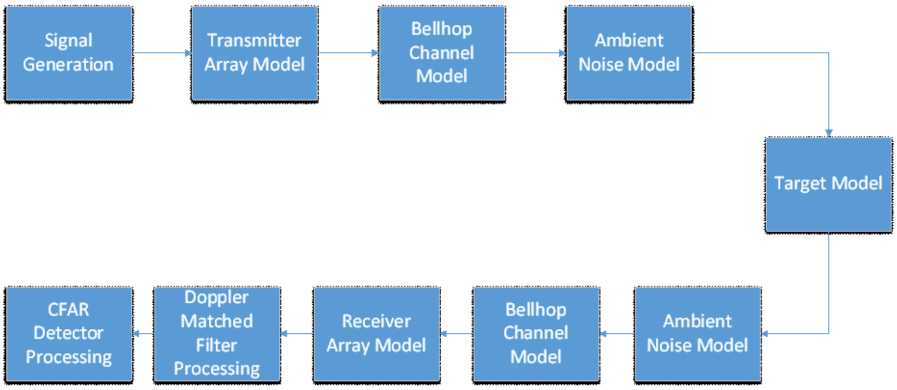

Fig. 2. Sonar Simulation Model

In the simulations for Case 1 (submarine detecting another submarine) and Case 2(torpedo detecting a submarine), Munk Sound profile is used for examination of Bellhop Paths which is illustrated in Figure 3.

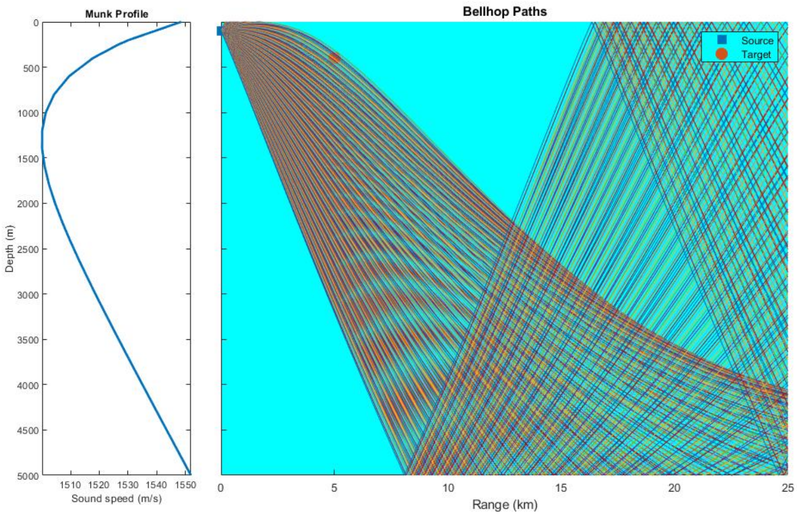

Fig. 3. Bellhop Ray Trace for Case 1 and Case 2

For Case 3 (submarine detecting a surface ship), Bellhop Ray Trace is shown in Figure 4.

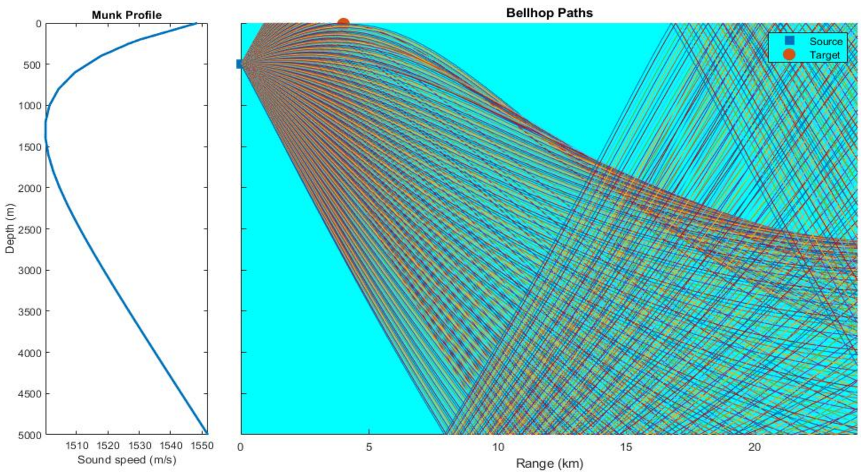

Fig. 4. Bellhop Ray Trace for Case 3

For Case 1, Case 2 and Case 3, the analysis on probability of detection, false alarm rates and Doppler speed error of CW, LFM and coded waveforms (Barker, Frank) are examined respectively in Table 2, Table 3 and Table 4.

Table 2. Case 1: A submarine detecting another submarine.

	CW	LFM	Coded Waveform (Barker)	Coded Waveform (Frank)
Probability of detection	0.99	0.55	0.83	0.98
False alarm rate	5.9×10^{-5}	4.9×10^{-5}	3.8×10^{-4}	4.7×10^{-5}
Doppler Speed Error (m/s)	0.19	2.26	2.13	1.23

Table 3. Case 2: A torpedo detecting a submarine.

	CW	LFM	Coded Waveform (Barker)	Coded Waveform (Frank)
Probability of detection	0.85	0.42	0.61	0.85
False alarm rate	7×10^{-5}	1.1×10^{-4}	6.1×10^{-4}	2.1×10^{-5}
Doppler Speed Error (m/s)	0.08	6.64	4.24	1.1

Table 4. Case 3: A submarine detecting a surface ship.

	CW	LFM	Coded Waveform (Barker)	Coded Waveform (Frank)
Probability of detection	0.44	0.53	0.88	0.98
False alarm rate	9.3×10^{-6}	0	1.9×10^{-5}	1.9×10^{-6}
Doppler Speed Error (m/s)	0.75	1.25	0.67	0.37

The probability of detection statistics and false alarm rate of Frank polyphase coded waveform are generally better than other pulses, which confirms their advantages while Doppler estimation of CW is better in some cases. The maximum length of Barker code is 13, which limits its performance compared to other waveforms like Frank having 16 chips that is a better alternative than CW and FM in some situations. Doppler map plots for CW, FM, Barker and Frank Codes for case 3, a surface ship at 4 km range and 5 m/s speed are shown in respectively Figure 5, Figure 6, Figure 7 and Figure 8.

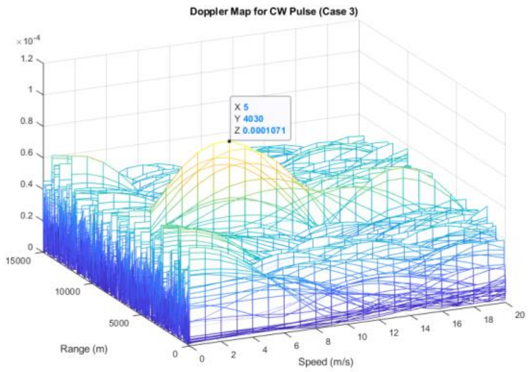

Fig. 5. Doppler Map for CW Pulse

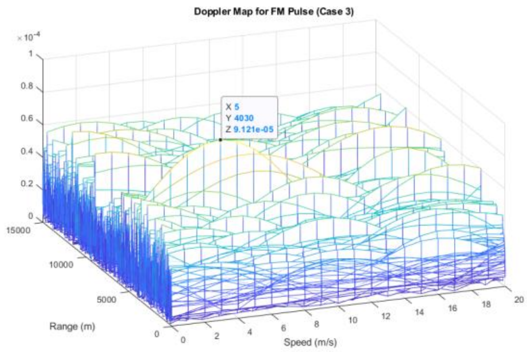

Fig. 6. Doppler Map for FM Pulse

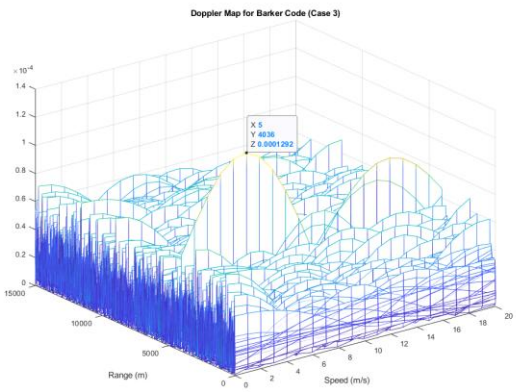

Fig. 7. Doppler Map for Barker Code

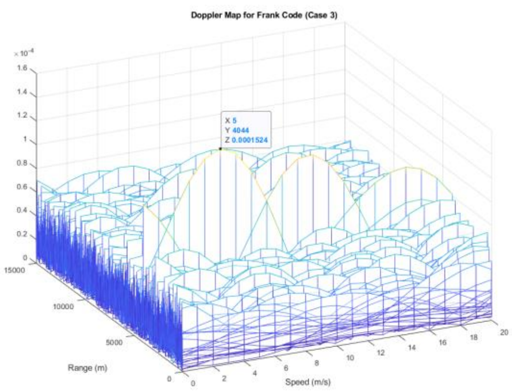

Fig. 8. Doppler Map for Frank Code

As can be seen from the Figure 5 and Figure 6; when FM pulse or CW pulse is used for case 3, high sidelobe levels occur around maximum speed vertical neighbourhood that causes ambiguity in target range for maximum speed, which reduces CFAR algorithm's probability of detection rate.

The AF of the simulations generally exhibit larger sidelobe levels in range and Doppler axis than theoretical values due to multipaths, exposing the need for proper filter design in Doppler processing.

The simulation framework does not model the hardware limitations such as the amplifier responses, the transducer responses and the nonlinearities of electronic components. Therefore the signals in the simulations are assumed to be generated and transmitted without distortion in the context of this study.

The Bellhop Ray Tracing is known to be accurate at high frequencies and deep water environment which is the case for this study. Other methods like normal mode, parabolic equation should be used for satisfactory results for low frequencies and shallow water environment [4].

To summarize [6];

Barker codes (binary codes) have range cut side lobe levels around 1/N which is limited by max code length (where N is the code length) of 13 but they have higher side lobe levels at Doppler cut.

Polyphase coded signals like Frank have high Doppler tolerance and have low peak side lobe levels while the ridge characteristic of ambiguity function of Frank is similar to LFM signals.

Characteristic of the Frank waveform resemble quadratic phase form, which may cause limitation for practical applications having traditional hardware. Thereby, numerous phase shifts in polyphase codes require quadratic modulators and complex signal processors.

Fixed side lobes of Barker waveform cause range cut matched Doppler. However, practical application of Barker is easier than the Frank codes, as (boolean) registers/comparators are used for signal generation.

Moreover, generation of binary phase coded waveform by pseudo random noise (PRN) can be used for longer derived codes ($N = 2^K - 1$, where N is the code length and K is an integer number). Using feedback shift registers, the PRN codes can be generated within the concept of practical implications.

3 Conclusion and Future Work

Phase coded waveforms offer good range resolution and Doppler sensitivity as these qualifications lack for FM pulse.

Considering the analysis results, it is seen that probability of detection with CW and phase coded waveforms are almost %50 percent higher than LFM for the case 'submarine detecting another submarine'. It is observed that false alarm rates are decreased around 6.44 times when CW, LFM and Frank waveforms are used. Comparing the Doppler speed errors, the performance with Frank coded waveform reaches %15 of CW performance when submarine-submarine target-source scenario is evaluated.

Target detection by CW and Frank coded waveforms is consistently same rate for the case 'torpedo detecting a submarine'. Frank coded waveform has a 3.3 times better performance than CW when the false alarm rates are considered. On the other hand, CW performance is 14 times higher than phase coded signals when the Doppler resolution is examined.

In the case 'submarine detecting a surface ship', phase coded waveforms nearly double up the detection rate. In Monte Carlo runs, it is observed that LFM has zero false alarms while Frank coded waveform has 4.8 times better performance than CW. In the comparison of Doppler resolution which is analysed by speed error, phase coded waveforms are seen to have averagely 1.9 times better performance than LFM and CW.

As stated in introduction, waveforms like Costas phase code, hyperbolic FM, long M-sequences with reduced power and CAN based signals are expected to provide satisfactory Doppler and range resolution concurrently which are planned to be included in the forthcoming studies.

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