Continuous-Wave Laser Range Finder Based on Incoherent Compression of Periodic Sequences

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Abstract: Continuous and incoherent laser range finder is presented, based on repeating transmission of Legendre amplitude codes and post detection compression. The cyclic correlation sidelobes of the sequences are identically zero. The concept is demonstrated experimentally.
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1. Introduction

Laser range finders and lidars are widely employed in a variety of civilian and defense-related applications [1]. The most common protocol in high-resolution lidar relies on time of flight (ToF) measurements of intense, isolated laser pulses. However ToF lidars transmit at very low duty cycles. High instantaneous power levels are necessary, which increase the probability of intercept, may cause safety concerns and may require bulky and expensive components. An alternative procedure, which is heavily employed in radar systems, is based on the transmission of extended phase-coded sequences of short elements, and the post-processing of collected echoes at the receiver end [2]. With judicious sequence design, the extended waveform is compressed to a virtual narrow peak, which provides high resolution while alleviating the need for high peak power. One key metric of sequence compression protocols is the suppression of residual delay sidelobes, which contribute noise and may conceal neighboring weaker targets.

Sequence compression in lidars faces two primary challenges. First, the pulse compression and sidelobe suppression of amplitude modulation sequences is usually inferior to that of phase codes [2]. However the latter require coherent optical receivers, which are generally more complicated. Second, the compression of many sequences is based on the properties of their aperiodic auto-correlation functions. Aperiodic processing mandates that 'dead times' are kept between waveform repetitions. Higher energy efficiency may be obtained in *continuous* operation, in which codes are repeated without interruptions, and compression is based on their *cyclic* correlation properties. Recently we reported the incoherent compression of amplitude-modulated sequences that were drawn from bipolar codes with particularly low sidelobes [3,4]. However, the processing of waveforms remained aperiodic.

Herein we report a laser range finder that is based on the incoherent compression of a continuous transmission, consisted of repeating unipolar Legendre sequences [5]. Reflected echoes are directly detected, and compressed through their cyclic cross-correlation with a digitally stored reference sequence. Off-peak values of the cyclic cross-correlation are identically zero [6]. The principle is demonstrated in measurements at 100 m distance, at a poor electrical signal to noise ratio (ESNR) of -30 dB.

2. Principle of operation and performance estimates

The sequences used in this work are drawn from bipolar (±1) Legendre sequences [5] or m-sequences [6] of length M. The cyclic autocorrelation of the original codes has a peak of M and uniform off-peak sidelobes of -1. Here we use a unipolar version of the code, in which '-1' symbols are replaced with '0', in amplitude modulation of the lidar source, whereas the original bipolar code is digitally stored as reference. The transmission or detection of phase information is not required. The cyclic cross-correlation between the transmitted and reference sequences is 'perfect', with peak value that equals the number of '1' symbols in the code ($\sim M/2$) and delay sidelobes that are identically zero. Legendre sequences are available for lengths $M = 4k - 1$, with M a prime and k an integer. 519 different code lengths M are available between 1,000 and 10,000 bits. Using $N > 1$ code periods implies energy integration. The periodic cross-correlation maintains its perfect property of zero sidelobes as long as the duration of the integer number of reference periods is shorter than the duration of the collected lidar echo.

Additive detector noise introduces imperfect delay sidelobes. The tradeoffs among maximum range R_{max}, receiver aperture diameter D_r, range resolution Δz, transmitted optical power P_t, and number of code periods N in the acquisition trace can be quantified in terms of the following relation:

$$R_{max}^4 = (N \cdot M \cdot D_r^4 \cdot \rho^2 \cdot \Delta z \cdot P_t^2)/(8c \cdot NEP^2 \cdot Q_{min}) \quad (1)$$

Here Q_{min} denotes the minimum required ratio between the magnitude squared of the compressed main lobe and the standard deviation of noise-induced sidelobes in the cross-correlation function. It is set arbitrarily to 10 dB. NEP denotes the noise-equivalent optical power of the photo-receiver, in units of [W/Hz$^{1/2}$], and ρ represents the relative power reflectivity of the target. Equation (1) is valid provided that: a) the ESNR is restricted by additive thermal and amplifier noise at the receiver; b) the receiver bandwidth matches the symbol rate of the code; c) the target area is larger than that of the incident beam; and d) the target may be modelled as a Lambertian reflector. Figure 1 shows the calculated compressed forms a 4003 bit-long code, with simulated additive noise at ESNRs of 2 dB (left) and -30 dB (right) and using $N = 3$ periods. The numerical simulation includes the transfer functions of components used in the experimental setup below. The simulated peak-to-sidelobe ratios (PSLRs) are 34 dB and 9.8 dB, respectively.

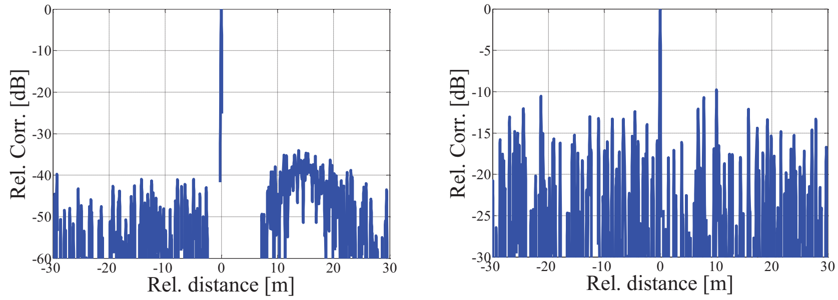

Fig. 1. Simulated compressed forms of a 4,003 bit-long code, at ESNRs of +2 dB (left) and -30 dB (right). The length of the processed trace equaled $N = 3$ code periods. PSLRs are 34 dB and 9.8 dB, respectively.

3. Experimental results

The amplitude of light from a laser diode was repeatedly modulated by a 4,003 bit-long Legendre sequence. The symbol duration was 1 ns, corresponding to Δz = 15 cm. First, the modulated output was directly connected to a photo-receiver (1 GHz bandwidth, NEP = 1.5 pW/Hz$^{1/2}$), and detected at an ESNR of +2 dB. Figure 2 (left) shows the compressed form of a trace consisted of N = 3 code cycles. The obtained PSLR is 40 dB. Next, the modulated waveform was amplified to P_t = 22.5 dBm and launched towards a white-paper target (ρ = 0.07) at 100 m distance. Reflected echoes were collected by a lens (D_r = 10 cm) into the receiver. The optical power of collected echoes P_r was -58 dBm (ESNR of -30 dB). The ESNR could be controlled by changing P_t. P_r was 5 dB weaker than the theoretical limit, due to coupling losses into the receiver. The compressed form of the collected trace (N as above) is shown in Fig. 2(right). The obtained PSLR is 10.6 dB, in good agreement with simulation. The experimental parameters correspond to R_{max} of 120 m (with coupling losses included in the estimate).

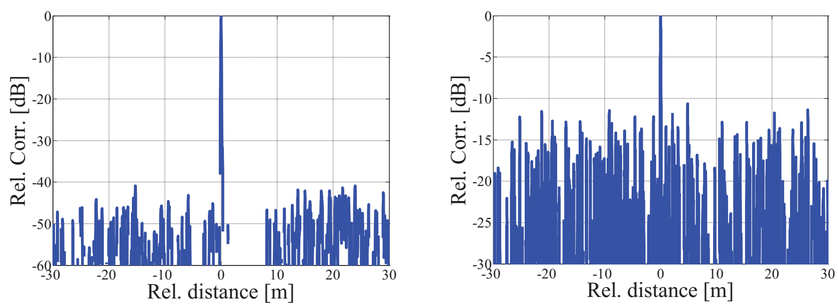

Fig. 2. Left – compressed form of a continuous sequence, detected incoherently at an ESNR of +2 dB. The PSLR is 40 dB. Right – compressed form of the same sequence, collected from a Lambertian reflector at 100 m distance and detected at ESNR of -30 dB. The PSLR is 10.6 dB.

In summary, a novel lidar concept is proposed and demonstrated, based on the compression of a continuously-coded and incoherently-detected transmission. The method provides zero sidelobes and improved energy efficiency.

4. References

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