On the Design of Direct Sequence Spread-Spectrum Signaling for Range Estimation

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Abstract— **Precise range measurement by time-of-flight sonar is important for underwater positioning, oceanography (tomography) and marine geology (geodesy). This paper reports on the design of spread-spectrum codes for range measurement in a variety of important underwater environments. Direct sequence spread-spectrum (DSSS) signal processing has many advantages over continuous wave techniques for time-of-flight range estimation: improved precision, extended effective range, robustness to ambient or jamming noise, increased update rate, and simultaneous multi-user capability.**

Design of appropriate DSSS codes requires matching the code parameters to the acoustic operating environment to maximize system performance. We consider three canonical ocean environments: a laboratory test-tank, the littoral zone, and the deep water channel. The characteristics of these acoustic channel models directly influence the code design to maximize range estimate performance. We parameterize the design choices for DSSS codes by code type, code length, carrier frequency, and chip rate.

The paper concludes with experimental results for spread-spectrum range estimation in a shallow water dynamic environment and on an operation ROV in deep water.

I. Introduction

Precise estimation of spatial range underwater is important for a variety of underwater applications: positioning and navigation (long baseline and short baseline positioning); physical oceanography (tomography); and marine geology (geodesy). Range estimates are typically obtained by observing one-way or two-way acoustic travel times. Since the ocean environment is opaque to most conventional electromagnetic signals, acoustic signals are the preferred method for making range measurements. Acoustic signals are not perfect, however, and are still limited by the dynamics of the underwater channel—specifically multipath and fading [1], [2]. These dynamics depend on the details of the particular ocean environment: water dynamics, sound velocity structure, surface motion and bathymetry. These details can vary greatly from place to place so the ocean cannot be viewed as a ubiquitous environment.

In this paper we focus on spread-spectrum acoustic signaling because of its many advantages: selective addressing, multiple user access, signal hiding, anti-jamming, interference rejection, and high-resolution ranging [3]. Spread-spectrum techniques continue to use the capabilities of acoustic communication [2] and have been applied to navigation applications [4]. One main benefit of spread-spectrum signaling is more energy can be transmitted without sacrificing range resolution—increasing both range and precision simultaneously. With this improvement comes a richer signal design space. Selecting appropriate signal parameters (eg., code-type, code-length, chip-rate (bandwidth), etc.) is not obvious for the acoustic ranging application and requires an understanding of the acoustic channel.

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The goal of this work is to bring knowledge of the variety of acoustic channel characteristics together with the design options of direct sequence spread-spectrum (DSSS) signal processing resulting in a set of guidelines for matching DSSS signals to appropriate acoustic environments. Our practical work using DSSS coding to measure ranges for navigation shows that the DSSS signal processing choices affect the estimation performance. In what follows we offer an explanation for this observation and build design guides for selecting DSSS signals matched to particular acoustic environments. Section II elucidates the background and related work. Section III describes our approach and the models we created to help understand the different ocean environments. Using these models, section IV explains some of our results followed by section V describing some real world experiments and shows how our models compare with real data. Finally section VI gives our results, conclusions—considerations when one is designing a DSSS ranging signal.

II. Background and Closely Related Work

Precise range measurements are perhaps most useful for positioning and navigation. For example, conventional long baseline (LBL) systems require multiple fixed transponders located on the seafloor, mounted to the bottom of ships, or on sea-ice. These networks provide a framework where ranging signals can be used. These networks have a maximum range of 5-10 km and are therefore cover only limited mission areas. Other types of modern ranging networks include short baseline [5] and one-way travel time [6]. The performance of each of these applications is dependent on precise measurement of one-way or two-way acoustic travel times to estimate range.

Ranging and communication in the underwater environment share a common goal: to convey information from one point to another underwater and to do it acoustically. Acoustics are the de-facto standard for transmission of information in the underwater environment due to the physics, large body of knowledge, and practicality of the approach. Much research has taken place for reliable acoustic communications [2], but the problem has still remains open. Advances in the physical understanding and technological understanding of acoustics help not only communications, but also ranging. In fact, time of flight estimation is very closely related to the synchronization problem in digital communications [7]. However, many modern approaches to acoustic communication require a large amount of processing and therefore power and space.

Often in acoustic ranging the system is power limited, space limited, or both, so a simple system is desirable. Many techniques used in communication (rake receivers, decision feedback equalizers, etc.) may not improve ranging performance enough to be practical. However, when designing a ranging system one must still be aware of the difficulties of transmitting an acoustic signal through water. The underwater acoustic channel is spread both in time and frequency. This type of channel is known as a doubly spread channel. The implications of this for ranging are that frequency spreading causes the effective SNR to decrease since some of the energy from the signal pulse is no longer in-band. Time spreading decreases the precision of range measurement since the pulse is spread out in time.

In addition to being doubly spread, there is also a strong multipath effect for many underwater environments. This effect happens when a signal bounces off obstacles, or the sea floor, or the sea surface in addition to the direct path propagation. It is convenient to classify the multipath propagation into two categories: *macro-multipath* and *micro-multipath*. Micro-multipath is caused by small perturbations in the water column, rough obstacles that have many reflections of the same signal, and small waves on the surface. Micro-multipath is generally non-resolvable and exhibits itself as spreading of the signal. Macro-multipath, conversely is caused by reflections off of large object objects such as large rocks, big waves, or aquatic life. This type of multi-path is resolvable if the chip rate in the DSSS signal is sufficiently high. Methods for combating this in communications include rake-receivers and equalizers, which add significantly to system complexity.

The environments which one wants to perform ranging in the ocean are diverse. The deep ocean environment is the quietest and easiest to model since there are often no bottom or surface bounce multipaths, and the water is fairly still so the channel is very stable. The shallow water environment is much more dynamic and the surface bounces add randomness due to wind, wave, and bubble effects. The tank environment, while very convenient for experiments, has a strong macro-multipath effect, but very little in the way of micro-multipath. Therefore, as in communication, the shallow water environment is the most challenging since it is the most dynamic.

The use of direct sequence spread spectrum (DSSS) ranging codes combat many of the problems imposed by multipath and phase coherence of the channel. DSSS codes have been studied thoroughly in the literature and the properties of the codes, such as their autocorrelation and cross-correlation properties, are well known [8]. These codes provide good noise rejection properties, allow for more energy to be sent without loss of precision, and provide the opportunity for multiple users to send ranging signals simultaneously. Research on acoustic communications for the underwater channel is closely related to the problem of precise time-of-flight detection, but the signal processing requirements are sufficiently different to require separate consideration. For the reasons already stated above, spread spectrum (both direct sequence and frequency hopping techniques) have proven successful for underwater communication [2].

III. Approach

The central question of this investigation is how to design DSSS codes for a set of acoustic channels with disparate dynamics. Our approach to this problem is to build a simulation framework for quickly testing a variety of DSSS codes with simplified acoustic channel models, matching the salient dynamics of each model to the particular DSSS design choices. Based on this analysis we implement a subset of these codes in a real ocean environment, testing the validity of our theoretical results.

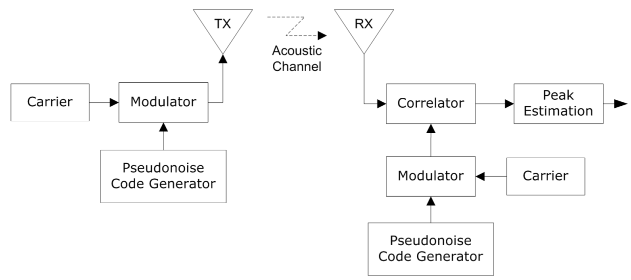

Fig. 1. Flowchart of range estimation using pseudonoise (PN) codes. The output, an estimate of the autocorrelation peak, is used to estimate the time of arrival and then the range between transmitter (TX) and receiver (RX). Carrier modulation is typically done using binary phase shift key (BPSK) modulation. This paper explores the association between the acoustic channel and the code characteristics.

A. Assumptions

We make simplifying assumptions to preserve tractability of the problem and maintain generality of the results. First we concentrate on direct sequence spread spectrum signaling and the associated code design. We do not consider frequency-hopped spread-spectrum (FHSS) or Chirp signaling. We assume binary phase-shift key (BPSK) modulation in our simulations. We do not explicitly consider absorption in the channel; this characteristic is captured by the signal to noise ratio in the various channel models. We also assume that the ranging system is implemented using general purpose digital hardware. This allows for peak detection at the receiver rather than threshold detection—increasing the available precision. We also use coherent detection rather than demodulation and baseband detection. In practice the phase stability of the channel has supported this method for implementation. These assumptions are not limiting, but rather allow us to focus on the central question of matching code design parameters to channel dynamics.

B. Channel Model Implementation

To explore DSSS signal design space we examine the performance of a variety of code designs using archetypical acoustic channel models for the underwater environment. The following sections start with a simple additive white Gaussian noise (AWGN) model and incrementally examine how multipath dynamics affect the code design choices and system performance. The channel models we use to explore the design space are not meant to exactly reproduce particular environment, but are instead archetypes for classes of important underwater environments.

We model the structure of the channel with time varying multipath. The impulse response of the channel with K paths at time t is

$$g(t) = \sum_{k=1}^{K} c_k(\tau_k, t) + \omega(t) \quad (1)$$

where τ_k is the multipath delay for each path k and $\omega(t)$ is additive Gaussian process noise. Note that the amplitude of each path is time varying to capture the fading characteristic of the channel.

A key determinant of performance is the signal to noise ratio (SNR). In this context SNR is the ratio of energy per code (E_c) and the power spectral density of the Gaussian process noise.

$$\text{SNR} = \frac{E_c}{N_\omega} \quad (2)$$

C. DSSS Codes

Much research had gone into the properties of DSSS codes and their associated performance for various applications [7], [8]. Here we describe the important characteristics of the standard codes we will investigate in simulation and experiment.

1) Barker Codes: The autocorrelation properties define the members of the Barker code family. The absolute value of the autocorrelation is less than 1 except for the zero shift, providing excellent process gain and low side-lobe interference. The lengths of known Barker sequences are $N = 2, 3, 4, 5, 7, 11$, and 13 and it is conjectured that there are no Barker codes longer than 13. These code sequences are commonly used for RADAR pulse compression and frame synchronization in digital communication systems. These codes are not useful for multi-user environments where cross-correlation properties are important.

2) Maximal Sequences: These sequences are so named because they are the maximal length sequence that can be generated by a shift register of a certain length. For instance, if a shift register is of length 4, the maximum number of outputs it can have before it starts repeating is 15. If one considers the possible states of the shift register, it is possible to see that, excluding the all zero state, that there are $2^n - 1$ possible states, where n is the length of the shift register, after which the states start to repeat.

The autocorrelation of the repeated m-sequence is -1, except when aligned. However, for ranging, it is not practical to use a periodic sequence, so the m-sequence is truncated, either to one period with some additional cyclic padding. The autocorrelation properties of the truncated m-sequence are still quite good, but the cross correlation is still not useful in general for multi-user ranging.

3) Gold and Kasami Codes: Gold codes and Kasami codes are both derived from m-sequences. These codes have bounded cross-correlation and thus are very useful for multi-user ranging. current GPS system uses Gold codes. Gold codes are formed by taking two specific m-sequences, called preferred sequences, which have only three values for their periodic cross correlation. Combining one m-sequence with all n shifts other using modulo two addition we arrive at the set of Gold codes.

Kasami codes are formed by taking an m-sequence and decimating it by taking every $2^{m/2} + 1$ bit from the periodic sequence, called decimating by $2^{m/2}+1$. Combining the cyclic decimated sequence with all shifts of the original, we create a set of n sequences with excellent cross-correlation properties. These codes meet the Walsh bound for cross correlation.

D. Performance Metric - RMS Precision

To enable performance comparisons between disparate code designs we propose a precision performance metric to summarize the capability of a particular code design for a particular channel. We estimate the time of arrival via simple peak detection—finding the absolute maximum value for the matched filter output. The precision of this peak detection is equivalent to the timing precision for range estimation. In what follows we look at the *RMS Precision* by calculating the RMS error between the autocorrelation peak and the known arrival time. This error metric is calculated via a Monte Carlo method where each detection simulation is run multiply times (typically 100 trials). The RMS Precision is then measured with units of code chips as the normalized RMS error for all trials.

IV. Performance Analysis - Numerical Examples

In this section we illustrate the predicted performance of a variety of DSSS codes in three disparate underwater acoustic channel models. Each model illustrates an important characteristic for how to design DSSS signals for precise range estimation.

For the purpose of comparison all the codes are implemented using the same carrier frequency (12 kHz), chip rate (4kHz or 3 cycles per chip) and sampling frequency (48 kHz). Other cases were considered to show the following results are insensitive to these parameter choices.

A. Additive White Gaussian White Noise Channel The Deep-Sea

This first archetypical acoustic environment we examine is the additive white Gaussian noise (AWGN) channel. This simplified channel is simply propagation delay (a single path) with white noise—in equation (1) $c_1 = 1.0$ and $c_k = 0 \; \forall \, k \geq 1$. The closest natural analog to this simple model is the deep-sea channel with little or no multipath and a known, deterministic impulse response.

For this channel signal to noise ratio is the critical signal parameter for determining ranging performance. In the context of DSSS signal design, using longer codes (increasing the spreading ratio) adds process gain to the system, increasing the range and preserving the precision of the range estimate. Figure 4 illustrates this conclusion. Considering a variety of codes and code lengths (3-127 chips) we examine how process gain for codes of increasing length improves the precision performance for lower signal to noise ratios. Equivalently

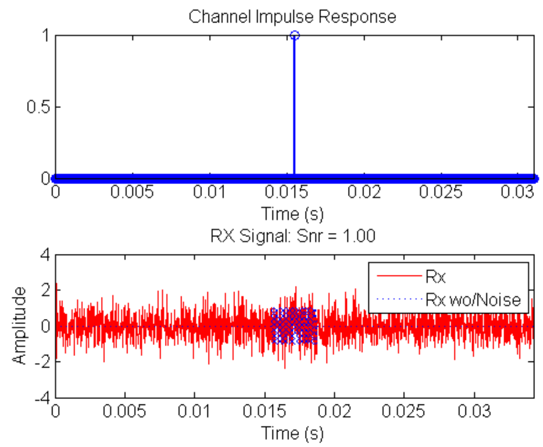

Fig. 2. Illustration of the AWGN channel response with SNR = 1.0. Note that the transmitted code is barely recognizable in the lower subplot due to the large additive noise component.

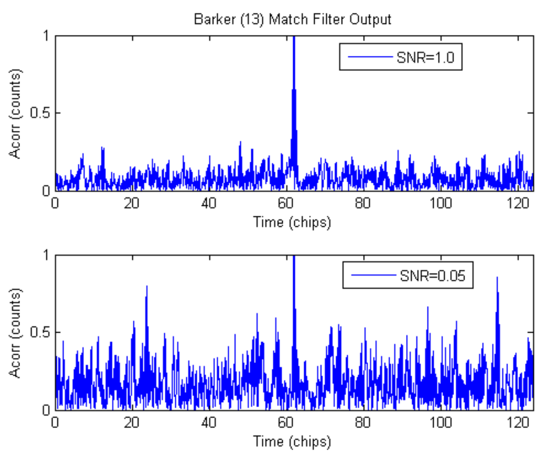

Fig. 3. Matched filter output for peak detection and time-of-flight estimation. The simple AWGN channel model is applied with two different SNRs: 1.0 in the upper plot and 0.005 in the lower plot. This figure clearly illustrates the power of process gain to allow detection when SNR ¡ 1.0.

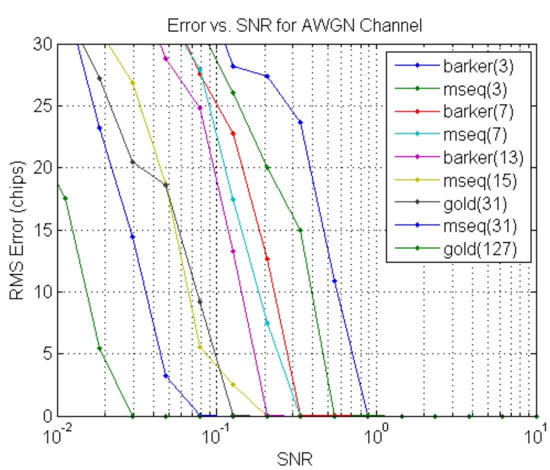

Fig. 4. Time of flight precision as a function of the SNR for the AWGN channel model.

we can conclude that the longer the code the better the performance when considering the AWGN channel. In what follows we will see how other properties of the channel limit the length of the code.

This result illustrates the notion of process gain—the added effective signal to noise ratio gained by increasing the spreading rate with longer codes. For DSSS signals the process gain is directly proportional to the code length [3].

$$\mathrm{PG} = 0.88 \left(\frac{BW_{DSSS}}{R_{info}} \right) = 0.88(\mathrm{CodeLength}) \quad (3)$$

B. Static Multipath Channel—Enclosed Environments

The next archetypical acoustic environment we examine considers a single static multipath defined by the impulse response—in equation 1 $c_1 = 1.0$, $c_2 = C$ and $c_k = 0 \; \forall \, k \geq 2$. The coefficients for the direct path (c_1) and the multipath (c_2) are both constant. This simple multipath environment allows us to examine the relationship between the code characteristics and the multipath delta (τ - the temporal difference between the direct path and the multipath measured in chips).

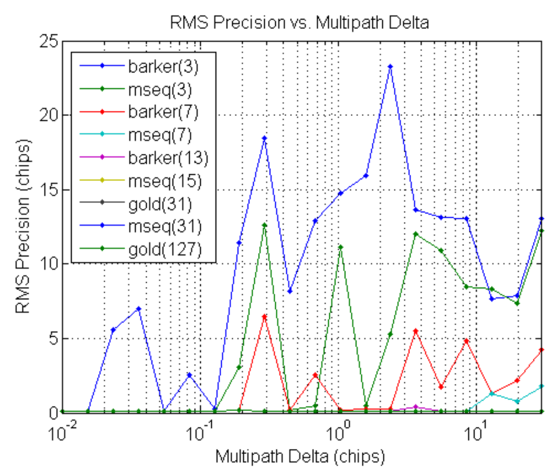

Fig. 5. Time of flight precision as a function of the multipath delta (τ). The multipath amplitude is half of the direct path ($c_1 = 1.0$ and $c_2 = 0.5$).

Figure 5 illustrates the utility of spread-spectrum signal processing to resolve various multipaths when amplitude of the direct path is larger than the multipath amplitudes. Despite the fact that the code durations are much longer than the multipath delay, the autocorrelation properties of the DSSS codes prevent the multipath from eroding system precision. The longer codes perform much better for delays between a fraction of a chip length and up to 30 chips—showing almost no degradation of precision. The shorter codes (Barker(3), Mseq(3) and Barker(7)) do exhibit decreased performance in this simple multipath environment.

Figure 6 illustrates how the performance changes if the first return is no longer the dominant path. In this case the direct path and multipath have equivalent amplitudes ($c_1 = c_2 = 1.0$). Two phenomena are evident. First, in general as the multipath delay increases the RMS precision value increases linearly. This is due to the peak detection method of time-of-arrival estimation. Since the two paths have equal amplitude they are equally likely to be selected by the peak detection. Second, we see a similar result for the shorter length codes (Barker(3), Mseq(3) and Barker(7)) which demonstrate a large decrease in performance for disparate paths with only small delays (less than 1 chip).

C. Summary of Numerical Examples

For the two examples shown above longer codes increase the performance. In the presence of noise, the process gain from long codes improves the effective signal to noise ratio. These long codes are impervious to small, static multipath channels because of the autocorrelation properties of DSSS codes, therefore the designer is free to use long codes in high multipath environments.

V. Experimental Evidence

A. Harbor Channel

To have a representative shallow water environment, we performed experiments from the WHOI pier. The transmitter and the receiver were approximately 30m apart and both approximately mid-water column in 15m of water. The transmitter was a Benthos AT12-ET transducer powered by a Kenwood amplifier. The receiver was an array of 4 hydrophones, only one of which was used for receiving. The signals were played and recorded using an Alesis HD24 ADAT recorder and all signals were created and analyzed using MATLAB. The dock is a large concrete dock into the Woods Hole harbor, which has heavy boating traffic, and so the signal level was set to maximum to always have enough SNR (approx. 20 dB) for signal processing.

For the Harbor channel experiments we sent a variety of code lengths, from a one chip ping to a 1023-chip Gold sequence. This wide range of code lengths allowed us to explore the effect code length had on ranging for a shallow water channel. examining figure 8, we see that longer codes help with multipath and give us better immunity to errors. The longer codes appear to drastically reduce the interference from multipath and increase the signal to noise ratio. Using an LMS filter we were able to infer the channel impulse response from the data, which is shown in figure 7. this agrees with our early assessment, based on theoretical and numerical results, that longer codes give better noise and multipath immunity.

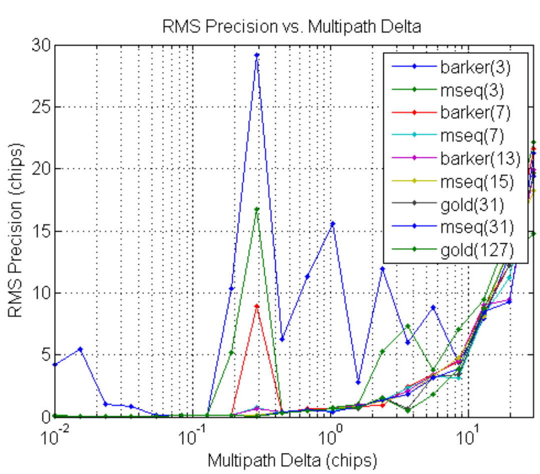

Fig. 6. Time of flight precision as a function of the multipath delta. Compare this figure with figure 5. Here the fact that both static paths have equivalent amplitudes ($c_1 = c_2 = 1.0$) has a dramatic effect on the detection precision using peak detection relative to the case shown in figure 5 where the direct path has the highest amplitude.

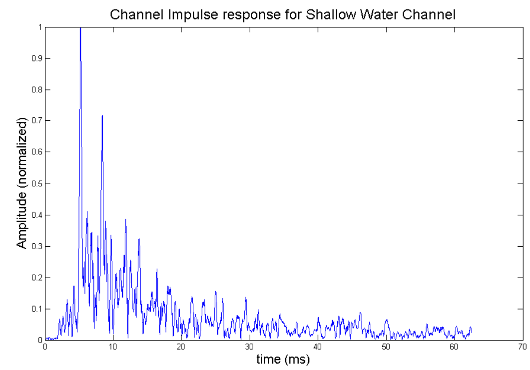

Fig. 7. Derived impulse response using least mean square filtering. The channel is the water immediately surrounding the Woods Hole Oceanographic Institute dock in Woods hole, MA. This channel is used for all experimental data taken for the shallow water channel.

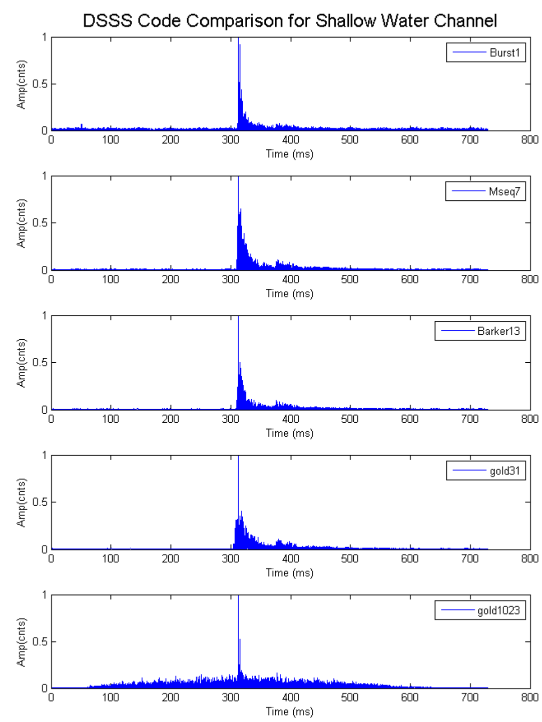

Fig. 8. Correlation response for a variety of codes in a shallow water channel. The codes are (a) one chip pulse for estimate of channel impulse response. (b) 7-chip M-sequence (c) 13-chip barker code (d) 31-chip Gold Sequence and (e) 1023-chip Gold Sequence. All codes were sent from a transducer to a 4-element hydrophone with a 12kHz carrier, 4kHz chip rate, and 48 sampling frequency.

B. High Frequency Ranging in Deep Water

Another set of experiments were performed in a very different environment. We tested the short-range deep-water acoustic channel by transmitting individual codes between two ROVs, Jason and Medea, using a short baseline relative positioning system—Sharps [9]. Again, a variety of codes were transmitted, varying from a 1 chip burst to a 31 chip Gold code. The chip time for each code is 20 μs. Each code is used to BPSK modulate a 100 kHz carrier signal and sampled at 500 kHz.

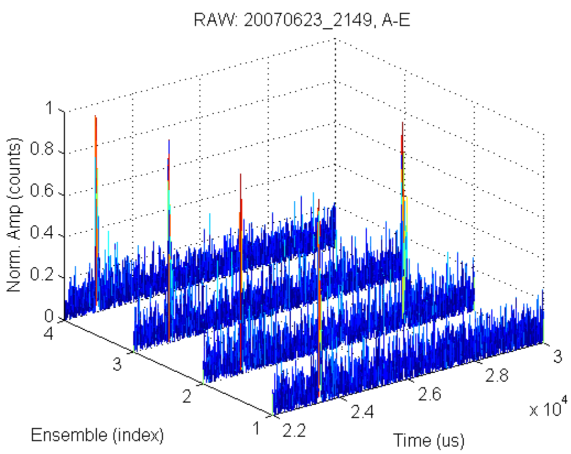

Fig. 9. Waterfall plot for multiple instances of the raw A/D output for 100 kHz pulse of 27 μs duration. Each of the four instances is taken with a 12 second delay. Despite the consistency of the first arrival there is an intermittent multipath evident in the second instance.

To estimate the impulse response of the channel we transmit a one chip pulse. The results are shown in figure **??**. The SNR for the first arrival is approximately 14 dB. In the second ensemble an intermittent multipath is evident, delayed from the first response by approximately 2 ms and with roughly the same amplitude as the direct path.

Figure 10 illustrates a result observed in practice when using DSSS codes for precision ranging. Despite the prediction from simple, deterministic channel models, there is a physical limit on the length of DSSS codes to preserve precision in the time-of-flight range estimation. As the length of the codes are increase, we add more process gain to the system effectively increasing the SNR. However, for this experiment, as the codes get longer (eg., 28-31 chips) the matched filter output begins to spread out in time leading to a degradation of the ranging precision. This result is not predicted by simple static models which indicate that there is channel-based upper bound on the length of DSSS codes used for timing and that the longer the code the better performance. In practice, the authors have found that a good compromise is reached for this system with the 13 chip Barker code, balancing the process gain of spreading the signal with the channel effect of distorting longer codes.

We suspect that this is because of a lack of phase coherence in the channel - effectively causing fading on scales commensurate with the code transmit time. This fading constrains the practical code length for a given application.

VI. Results and Conclusions

The results of the analysis, simulations and experiments presented here are perhaps not surprising—range estimation can be enhanced by using long DSSS codes with good autocorrelation properties. In particular our experiments led to the conclusion that the 1024 chip Gold code provides very good performance in a challenging harbor environment despite high multipath and fast fading in the channel. The more subtle point of this article is the presentation of a framework for considering the design tradeoffs in designing DSSS signals matched for performance in particular acoustic channels. In practice there are constraints not fully captured by our simplified model. Memory and processing are always finite, there is a need for high update rate measurements and the underwater channel is always more challenging than our models. As a whole these results show not only that longer codes increase process gain and thus performance (more is better), but also quantify the sensitivity of range precision to DSSS signal design choices. As such, these results can be

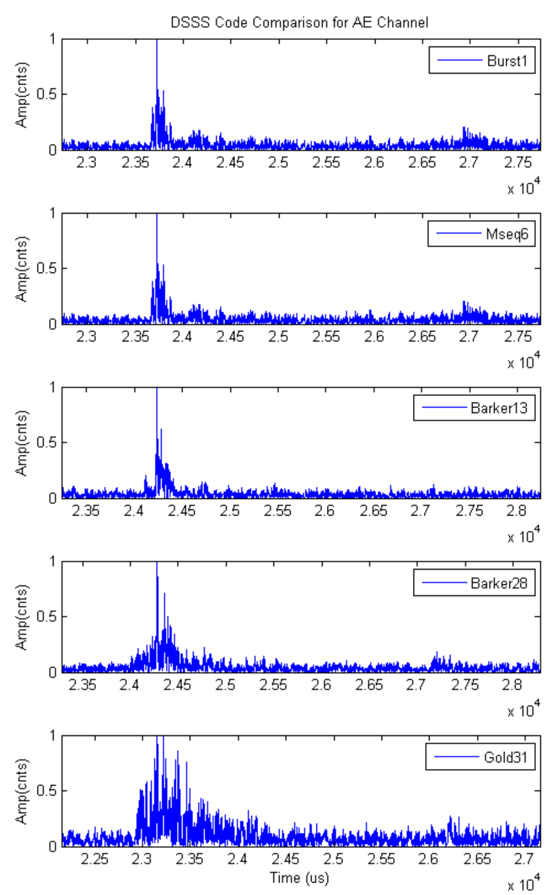

Fig. 10. Matched filter output for 5 different DSSS codes transmitted over the short deep-water channel A-E (between two ROV's). Note how the codes of increasing length spread the correlator output over a larger time envelope - decreasing the effective signal to noise ratio for time-of-flight estimation. This result is contrary to the prediction using simple models.

used by the system designer, in conjunction with the overall constraints, to make informed choices for improved acoustic ranging performance.

A. Future Work

The results from the deep water, showing that there is a channel-based limit to the length of the DSSS codes used for ranging, contrast with the predictions from the simple multipath models presented here. The authors speculate that this is an effective the lack of phase coherence in this particular channel. One method for explaining this observation would be to develop more thorough channel models, emulating the dynamics of this particular channel, to determine how best to understand and design for these conditions.

VII. Acknowledgments

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