FREQUENCY HOPPING WAVEFORMS FOR CONTINUOUS ACTIVE SONAR

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ABSTRACT

Due to the relatively low speed of sound long range active sonar has a low update rate compared to radar systems. A possible solution to mitigate this problem is continuous active sonar. The source transmits sound continuously resulting in a continuous return echo. A problem is separating the transmission from the (weaker) returns from the target. This may be accomplished by transmitting very long linear frequency modulated (LFM) chirps so that the transmission and any target return are at different frequencies but this restricts the range resolution of the sonar system. In this paper, frequency hopping pulses are explored as an alternative approach to distinguish between the transmission and a target return.

Index Terms— Sonar, Range ambiguities

1. INTRODUCTION

Long range active sonar systems have a lower update rate than radar systems because the speed of sound is much lower than that of light. A fast moving aircraft (Mach 2) at a range of 15 kilometres can travel less than seven centimetres between radar pulses while a slow moving ship (five knots) at the same range will move more than fifty metres between sonar pulses. The slow update rate causes two problems. Target tracking is more difficult and maintaining contact with a fluctuating target signal is more difficult than it would be otherwise.

A Continuous Active Sonar (CAS) [1] transmits continuously rather than as a sequence of pulses. The continuous transmission will hopefully result in a continuous return from the target. The received signal consists of the sum of the current transmission (very strong), reverberation, ambient noise and possibly an echo from a target. It is necessary to be able to separate the transmission from the echo, requiring that a delayed signal must be distinct from the current signal. One way to do this is to slowly sweep the transmission through the available bandwidth so that the delayed signal is in a different frequency band to the current transmission.

Movements of the sonar platform(s), the target and the ocean medium give rise to spreading of the spectrum of the received waveform. A result of spectral spreading [2] is a loss of temporal coherence. Coherence loss limits the gain that can be achieved by integrating longer and longer signals. In CAS implementations coherence loss requires that the detector attempts to detect relatively short segments of the transmitted signal. Hickman and Krolik [3] note that if we are using a long slow LFM pulse and are forced by coherence considerations to only apply the detector using a small segment, then we are only using a fraction of the bandwidth and lose a substantial portion of the potential range resolution of the sonar. They propose a waveform which involves transmitting a series of FM chirps that are distinguished by different centre frequencies. The sequence of centre frequencies is drawn from a Costas sequence [4]. Limiting the utility of this approach is the need to have sufficient separation of the centre frequencies to distinguish the current transmission from the echo of an earlier chirp.

DeFerrari and Wylie [5] propose the use of an M-sequence coded pulse as the CAS transmission waveform. This pulse has the advantage of approximating the ideal "thumbtack" ambiguity function with little leakage in time or Doppler. A proplem is that because of the coherence behaviour of the ocean described above, it cannot be guaranteed that the ocean will always support the phase coherence needed to use a pulse of this type [6].

The contribution of this paper is to investigate the properties of a class of frequency hopping waveforms for CAS systems. The waveforms achieve high range resolution even when only a small segment is coherently detected by sweeping through the available hop frequencies repeatedly and relying on varying the sequence of the frequencies to prevent interference and range ambiguities. Pecknold *et al* [7] describes a similar idea using different Costas sequences to prevent ambiguities but that is not a CAS system so that the interference between transmission and echo resulting from the high correlation observed between some Costas sequences [8] is not critical since there is no attempt to detect and transmit at the same time.

This paper is organized as follows. Section 2 describes frequency hopping waveforms and the benefits of sequencing the hops using the low auto and cross correlation sequences considered in this paper rather than a Costas sequence. Section 3 presents investigation of the effects of changes to parameters of the proposed waveforms on range resolution and interference between the current transmission and received echoes. Section 4 presents conclusions and areas for future work.

2. FREQUENCY HOPPING WAVEFORMS

In the selection of waveforms for use in sonar systems a frequently chosen objective [4, 5] is a waveform giving high resolution in both range and Doppler. To approximate this goal Costas [4] proposed a frequency hopping waveform of the form

$$s(t) = \sum_{k=0}^{K-1} \mathrm{rect}\left(\frac{t-kT_c}{T_c}\right) \exp(j2\pi[f_c + a_k f_H][t-kT_c]) \tag{1}$$

where a_k is the k-th member of a sequence of integers, T_c is the duration of each hop, f_H is the minimum separation of the hops in frequency, K is the number of hops and

$$\mathrm{rect}(t) = \begin{cases} 1 & 0 \le t < 1 \\ 0 & \text{otherwise} \end{cases}$$

is a window function. An orthogonality constraint

$$f_H = \frac{1}{T_c} \tag{2}$$

is applied to the separation of the hop frequency. The orthogonality constraint forces the ambiguity function of the pulse to be zero whenever the delay is a multiple of the hop period (T_c) while the Doppler shift is a multiple of the hop span (f_H). This constraint tends to supresses the correlation when an echo has a mismatch in either range or Doppler helping to achieve a good approximation to the ideal "thumbtack" ambiguity function.

Using the Costas array to set the sequence of frequencies (via a_k) also contributes to the good ambiguity properties of the Costas Signal [4]. The Costas array is represented as a $K \times K$ matrix with all elements zero with the exception of a one in each row and column. The Costas array has the property that if the matrix is shifted horizontally or vertically then at most one of the ones from the original matrix overlaps a one from the shifted matrix. In the Costas signal the rows of the array represent hop frequencies and the columns hop periods. For a given period (column) the frequency corresponding to the row with a one in it is transmitted. As a result of using the Costas array to select hop frequencies, if a signal experiences a delay and Doppler shift, then at most one hop in a mismatched replica will match the received signal.

The underwater channel has a limited correlation time [2] during which coherent detection of the signal is beneficial. In a CAS system this means that it is only feasible to matched filter using segments of the transmission shorter than a full cycle of the transmission. It is this property that limits the bandwidth (and hence the range resolution) when an LFM chirp is used as the transmission. With a Costas signal correlating against only a small segment means that many (probably most) of the hop frequencies do not contribute to resolving the target. The Costas signal auto-correlation function approximates the ideal (the delta function) because energy is evenly spread over the available band [9]. If required to correlate using only a segment of the signal, the uneven distribution of energies over the band will result in auto-correlation with spurious peaks, reduced resolution or both.

2.1. Hop sequences with low auto and cross correlation

To achieve high resolution the CAS waveform must sweep through the available hop frequencies (and hence use the available bandwidth) in a period less than the correlation time of the channel. At the same time, to achieve a useful range, the signal must not repeat too quickly. If we sweep through the available hop frequencies more than once in the pulse, it is desirable that, for any delay, the number of bursts with the same frequency is minimised. This problem also arises in frequency hop spread spectrum communication systems. The auto correlation of the spreading sequence of the current user should have low autocorrelation when there is any delay in the sequence so that multipath interference is suppressed and it is also important that the correlation between the spreading sequence of the current user and the sequences of other users is low to reduce multiuser interference. Frequency hop sequences optimized to these requirements are known [10]. If there are M frequencies (where M is a power of two) there exist $M+1$ sequences of length $M-1$ where the frequencies from any two of the sequences (regardless of relative delay) can have only one clash where the frequencies match.

3. SIMULATION RESULTS

Two important properties of the waveform are the range resolution (the improvement of which is the objective of this paper) and interference rejection. Interference rejection indicates the ability of a detector to distinguish the current transmission from (weaker) echoes. Good interference rejection requires that a matched filter using a segment from one part of the transmission has a low response to other parts of the transmission. The important parameters of the waveform are the bandwidth of the signal, number of hop frequencies and the burst length. These parameters are not independent since the separation of the hop frequencies depends on the burst length as described in equation 2 and the number of hop frequencies that fit in the available bandwidth depends on the separation of the frequencies. The integration time is the length of the segments used to form the matched filters used for the detection of echoes. It should not be longer than the coherence time of the underwater channel.

Table 1 shows the impact of waveform parameters and integration time on resolution and interference rejection for an ideal channel (without multipath or variability). The integration time has been constrained so that a matched filter includes the full length of a low cross correlation hop sequence. This is the reason for the rather odd values investigated for this parameter. Resolution is measured as the temporal sep-

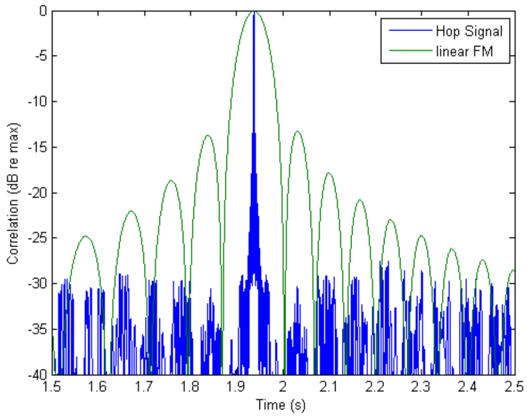

Fig. 1. Comparison of range resolution for Hop signal (blue) and Linear FM (green)

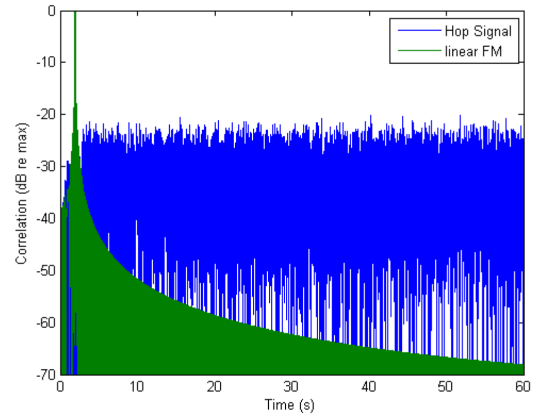

Fig. 2. Comparison of sidelobes for Hop signal (blue) and Linear FM (green)

aration of the peak correlation from the first minimum. Interference level is measured as the ratio of maximum detector output when the detector segment is not in the return to output when the input is perfectly matched.

As expected [11] the delay resolution improved with increased bandwidth. The interference level also decreased when the bandwidth increased. This indicates that the interference level is not just a function of the clashes that occur when the hop frequencies in two different segments coincide or "clash" but also upon the interaction of bursts for delays that are a fraction of a burst length (the orthogonality condition only guarantees zero correlation for delays that are an integer multiple of the burst length). With more bandwidth it is more likely that bursts are well separated in frequency so that interactions are reduced resulting in a lower level of interference.

Increasing the burst length to reduce the required separation of frequency had little impact on the interference level. Increasing the number of frequencies reduced the number of clashes but the increased length of the bursts meant that those clashes that did occur contributed proportionately more energy. A smaller number of serious interactions between closely spaced frequencies was also countered by an increased energy contribution from those interactions that did occur. The results also indicate (as expected) that increasing the integration time reduces the interference level.

It is interesting to compare the behaviour of the frequency hop waveform with the linear frequency modulated (LFM) waveforms usually considered for CAS systems. Figure 1 verifies that the range resolution is improved (range uncertainty is reduced) by using the Hop frequency waveform where both waveforms have a bandwidth of 500 Hz.

The situation with regard to interference from the current transmission is different however. In Figure 2 it can be seen

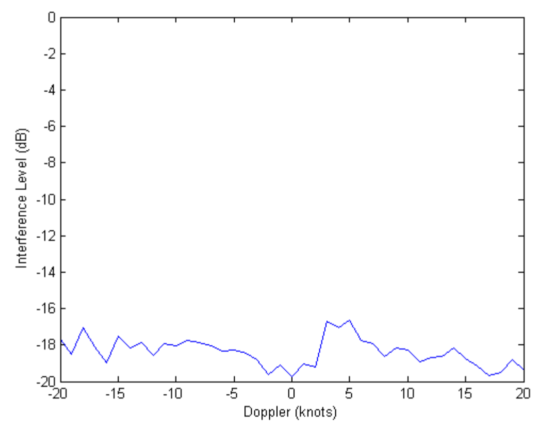

Fig. 3. Doppler sensitivity of interference

that the correlation of the frequency hop waveform with a segment from the start of the waveform does not vary with time while the correlation of an LFM waveform with the segment decreases with time. This means that the ability of the LFM waveform to reject interference will improve for more distant echoes (which will be weaker). More importantly, the LFM waveform has lower correlation at most times so that it will have a better ability to reject interference than the frequency hop waveform.

An issue that might arise is that unlike the Costas codes the optimum sequences used in this work are not guaranteed to have good correlation properties regardless of the effects of Doppler. Therefore it is important to verify that changes in Doppler cause small changes in the interference level. For the case of the 32 Hop sequence with a 5 Khz centre frequency and a 500 Hz bandwidth this is verified in Figure 3.

Bandwidth (Hz)	No. Frequencies	Burst Length (s)	Integration Time (s)	Resolution (s)	Interference Level (dB)
250	16	1/16	3.75	0.004	-17.5
500	32	1/16	3.88	0.002	-21.3
1000	64	1/16	3.94	0.001	-23.2
500	16	1/32	7.97	0.002	-23.0
500	32	1/16	7.75	0.002	-23.2
500	64	1/8	7.88	0.002	-22.0
500	32	1/16	1.93	0.002	-17.9
500	32	1/16	3.88	0.002	-21.3
500	32	1/16	5.81	0.002	-22.4
500	32	1/16	7.75	0.002	-23.2

Table 1. Dependence of resolution and interference level on variation of pulse and detector parameter

4. CONCLUSIONS

The frequency hopping signal exhibits improved range resolution compared to LFM. This improvement in resolution is at the cost of a deterioration in the interference level. The frequency hop waveform also lacks a desirable property the LFM has: for an LFM transmission the interference level from the current transmission decreases as the delay increases so that as an echo becomes weaker it has to compete with less severe interference. The interference experienced by an echo when using the frequency hop waveform is constant with range.

The interference level experienced by the frequency hop waveform can be reduced by increasing the bandwidth of the transmission or the the length of the segment of the waveform used to matched filter for echoes. The length of a transmission that can be used to effectively detect echoes is limited by the environment and the movements of the target vessel and is beyond our control. The system bandwidth can be increased but this will result in increased projector and sensor costs.

Another option that is worth investigation to reduce interference between the current transmission and possible echoes is applying adaptive filtering to suppress the current transmission. This will be investigated further in future work.

5. REFERENCES

[1] Robbert van Vossen, S. Peter Beerens, and Ernest van der Spek, "Anti-submarine warfare with continuously active sonar," *Sea Technology*, pp. 33–35, 2011.

[2] A. G. Voronovich, V. E. Ostashev, and J. A. Colosi, "Temporal coherence of acoustic signals in a fluctuating ocean," *Journal of the Acoustical Society of America*, vol. 129, no. 6, pp. 3590–3597, June 2011.

[3] Granger Hickman and Jeffrey L. Krolik, "Non-recurrant wideband continuous active sonar," in *Oceans 2012*, Hampton Roads, VA, 2012, MTS/IEEE.

[4] John Costas, "A study of a class of detection waveforms having nearly ideal range-doppler ambiguity properties," *Proceedings of the IEEE*, vol. 72, no. 8, pp. 996–1009, August 1984.

[5] Harry DeFerrari and Jennifer Wylie, "Ideal signals and processing for continuous active sonar," in *International Congress on Acoustics 2013 Montreal*. 2013, vol. 19, Proceedings of Meetings on Acoustics, Acoustical Society of America.

[6] Mathieu E. G. D. Colin and S. Peter Beerens, "False-alarm reduction for low-frequency active sonar with BPSK pulses: Experimental results," *IEEE Journal of Oceanic Engineering*, vol. 36, no. 1, pp. 52–59, January 2011.

[7] Sean P. Pecknold, Wayne M. Renaud, Donald R McGaughey, James A. Theriault, and Richard F. Marsden, "Improved active sonar performance using Costas waveforms," *IEEE Journal of Oceanic Engineering*, vol. 34, no. 4, pp. 559–574, October 2009.

[8] David Mark Drumheller and Edward L. Titlebaum, "Cross-correlation properties of algebraically constructed Costas arrays," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 27, no. 1, pp. 2–10, January 1991.

[9] John G. Proakis and Dimitris G. Manolakis, *Digital Signal Processing: Principles, Algorithms and Applications*, Prentice Hall, Upper Saddle River, New Jersey, third edition, 1996.

[10] Cunsheng Ding, Yang Yang, and Xiohu Tang, "Optimal sets of frequency hopping sequences from linear cyclic codes," *IEEE Transactions on Information Theory*, vol. 56, no. 7, pp. 3605–3612, July 2010.

[11] Nadav Levanon and Eli Mozeson, *Radar Signals*, Wiley, Hoboken, New Jersey, 2004.