Incoherent pulse compression in laser range finder

Daniel Grodensky[a], Daniel Kravitz[a], Nadav Arbel[a], Nadav Levanon[b], and Avi Zadok[a*],
[a]Faculty of Engineering, Bar-Ilan University, Ramat-Gan 5290002, Israel
[b]Faculty of Engineering, Tel-Aviv University, Tel-Aviv 6997801, Israel

ABSTRACT

Laser ranging measurements using incoherent pulse compression of complementary code pairs is reported. The two bipolar codes are converted to unipolar representations using a pulse position modulation algorithm, and used in succession in intensity modulation of a laser ranging source. Reflected echoes from a wall target are directly and incoherently detected. The cross-correlation between each of the two collected echoes and its respective, reference bipolar sequence, that is digitally stored at the receiver, is calculated. The two correlation functions are then added together. The off-peak aperiodic correlation functions of two codes sum up to zero, hence they are particularly suitable for low-sidelobe radar and laser ranging and detection systems. The scheme does not require the preservation of phase information in transmission or reception and provides superior sidelobe suppression compared with that of longer single codes. The code pairs are scalable to arbitrary lengths through simple procedures. Simulated and experimental ranging measurements in the presence of additive noise are discussed. The distance to the target could be recovered based on weak collected echoes, with an average optical power as low as 2 nW, without averaging over repeating measurements.

Keywords: Complementary code pairs, LADAR, Matched filtering, Optical signal processing, Pulse compression, Laser ranging.

1. INTRODUCTION

High resolution ranging systems are of great importance for both civilian and military applications. Both radio frequency (RF) waveforms and optical waveforms (in laser detection and ranging, or LADAR) are used for range detection purposes. Use of each spectral range has its advantages and drawbacks. While radars are less sensitive to alignment and atmospheric disturbance, optical waveforms can carry broader bandwidth signals and thus give better range resolution, are inherently immune to electromagnetic interference, and are readily integrated with fiber-optic distribution. In both techniques, high range resolution can be obtained using short and intense pulses. However, the transmission and processing of such pulses is difficult and potentially unsafe. In addition, the overall signal energy falls off with the use of short pulses, and the signal to noise ratio (SNR) is thus degraded. Instead, temporally extended waveforms or sequences, in conjunction with proper compression techniques at the receiver end, may be used. The autocorrelation, or matched-filtering, of carefully-constructed long sequences effectively compresses their entire energy into an intense and narrow virtual peak with low residual sidelobes[1]. Such sequences may therefore reproduce the high resolution and low background that are provided by a short and high-power single pulse, with significant added values: The instantaneous power of coded sequences can be orders-of-magnitude lower, making them safer and simpler to generate in a real-world system and more difficult to intercept by an adversary[2].

In most scenarios, effective compression requires phase coding, whereas intensity coding leads to inferior performance[1]. The overheads associated with coherent transmit/receive in RF and microwave-frequencies systems are relatively modest. Coherent detection in the optical domain is more troublesome, since the current that is directly provided by a photo-detector is phase insensitive. Although coherent optical receivers using interferometric techniques are widely known, they come at the expense of significant complexity[3]. Alternatively, we have recently proposed and demonstrated a novel incoherent compression scheme, in which binary phase sequences are converted to a unipolar, intensity modulation representation through a position-coding algorithm, and then used to modulate the intensity of a laser ranging source[4-6]. Reflected echoes undergo simple direct detection, followed by correlation with a bipolar reference sequence that is digitally stored at the receiver. With the exception of the two time slots immediately adjacent to the main lobe, the sidelobes suppression in the incoherently compressed unipolar representation matches that of the original bipolar code[4-5].

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[*] Avinoam.Zadok@biu.ac.il Tel.: +972-3-5318882; Fax: +972-3-7384051.

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Two classes of phase codes were employed in laser ranging experiments based on incoherent pulse compression. In a first set of measurements, the binary unipolar sequence used was generated from a bipolar, minimum peak sidelobe (MPSL) code that was 1112 bits long[5]. The ratio of main lobe peak power to the power of the highest sidelobe (PSLR) in the experiments was 33 dB, in agreement with predictions. A spatial accuracy of 2.5 cm was demonstrated. Incoherent compression was successfully carried out in the presence of additive noise, at SNR values as low as -20 dB[5].

The further suppression of sidelobes would require longer MPSL sequences. However, the search for such codes is a daunting task. Alternatively, in a second set of experiments we have demonstrated the incoherent pulse compression of a pair of complementary codes[6]. The auto-correlation sidelobes of one code are equal in magnitude to those of the other code, albeit with an opposite sign[7]. Adding the matched-filtered forms of the two codes together, therefore, reduces the sidelobe power drastically[8]. Unlike MPSL sequences, the length of complementary code pairs is scalable through several simple procedures[9]. Here too, incoherent compression was successfully preformed in the presence of additive noise at SNR values of -20 dB[6].

In the following, we elaborate on both the numerical simulations and the experimental demonstrations of incoherent pulse compression of complementary code pairs. Calculations of the compressed forms a of 416 bits-long code pair are provided, in the presence of additive noise of different SNR levels. In addition, while our previous experiment demonstrated the compression principle[6], it nevertheless relied on a reflection form a retro reflector placed in front of the ranging transmitter. Here we report the successful incoherent compression of code-pair echoes that are collected from a realistic Lambertian reflecting target, which further substantiate the applicability of the proposed technique.

2. SIMULATIONS OF INCOHERENT PULSE COMPRESSION OF COMPLEMENTARY CODE PAIRS

The principle of incoherent pulse compression was presented at length in our earlier works[4-6], and it is reiterated here only briefly. Consider a bipolar code of length N: $c[n]$, where $n=1\ldots N$. A unipolar code of length $2N$ is generated based on $c[n]$ through pulse position modulation: if $c[n]=1$, then $T[2n-1]=1$ and $T[2n]=0$. For $c[n]=-1$, $T[2n-1]=0$ and $T[2n]=1$ are chosen instead. This procedure resembles the Manchester coding known in telecommunications. The code T is used to modulate the intensity of a laser range-finder light source. A bipolar matched filtering sequence R of length $2N$ is constructed in a similar manner: $R[k]$ is set to 1 if $T[k]=1$ and equals -1 if $T[k]=0$, $k=1\ldots 2N$. The code R is digitally stored at the receiver for post-detection processing.

A complementary pair of sequences satisfies the property that their out-of-phase a-periodic autocorrelation coefficients sum to zero[7]. The ideal zero-sidelobes correlation property of the complementary pair is nearly preserved by the Manchester encoding, with a peak-to-sidelobe ratio (PSLR) of $1/(2N)$ instead of zero where N is the length of each code in the pair[8]. In contrast to MPSL sequences, the construction of long complementary pairs is relatively simple. The codes used herein are derived from the following, 26 bits-long primitive pair: **a** = [++++-++--+-+-+--+-+++--+++], and **b** = [++++-++--+-+++++-+---++---]. The length of the codes are extended using the following construction rule: {**c**, **d**} = {cat(**a**, **b**), cat(**a**, -**b**)}, where cat(**a**, **b**) stands for the concatenation of the two sequences **a** and **b**. The construction rule was applied four times for the generation of a pair of 416 bits-long codes. A detailed description of the presently known construction rules was recently given[9].

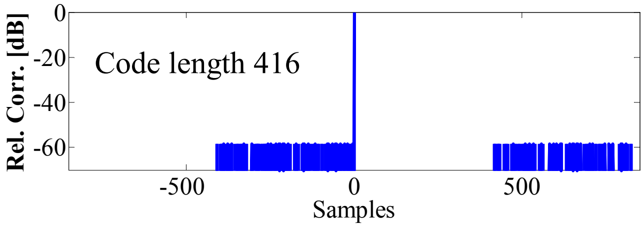

Figure 1: Calculated, incoherently compressed forms of a complementary code pair, added together to obtain a narrow virtual peak with strongly suppressed sidelobes[6]. The length of each code in the pair was 416 bits. Calculations were carried out for zero additive noise.

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Figure 1 shows the calculated incoherently compressed forms of the pair of complementary codes added together[6]. The PSLR of the incoherently compressed noise-free code pair is 58 dB, in agreement with expectation[8]. The PSLR of the incoherently compressed code pair is degraded by additive noise. Figure 2 shows the calculated incoherently compressed forms of the same code pair of Figure 1, in the presence of additive noise with SNR values of +20 dB, 0 dB and -20 dB. The calculated PSLR values are 46.7 dB, 25.7 dB and 8 dB, respectively.

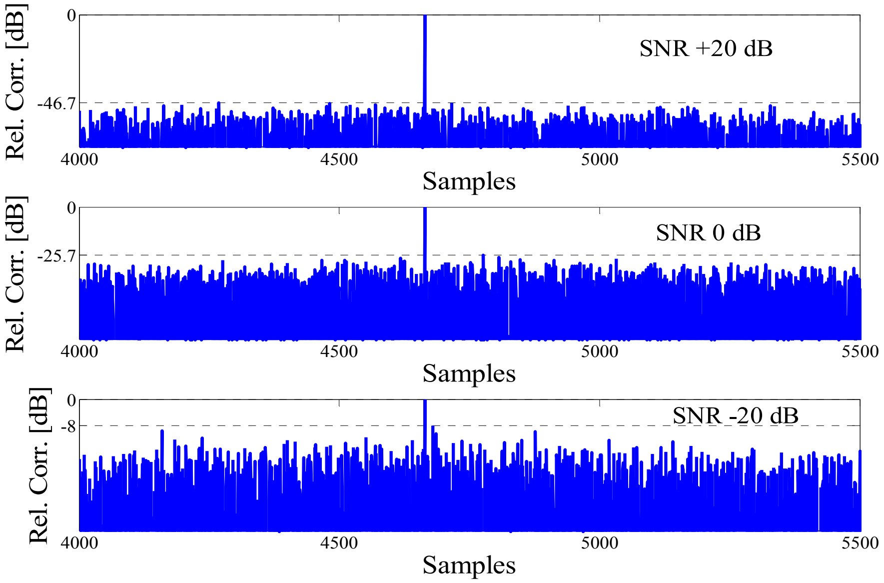

Figure 2: Calculated, incoherently compressed forms of a complementary code pair added together, in the presence of additive noise. The length of each code in the pair was 416 bits. The signal to noise ratios of the simulated sequences were +20 dB (top), 0 dB (center), and -20 dB (bottom). The calculated PSLR values are 46.7 dB, 25.7 dB and 8 dB, respectively.

3. EPXERIMENTAL SETUP AND RESULTS

The experimental setup for laser ranging measurements using the incoherent compression of a complementary code pair is shown in Figure 3. Light from a laser diode at 1550 nm wavelength passed through a Mach-Zehnder electro-optic intensity modulator (MZM), driven by an arbitrary waveform generator programmed to the transmission of the code pair. The coding symbol duration was 1 ns, corresponding to an expected spatial resolution on the order of 15 cm. The 416 bits-long codes used in the experiment were the same as those of the simulations in Figures 1 and 2. The codes were repeatedly transmitted every 10 μs. The modulated waveform was amplified by an erbium-doped fiber amplifier (EDFA) to an average output power of +20 dBm, and launched towards a white wall through a collimating og 2" diameter and a focal length of 150 mm. The distance to the wall was 8 m, and its relative power reflectivity was 0.07.

Reflections from the wall were partially collected by a telescope mirror of 20 cm diameter into a multimode fiber with a core diameter of 200 μm, and detected by an InGaAs avalanche photo diode (APD). The bandwidth of the APD was 1 GHz, and its noise-equivalent power level (NEP) was -42 dBm. The output of the APD was sampled by a real-time digitizing oscilloscope of 6 GHz bandwidth, and the detected sequences were incoherently compressed through digital match-filtering of both codes, using the corresponding bipolar reference sequences as described in the previous section. The cross-correlation of the two codes were then added together to obtain a ranging measurement with low sidelobes.

The average optical power of the collected reflection echoes was -41 dBm, representing an estimated SNR of +1 dB. The collected power is approximately 10 dB lower than expected, due to alignment difficulties and transmission losses at the telescope mirror. The reflective coating on the mirror surface was designed for visible light, and not intended for use at telecommunication wavelengths. The measurement SNR could be lowered through reducing the output power of the EDFA.

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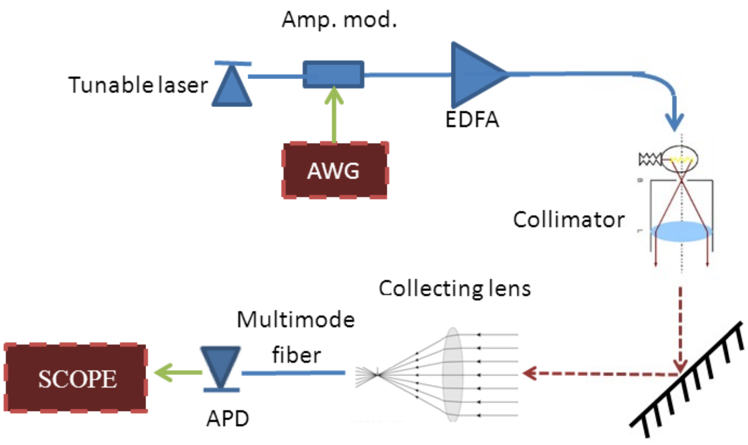

Figure 3: Experimental setup for laser ranging measurements using incoherent pulse compression of complementary code pairs. APD: Avalanche photo diode. Amp. Mod.: amplitude modulator. AWG: arbitrary waveform generator. EDFA: erbium-doped fiber amplifier. Blue solid lines denote optical fibers; green solid lines denote radio-frequency electrical cables; dashed, red lines denote free-space propagation.

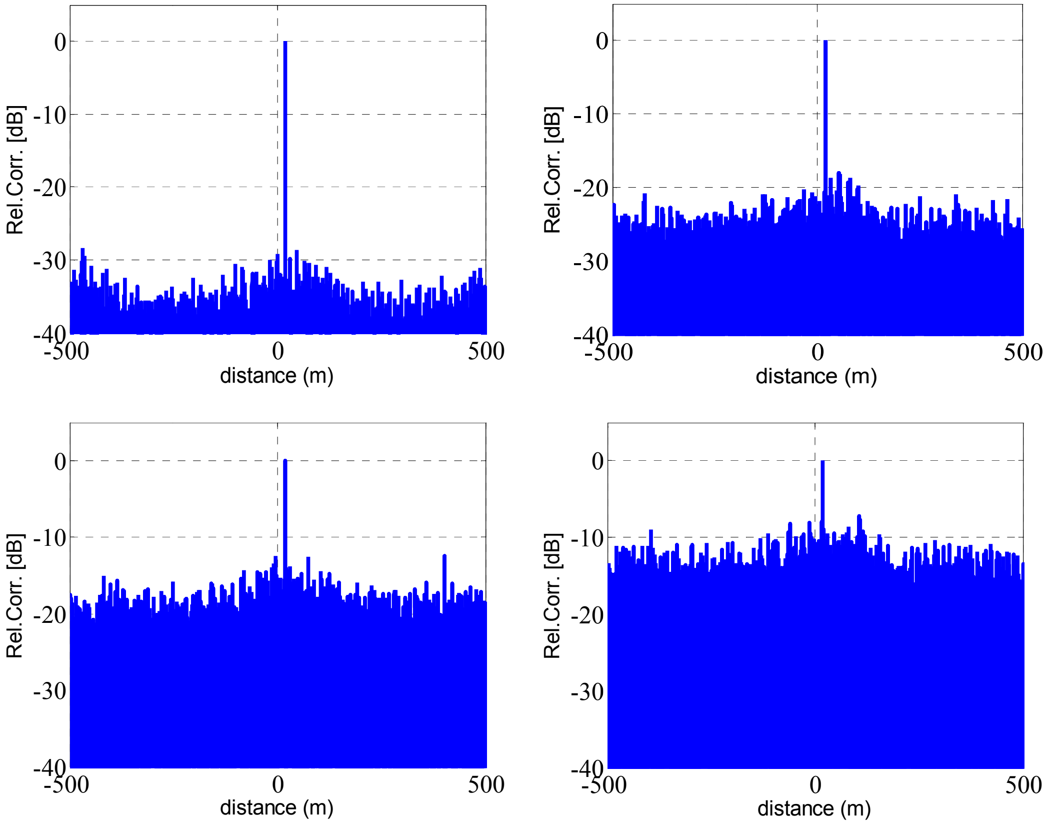

Figure 4: Incoherently compressed forms of experimentally obtained complementary code pairs, reflected from a white wall located 8 m away from the laser range-finder. The length of each code in the pair was 416 bits. The duration of each transmitted symbol was 1 ns. The average optical power levels of the collected echoes were -45 dBm (top left), -51 dBm (top right), -54 dBm (bottom left), and -57 dBm (bottom right). The distance to the target could be resolved in all measurements. The corresponding PSLR values were -28 dB, -18 dB, -13 dB and -8 dB, respectively.

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Figure 4 shows the experimentally obtained, incoherently compressed code pair echoes. The traces shown in the four panels correspond to average received optical power levels of -45 dBm, -51 dBm, -54 dBm and -57 dBm. The distance to the reflecting wall target is clearly identified in all traces, with PSLR values of 28 dB, 18 dB, 13 dB and 8 dB, respectively. The PSLR values obtained for received power of -45 dBm (SNR of -3 dB) are in agreement with simulations. Ranging measurements at SNRs below -15 dB required averaging over multiple repetitive transmissions of the two codes. Figure 5 shows the incoherently compressed code pair detected at an average optical power of -63 dBm, following 1024 averages. The range to the target was measured with a PSLR of 20 dB.

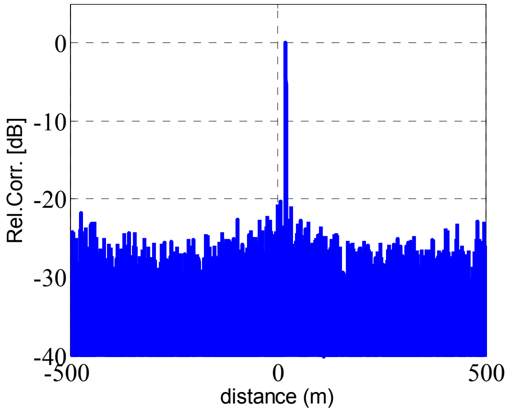

Figure 5: Incoherently compressed form of an experimentally obtained complementary code pair, reflected from a white wall located 8 m away from the laser range-finder. The length of each code in the pair was 416 bits. The duration of each transmitted symbol was 1 ns. The average optical power level of the collected echoes was -63 dBm, and the received waveform was averaged over 1024 repetitions. The distance to the target could be resolved with a PSLR value of 20 dB.

4. SUMMARY

Ranging measurements using incoherent pulse compression of complementary code pairs was demonstrated experimentally. Previous results were extended to the processing of echoes reflected from a realistic target. The method brings together the simplicity of a direct detection, intensity-modulated incoherent ranging system, and the strong sidelobe suppression that is normally provided by phase-modulated sequences only. The large gain provided by the complementary codes allows for the processing of very weak reflected echoes. The range to the target could be recovered even when the optical power of the received signal was -57 dBm, or 15 dB below the noise-equivalent power of the APD used, without averaging over repeating patterns. The processing gain of incoherent pulse compression can be leveraged towards laser ranging systems with smaller receiver apertures and/or reduced transmitted power and energy consumption. Low-power ranging systems which take advantage of a strong processing gain would be better immune against interception and jamming by an adversary.

Compared with single low-correlation-sidelobes sequences, such as MPSLs, complementary code pairs provide a simple, unrestricted scaling in length. The effective sidelobe suppression of code pairs is achieved using a binary-valued matched filter, and does not require complicated miss-matched filters which are longer and consist of precision analog-like values. A large number of different, long code pairs are available, providing additional protection against prospective interception.

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