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High-Resolution Low-Sidelobe Laser Ranging Based on Incoherent Pulse Compression

Daniel Kravitz, Daniel Grodensky, Nadav Levanon, and Avi Zadok

***Abstract*—A technique for high-resolution laser detection and ranging with strong sidelobe suppression is experimentally demonstrated. This method relies on the transmission of a long unipolar sequence of intensity-modulated pulses, the incoherent direct detection of reflected echoes, and subsequent processing by proper digital filters at the receiver end. The obtained sidelobe suppression nearly replicates that of the bipolar sequences, even though the transmitted sequence is unipolar. Both the transmitted sequence and the receiver-end filter are derived from a bipolar code through a pulse position modulation algorithm. Mismatched filters are used for further sidelobe suppression. Due to the processing gain, ranging measurements are successfully performed at signal-to-noise ratios as low as −20 dB. A range change of 2.5 cm is accurately resolved. The proposed method provides the sidelobe suppression of a complex coherent receiver while using simple incoherent detection.**

***Index Terms*—Laser detection and ranging (LADAR), matched filtering, optical signal processing, pulse compression, ranging measurements.**

I. INTRODUCTION

LASER detection and ranging (LADAR) systems have developed rapidly in recent years [1]. Their applications include range-finders [2], 2D and 3D imaging systems [3], Doppler vibrometers [4], and synthetic aperture imaging [4], [5]. The most commonly-used LADAR scheme relies on the transmission of short and intense isolated pulses, and time of flight measurements of collected reflections [1]. However, the generation and transmission of high-peak power laser pulses is complicated and potentially unsafe. Alternatively, many radio-frequency (RF) and microwave radar systems rely on the transmission of long sequences of pulses, and the compression of received echoes [6], [7]. Compression is carried out through matched-filtering processes, resulting in a virtual narrow peak with suppressed sidelobes [6], [7].

The majority of pulse compression waveforms are constructed using frequency modulation, either linear or nonlinear, or phase-coding (*bipolar* and polyphase sequences) [6]. Phase and frequency codes generally provide superior sidelobe suppression, compared with that of amplitude-based or *unipolar* sequences. However, the application of phase and frequency codes requires coherent receivers. While prevalent in RF and microwave systems, coherent receivers in the optical domain come at a cost of significant complexity [8]. Nevertheless, much effort is being dedicated to the development of coherent LADAR schemes [4], [9], [10].

In 2006, Levanon had proposed a novel coding scheme for the effective compression of incoherently detected, unipolar pulse sequences [11]. The unipolar sequences are derived from low-sidelobe, bipolar codes through a pulse-position modulation algorithm [11]. The sidelobe suppression of the compressed sequences nearly replicates that of the original bipolar codes, although simple, direct detection is employed [11], [12]. However, only a partial, preliminary experimental demonstration has been provided to-date [12].

In this letter, we report an experimental demonstration of the proposed principle, as part of a laser range-finder laboratory setup. Codes used were 1112 bits-long, with symbol duration of 200 ps. Carefully designed mismatched filters (see sec. 6.6 in [6], [13]) were used to improve the peak-to-sidelobe ratio (PSLR) of the processed sequence to 46 dB, and its integrated sidelobe ratio (ISLR) to 43dB. The two metrics signify the extent of disturbance due to point interference and distributed interference, respectively [6], [7]. A range change of 2.5 cm is accurately recovered. The filtering process allowed for ranging measurements at poor signal to noise ratios (SNRs), as low as −20 dB. The noise tolerance can be leveraged towards a longer measurement range, lower launch power and energy consumption, reduced apertures and improved operation at unfavorable atmospheric conditions.

II. INCOHERENT PULSE COMPRESSION

The incoherent compression of unipolar pulse sequences is reported in detail in [11], and will be 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 [11]. The code T is used to modulate the intensity of the LADAR 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 $T[k] = 0$, $k = 1 \ldots 2N$ [11]. The code R is digitally stored at the receiver for post-detection processing.

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D. Kravitz, D. Grodensky, and A. Zadok are with the Faculty of Engineering, Bar-Ilan University, Ramat-Gan 52900, Israel (e-mail: kravitzdn@gmail.com; grodensky@012.net.il; Avinoam.Zadok@biu.ac.il).

N. Levanon is with the School of Electrical Engineering, Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel (e-mail: nadav@eng.tau.ac.il).

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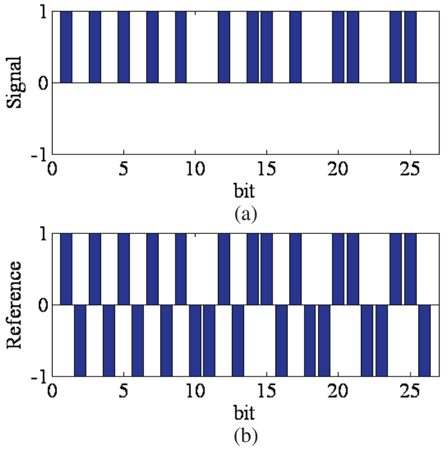

Fig. 1. (a) Transmitted code T and (b) matched filtering code R corresponding to the Barker 13 code: [1 1 1 1 1 −1 −1 1 1 −1 1 −1 1].

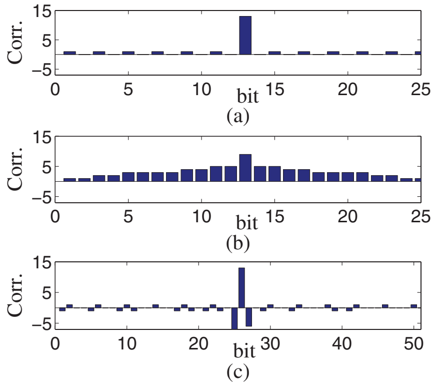

Fig. 2. (a) Aperiodic auto-correlation of the Barker 13 bipolar code: [1 1 1 1 1 −1 −1 1 1 −1 1 −1 1]. The correlation peak is 13, whereas the maximal sidelobe equals unity. (b) Aperiodic auto-correlation of a unipolar representation of the Barker 13 code: [1 1 1 1 1 0 0 1 1 0 1 0 1], showing a weaker central peak and inferior sidelobe suppression. (c) Aperiodic cross-correlation between the transmitted code T and matched filtering code R corresponding to the Barker 13 bipolar code (see Fig. 1). With the exception of the two time slots in the immediate vicinity of the central peak, the suppression of sidelobes reaches that of the original bipolar sequence.

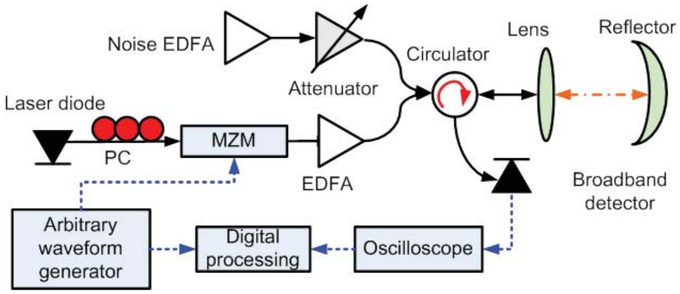

Fig. 3. Experimental setup for LADAR measurements using incoherent pulse compression. MZM: Mach–Zehnder modulator. PC: polarization controller. EDFA: erbium-doped fiber amplifier. Black solid lines: fiber connections. Blue dashed lines: electrical cables. Red dashed-dotted lines: free-space propagation.

As an example, the construction of the T and R codes corresponding to the Barker 13 bipolar sequence is illustrated in Fig. 1. The aperiodic cross-correlation between these two codes is shown in Fig. 2 (bottom), alongside the aperiodic auto-correlation of the original Barker 13 sequence itself (top). With the exception of the two sidelobes immediately adjacent to the main correlation peak, the cross-correlation replicates the sidelobe suppression of the original bipolar code [11]. The compression of an incoherent code T described above is applicable to a simple LADAR system using intensity modulation and direct detection. In contrast, the auto-correlation of a unipolar representation $\tilde{c}[n]$ of the Barker code itself, in which −1 symbols are replaced by 0, exhibits inferior sidelobe suppression performance (Fig. 2, center).

The cross-correlation sidelobes can be further suppressed using a mismatched filtering process, in which the sequence R is replaced by a longer code $\tilde{R}$ whose coefficients are not restricted to ±1. Substantial sidelobe suppression can be obtained, at the cost of a modest degradation in the central correlation peak power [6]. The sequence $\tilde{R}$ was designed to maximize the ISLR, according to principles described in sec. 6.6 of [6]. The mismatched filter was three times longer than the transmitted sequence. The incoherent compression of sequences drawn from long bipolar codes was successfully employed in laser ranging measurements, as described next.

III. EXPERIMENTAL RESULTS

The setup for laser ranging measurements using incoherent pulse compression is shown in Fig. 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 sequence T. The sequence was constructed from a 1112 bits-long maximum peak-to-sidelobe ratio (MPSL) bipolar code [14], following the above procedure. The coding symbol duration was 200 ps. The measurement SNR was controlled by the addition of amplified spontaneous emission (ASE) of variable power from an erbium-doped fiber amplifier (EDFA).

The modulated waveform was amplified by a second EDFA and launched towards a movable retro-reflector via a fiber circulator (55 dB isolation) and a collimating lens. Reflections were partially collected by the lens, directly detected by a photo-diode with 12 GHz bandwidth, and sampled by a digitizing oscilloscope of 6 GHz bandwidth. The detected sequences were compressed through matched and mismatched filtering, carried out using offline signal processing.

In a first set of experiments, the retro-reflector was placed a short distance (tens of cm) from the lens, and the detection SNR was varied through adjusting the power of both the laser diode and ASE noise source. In this manner the reflected signal remained above the thermal noise of the photo-detector, and the SNR could be quantified by switching the ASE on and off. The cross-correlations of incoherently compressed LADAR echoes are shown in Fig. 4, alongside the simulated correlations of compressed noise-free sequences. At a high SNR of 20 dB, the PSLR of the experimentally obtained sequence following matched filtering reached 33 dB, in agreement with the design prediction. A mismatched filter further improved the PSLR to 46 dB, while the peak power of the main correlation

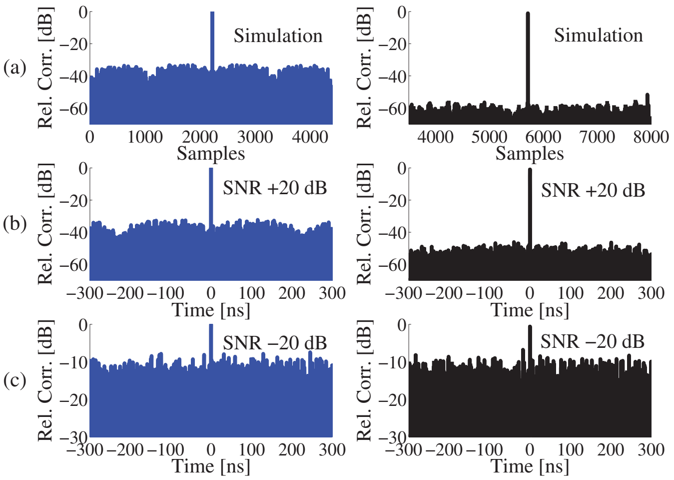

Fig. 4. Cross-correlations of an incoherently compressed 1112 pulses-long unipolar sequence. Both matched (left, blue) as well as mismatched (right, black) filters were used in the compression process. (a) Simulated compression of noise-free sequences. (b) Compression of experimentally obtained LADAR echoes detected with a signal-to-noise ratio of +20 dB. (c) Compression of experimentally obtained LADAR echoes detected with a signal-to-noise ratio of −20 dB (see text).

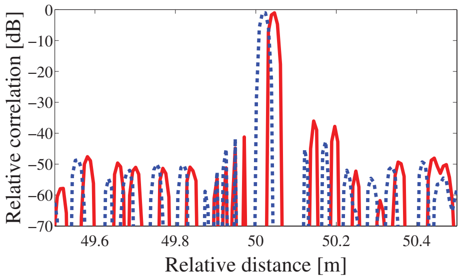

Fig. 5. Cross-correlations of incoherently compressed 1112 pulses-long unipolar LADAR echoes. The distances between the LADAR lens and a retro-reflector were 50 (blue, dashed) and 50.025 m (red, solid). The measurement SNR was 18 dB. A mismatched filter was used in the compression.

lobe was only 1 dB lower than that obtained with a matched filter. The results come close to the predicted 52 dB PSLR of the mismatched MPSL code. The experimentally obtained ISLR was 43 dB.

Remarkably, incoherent compression could still be carried out even when the measurement SNR was drastically degraded to −20 dB (Fig. 4, bottom row). Here the sidelobe suppressions obtained with matched and mismatched filters were practically equal, as the added value of the mismatched filter was overshadowed by the intense additive noise. The results demonstrate the potential of the incoherent compression scheme at poor SNR conditions.

Preliminary ranging performance was illustrated by placing the reflector 50 m away from the collimating lens, and changing its position by 2.5 cm. The average transmitted power was 100 mW, the collimating lens aperture was 25.4 mm, and the SNR of the collected reflection was 18 dB. A mismatched filter was used in the pulse compression. The symbol duration was 200 ps and the receiver sampling interval was 50 ps. Figure 5 displays the compressed waveforms as function of delay for the two reflector positions. The full width of the main lobe at 70 dB below the peak is about 4 cm, in agreement with the pulse duration and sampling rate. The PSLR of both curves is above 35 dB. The two peaks are approximately 2.4 cm apart, in agreement with the reflector position change.

IV. CONCLUSION

A high-resolution laser ranging system with strong sidelobe suppression was demonstrated experimentally. The system relies on simple intensity modulation and direct detection of a dense position-coded train of 1112 sub-pulses, each 200 ps wide, and the subsequent incoherent compression of the unipolar collected echoes. The high-SNR delay response exhibits very low sidelobes: PSLR and ISLR of 46 dB and 43 dB, respectively. The spatial resolution of the experimental demonstration is estimated as 3 cm. A change in range of 2.5 cm was accurately recovered in a high-SNR measurement.

The proposed scheme could facilitate simple LADAR systems with potentially longer measurement range, reduced power consumption and aperture size, and better performance in poor atmospheric conditions. Incoherent processing might not be suitable in Doppler-based LADAR applications.

The proposed method was demonstrated in a simple proof-of-concept ranging experiment. Further work is being dedicated to the employment of incoherent compression in long-range measurements and to its extension to 3D imaging.

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