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Noncoherent Radar Pulse Compression Based on Complementary Sequences

Noncoherent pulse compression (NCPC), suggested recently, uses on-off keying (OOK) signals, obtained from Manchester coding a binary sequence with favorable a-periodic autocorrelation. This paper investigates the use of binary complementary pairs as a basis for NCPC. It shows that a pair of Manchester coded, N-element binary complementary sequences will yield a peak sidelobe (PSL) ratio of $1/(2N)$.

I. INTRODUCTION

Pulse compression is a well-established radar technique that creates a virtual narrow strong pulse out of a weak long pulse. Pulse compression is achieved by modulating the transmitted long pulse and correlating its received reflection with a reference modulated pulse stored in the receiver. In coherent radar the modulated signal parameters are frequency (e.g., linear FM) or phase (e.g., Barker coding).

Noncoherent pulse compression (NCPC) was recently suggested [1–3], which employs on-off keying (OOK) modulation. NCPC is of interest to direct-detection laser radar (LIDAR), and to simple radar that utilizes noncoherent microwave power source like the magnetron.

The OOK transmitted signals suggested for NCPC are based on Manchester coding well-known binary sequences, like Barker or minimum peak sidelobe (MPSL) codes. With Manchester coding, a "1" symbol of the original sequence is transmitted as an early pulse, and a "-1" symbol as a late pulse. The transmitted envelope and corresponding reference elements are summarized in Table I. The duty cycle of the system can be controlled by inserting 0s into the code sequence (equal number of 0s after each element and in both transmitted and reference sequences).

It was shown [1–3] that when the transmitted (and detected) sequence of subpulses is cross-correlated with a reference sequence of subpulses, coded according to Table I, the resulted cross-correlation maintains the original sidelobe levels of the original binary code, except for two large negative

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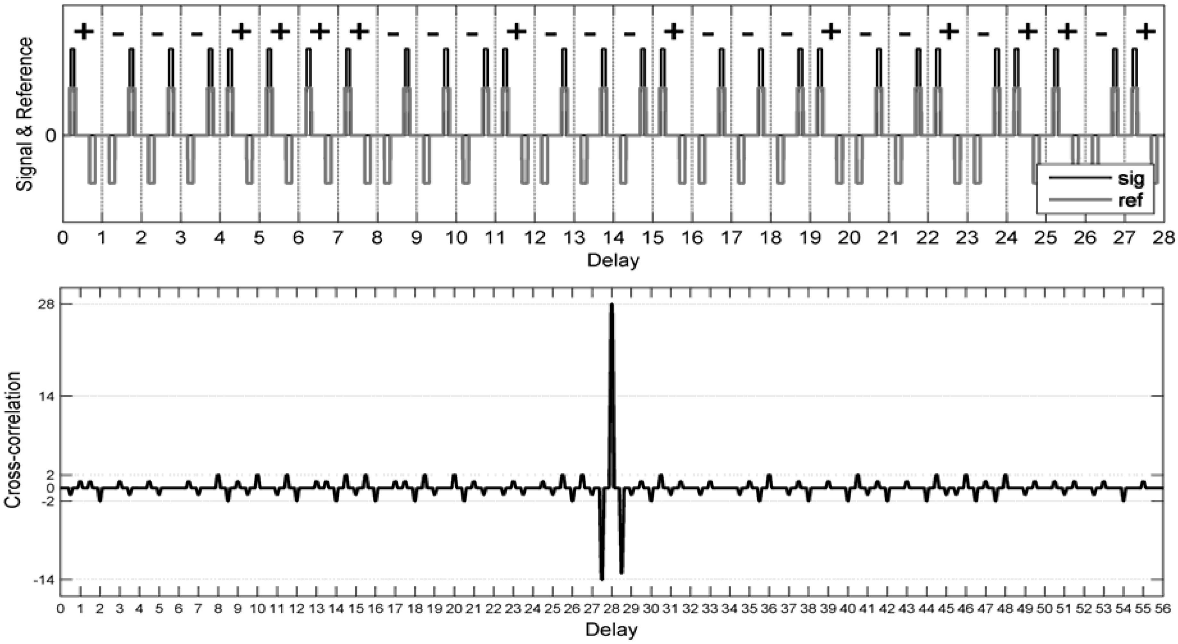

Fig. 1. Waveforms and correlation of Manchester-coded MPSL 28 binary sequence.

TABLE I
OOK Coding of Binary Symbol and Corresponding Reference

Binary	Transmitted 1 = on, 0 = off		Reference	
1	1	0	1	−1
−1	0	1	−1	1

sidelobes, immediately before and after the mainlobe. Fig. 1 (top) shows the real envelope of a transmitted waveform based on an MPSL 28 code (see e.g., [4, Table 6.3]), and of the reference waveform, with which the detected envelope in the receiver is correlated. Note that a noncoherent receiver performs envelope detection (magnitude or square-law), yielding detector output that is always positive. In the absence of noise and other targets the detected waveform is a replica of the envelope of the transmitted real envelope. The resulted cross-correlation appears in the bottom subplot of Fig. 1. MPSL 28 is the longest known binary code with autocorrelation peak sidelobe of 2. This PSL level is also observed in Fig. 1, when not counting the two large negative near sidelobes.

The fact that the reference sequence has twice as many non-zero elements as the transmitted sequence implies an inherent signal-to-noise ratio (SNR) loss (estimated from simulations to be between 1 and 2 dB). This mismatch loss is a penalty worth paying because NCPC allows using efficient high power transmitters.

The cross-correlation sidelobes can be further reduced by using a longer reference [2, 3], based on Manchester coding a mismatched filter designed for the original binary code. The penalties associated with such a filter are an additional SNR loss and a multilevel reference instead of the original three level reference $\{-1, 0, 1\}$.

II. USING COMPLEMENTARY SEQUENCES

Another approach for sidelobe reduction is to base the NCPC on complementary binary sequences ([5], [4, Sec. 9.3]). The autocorrelations of the sequences in a complementary pair have sidelobes with equal but opposite polarity. In coherent radar, the complementary sequences modulate consecutive pulses in a coherent pulse train. (The coherently processed interval must contain complete sets of complementary-coded pulses.) In the resulted correlation the near sidelobes are nullified. The difficulty with a train of complementary-coded coherent pulses is their poor Doppler tolerance. Relatively small Doppler shifts raise the autocorrelation near-sidelobes. Furthermore, the period of the signal is doubled, from a single pulse repetition interval (PRI) to two PRIs. This will cause the spacing between recurrent Doppler lobes of the ambiguity function to decrease by a factor of two [4]. The poor performances in the presence of Doppler shifts limit the use of complementary sequences. They are used in radar atmospheric probes, where the radial velocities are small [6].

The receiver of a noncoherent radar system performs envelope detection, hence loses the interpulse phase changes induced by Doppler shift. In that sense it is completely Doppler tolerant (in nonrelativistic scenes), which becomes an advantage when using complementary sequences.

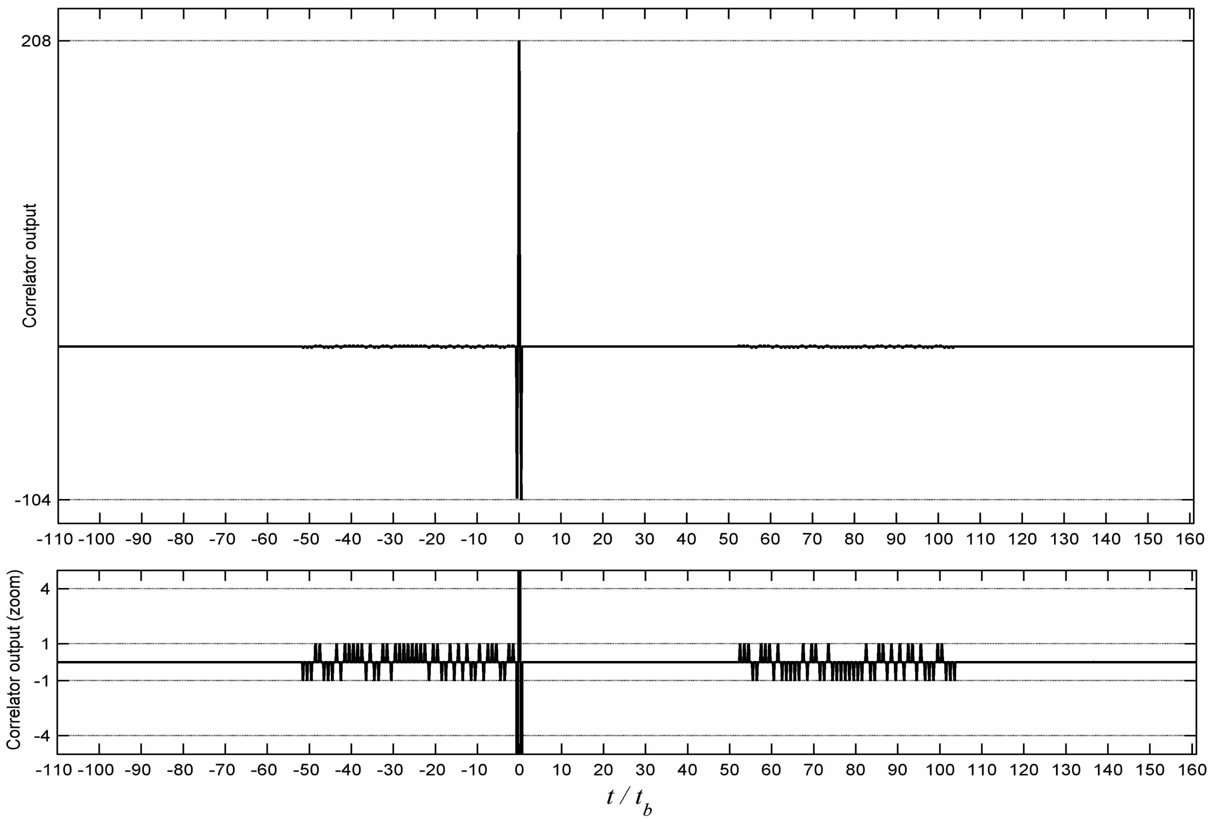

Fig. 2. Sum of two correlations of Manchester-coded complementary pair of length 104.

We explore the performances of a complementary pair based on the 26 element kernels:

$$\begin{aligned} S1 &= \{- - - + + - - - + - + + - + - + - + + - - + - - - -\} \\ S2 &= \{- - - - + - - + + - + - - - - - + - + + + - - + + +\}. \end{aligned} \tag{1}$$

The sequences were quadrupled in length to complementary sequences S5 and S6, of length 104 element each, using a recursion algorithm [5]:

$$\begin{aligned} \mathrm{S3} &= \{\mathrm{S1} \quad \mathrm{S2}\}, \qquad \mathrm{S4} = \{\mathrm{S1} \quad \overline{\mathrm{S2}}\} \\ \mathrm{S5} &= \{\mathrm{S3} \quad \mathrm{S4}\}, \qquad \mathrm{S6} = \{\mathrm{S3} \quad \overline{\mathrm{S4}}\} \end{aligned} \tag{2}$$

where $\overline{\mathrm{S2}} = -\mathrm{S2}$.

Manchester coding is applied to S5 and S6, according to Table I, to get the transmitted and reference sequences for the two complementary sequences. The sum of the two correlations is plotted in Fig. 2. The bottom subplot is simply a zoom of the vertical axis. The mainlobe height is 208 ($= 2 \times 104$) and the PSL is 1. That PSL will not change even if we keep doubling the sequence length. The sidelobes pattern seen in Fig. 2, in which half the sidelobes delay span has zero sidelobes, is typical for sequences obtained through the recursion algorithm. We can conclude that the PSL ratio is $1/(2N)$ where N is the length of each sequence in the pair. In dB the 104 element sequences yield a theoretical PSLR of -46.36 dB. The label "theoretical" was used to hint that in practical target scenes, degraded performances should be expected. The sidelobe behavior in a multi-target scene is simulated next.

III. MULTI-TARGETS, RANDOM PHASES AND INTEGRATION

When more than one target reflects the signal, and the delay separation is less than the sequence duration, the reflected signals add coherently in the antenna, and are then processed nonlinearly in the envelope detector. Coincidence between reflected subpulses from different targets can cause considerable degradation, as was described in details in [2], [3]. For comparison, in a coherent radar, the correlation mainlobe of one target will at most change by the PSL of the correlation of the second target. As pointed out in [2], [3] the problem in noncoherent radar can be mitigated by randomizing the phase of each subpulse in the sequences. This is inherent in many transmitters (e.g., laser or magnetron). Additional improvement can be achieved by integrating returns from many repetitions of the complementary pair, with continued phase randomization.

Integration of returns from many pulses is much simpler in noncoherent radar than in coherent radar. Fig. 3 displays a block diagram of an NCPC receiver designed to work with $M/2$ repetitions of a complementary pair of pulses. Note that envelope-detected reflections from even pulses are stored in the registers on the left hand side (l.h.s.),

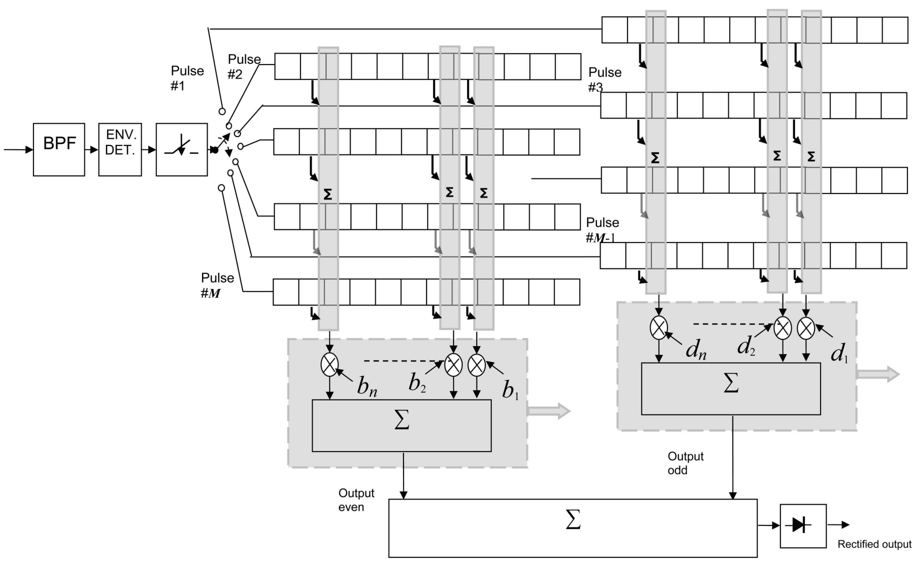

Fig. 3. Receiver block diagram with integration of $M/2$ pairs of complementary-coded pulses.

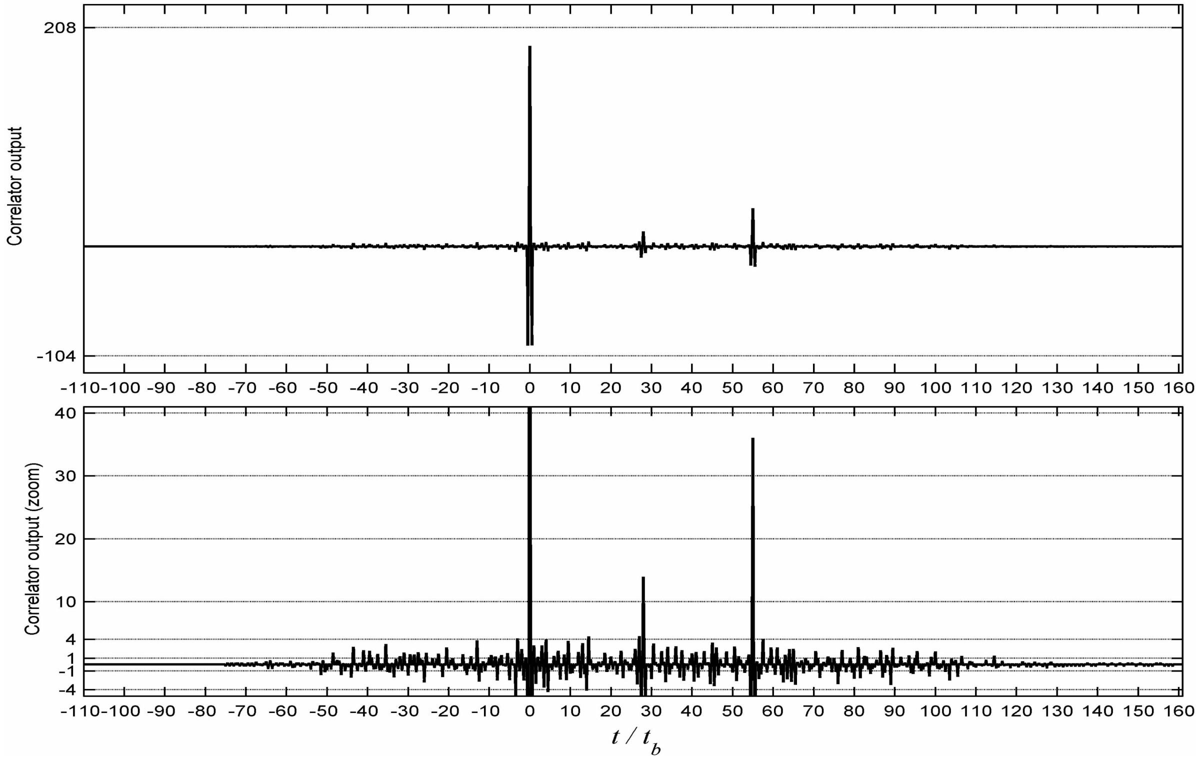

Fig. 4. Sum of the two correlations in three-target scene, using one pair of complementary pulses. Relative target intensities: 1, 0.15, 0.25.

and those of the odd pulses are stored on the r.h.s. The even pulses are based on one sequence of the complementary pair and their delay-aligned sum is cross-correlated with its corresponding reference sequence $\{b_1, b_2, \ldots, b_n\}$. The odd pulses are based on the other member of the pair and their delay-aligned sum is cross-correlated with its corresponding reference sequence $\{d_1, d_2, \ldots, d_n\}$. The correlation outputs are added and possibly rectified (one way), yielding one output for each delay unit. Fig. 4 presents the sum of the two correlations in a noise-free, 3 point-target scene (no integration). The three target returns are specified by their delay, magnitude, and phase. The 104 subpulses in each "pulse" are randomly phased.

Comparing Fig. 4 to Fig. 2 we note lower mainlobe and higher sidelobes. We also note that the relative intensities of the detected targets deviate from their true intensity proportions. All this is due to the nonlinear processing (envelope detector). Without random phase of the subpulses the effect will depend strongly on the particular phases of the

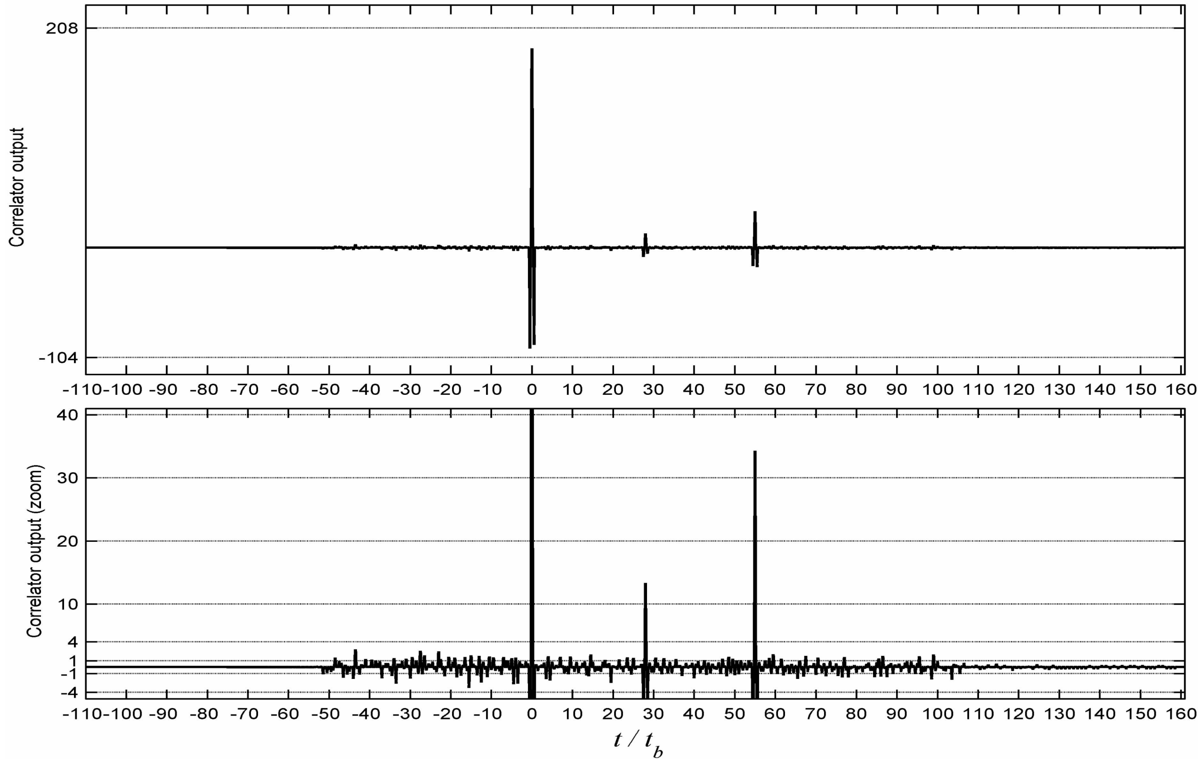

Fig. 5. Normalized sum of two correlations after integration of 200 pairs of complementary pulses. Three-target scene. Relative target intensities: 1, 0.15, 0.25.

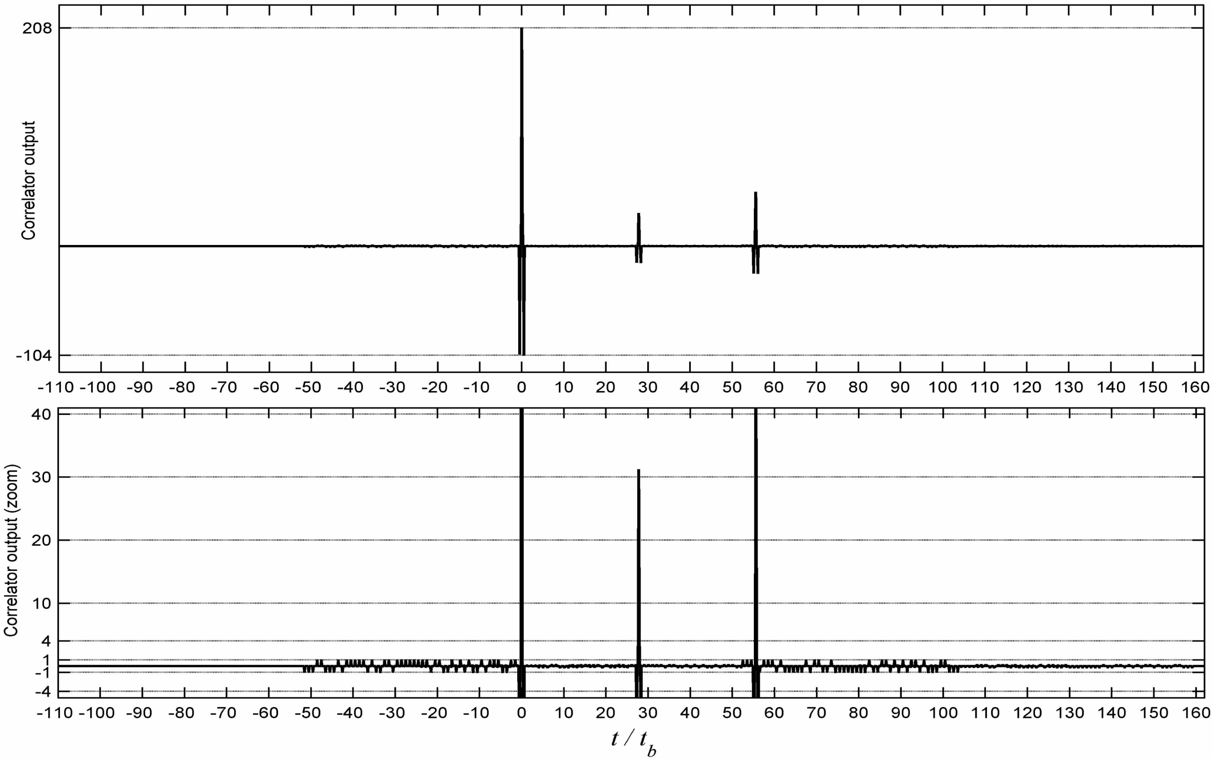

Fig. 6. Sum of two correlations in three-target scene. Relative target intensities: 1, 0.15, 0.25. No coincidence between subpulses of three reflected signals.

returns from the different targets. Fig. 5 presents the arithmetic mean of the two correlations, in the same 3-target scene, but after integration of 400 pulses (200 pairs). Comparing Fig. 5 to Fig. 4 we note reduction of sidelobes due to the integration of many pulses, each having its different random-phased subpulses. Quantifying the sidelobe reduction (theoretically or through Monte-Carlo simulation) was not performed.

It should be pointed out that the delay between targets was an integer multiples of the bit duration t_b. This is a worst case situation, since the reflected subpulses of one target coincide with those of the other targets.

Fig. 6 displays the output of a three-target scene, when the delay differences are such that the reflected subpulses from the three targets do not coincide. Recall that there is considerable overlap between the returns because the signal width extends over 104 bits, while the delay separation between the first and last target is approximately 56 bits. Note that the three mainlobes exhibit their expected peak value, compared with single target situations.

IV. CONCLUSIONS

Binary complementary pairs are shown to be a good candidate as a base for NCPC. Their poor Doppler tolerance, which limits their use in coherent radar, is of no concern in noncoherent processing that ignores Doppler. It was shown that after Manchester coding a pair of N-element binary complementary sequences, the correlation peak is $2N$ while the sidelobe peak is one, independent of N. Thus, for sequences with $N = 104$, the PSLR is -46 dB. This is 20 dB better than what can be obtained from a signal based on a single MPSL code of the same length.

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Configuration, Orbit Design of InSAR Formation Based on Mean Elements

A mission requirements-based configuration method of interferometric synthetic-aperture radar (InSAR) formation to design dual-satellite formation by mean orbital elements is derived. The configuration and initial orbital elements of two coordinated running satellites InSAR formation are designed when system parameters, such as the resolution of slant distance, latitude domain of ground coverage area, and the side-looking angle of the synthetic-aperture radar (SAR) beam center, are given.

I. INTRODUCTION

Space-based interferometer relying on formation flying satellites presents a very promising approach to achieve large observation baselines with lower cost and higher flexibility. The space-borne synthetic aperture radar (SAR) has evolved into a mature technology over the past two decades; there is a growing interest in the single pass interferometric synthetic-aperture radar (InSAR), including fully active SAR constellation and semi-active satellite formation [1, 2]. Fully active SAR constellations use two or more conventional radar satellites flying in close formation to acquire interferometric data during a single pass, such as twin satellite formations like the Radarsat2/3 tandem [3] or TanDEM-X [4] and multi-satellite constellations like the Techsat-21 [5]. Semi-active satellite formations use multiple passive receivers in combination with one conventional radar satellite, including interferometric Cartwheel [6] and interferometric Cartwheel Pendulum [2] concepts.

Some work has been done in the past on using orbital element differences [7–9]. For advanced fully active SAR applications, a typical helix-shaped formation flying configuration [10] has been presented. But the gap between theoretical studies and real applications is still in existence. In this paper, a practical method of formation configuration design is taken by relative mean orbital elements. In order to meet the stable cross-beam-sight baseline for digital elevation model (DEM) mission, a novel configuration, orbit design method of two satellites InSAR formation is presented in this paper. This paper

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