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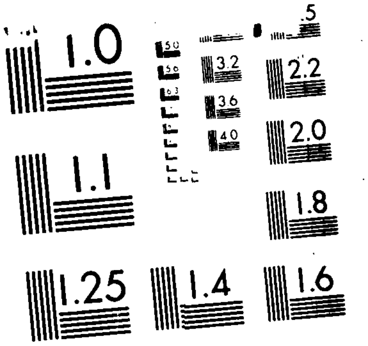

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AD-A166 407

TECHNICAL REPORT RE-85-24

THE TECHNICAL COOPERATION PROGRAM
SUBGROUP K PANEL PRESENTATIONS

E. M. Holliday
Advanced Sensors Directorate
Research, Development, and Engineering Center

September 1985

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35898-5000

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Group complementary coding	Correlation
Pulse compression	
Polarization	

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Two topics presented at recent annual meetings of The Technical Cooperation Program (TTCP), Subgroup K, are documented and discuss accomplishments and theory of group complementary coding for pulse compression in a radar system.

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PREFACE

The purpose of this report is to bring together and document two presentations prepared by the author. Each was presented to a separate convening of the SUBGROUP K Panel under THE TECHNICAL COOPERATION PROGRAM (TTCP) composed of technical representatives from the United States, United Kingdom, Australia, and Canada. Each presentation was made by the Director of the Advanced Sensors Directorate of the U.S. Army Missile Laboratory.

At the SUBGROUP K meeting in London in 1981 the paper entitled "Group-Complementary Code Sets with Desirable Correlation Properties" was presented. The second paper, entitled "Group-Complementary Code Sets: An Up-Date" was presented in Australia in 1984 at the 27th Annual K-Panel meeting.

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CONTENTS

ILLUSTRATIONS

I. GROUP-COMPLEMENTARY CODE SETS WITH DESIRABLE CORRELATION PROPERTIES

A. Summary

This presentation describes the structure and properties of a waveform design technique which provides desirable range resolution properties in radar sensor systems. The waveform design, which is called group-complementary coding, consists of groups of binary sequences which can be used for bi-phase coding of a radar carrier pulsed waveform.

When pulse compression processing is extended to include the composite of a number of pulses through coherent integration, then group-complementary coding provides the often desirable property of complete range sidelobe cancellation (for zero doppler shift).

The information presented here is based upon coding work accomplished at the US Army Missile Laboratory and more details may be found in reference [1].

B. Introduction

Pulse compression ideally rearranges the temporal distribution of energy in such a way that a long pulse with a given energy is transformed to a shorter pulse with the same energy. The process is useful in target sensor systems for improving range resolution and rejection of undesired clutter signals within the target resolution element. However, coding of the waveform, in general, produces undesired time or range sidelobes which cause signal competition between the in-range target element and the out-of-range clutter elements. This is illustrated in Figures 1 and 2. In the first figure the correlation function for a seven bit Barker (phase modulated) code is considered for one or two targets. The objective here is to illustrate how range sidelobes from two or more range resolution elements combine and can exceed the threshold for target declaration. The response from a single isolated target is shown at the top of Figure 1, being the autocorrelation function for the illustrated Barker code. The result is constant, peak level sidelobes. However, for two targets the cross-correlation result is as shown in the balance of the figure. Different target separations, D, are considered. If the uncoded pulse yields a resolution of ΔR, then phase coding the pulse with n bits will yield a resolution of $\Delta R/n$. For a target separation distance (D) of 2 $(\Delta R/n)$ the targets are not resolved and the sidelobes add such that the single target response is filled-in resulting with a constant sidelobe level. As the target separation distance is increased the target peak responses become resolved while the sidelobes combine as a function of separation distance D. In this case, it is not difficult to identify the individual targets. However, when many targets are present, false target declaration can occur. Figure 2 illustrates this point. Here, twelve targets in continuous range cells are considered. The sidelobes add up to the point where a false target may be declared, depending upon the threshold level. If the threshold were set for 3 dB of the peak response of a single target, then a false target is detected in addition to the twelve true targets. However, raising the threshold level to the expected peak response for a single target will permit proper detection of the twelve targets without false declarations. Obviously, the time sidelobes resulting from waveform encoding can be very undesirable, especially those arising from out-of-range clutter cells. It is quite desirable, therefore, to have coding and processing which eliminates the time sidelobes. Such is provided with group-complementary code sets.

C. Group Complementary Codes

Group-complementary codes are extensions of the complementary code concept introduced by Golay. Application of Golay code pairs (also known as complementary sequences) involves processing two codes pulses at a time in a radar processor to eliminate the range sidelobes [2]. These codes have the property that when their individual range sidelobes are combined (algebraic addition), the composite sidelobes completely cancel, yielding the desired perfect correlation property.

The codes discussed here are matrices of K by N binary elements, and pulse-compression processing involves transforming K long pulses, each coded with one of the K rows of N-bit binary words, into one single short pulse. Therefore, the pulse compression is a composite operation over a number of pulses rather than on a single pulse. The implementation of the multipulse processing technique could take several forms but would necessarily require the storage of the partial correlation resulting from each of the K pulses to form the composite matrix correlation. This is illustrated in Figure 3 where K transmitted pulses are received and processed in the multiword correlation process to produce the desired result of a single peak response without nearby time sidelobes. The multiword correlation process is illustrated in Figure 4. The partial correlation result of K encoded pulses is coherently added to produce the cross-correlation result for one particular τ delay value. M(o) through M(K-2) are the maximal length pseudo-random phase codes used to encode each transmitted pulse. The "one" at the end of each pulse is an extra bit of coding added to support the basis of group-complementary codes. The last pulse transmitted is not coded and has constant phase as noted by the string of "ones". When the delay value is such that all received pulses are aligned with each corresponding reference pulse, total agreement in each pair of codes occurs with the peak response being produced.

An example of the coding for each of eight pulses is shown in Figure 5. This is a group-complementary code matrix with K rows and N columns. Each row is the phase coding for each transmitted pulse, each having N bits of phase coding. This structure is such that each row is a maximal length code with an extra bit added at the end. All subsequent rows are shifted versions of the first but with the extra bit added after the shift. In addition, the last pulse transmitted is not coded, as shown by the last row will be all ones.

The total multiword process is summarized in Figure 6 where eight pulses are transmitted, received, and cross-correlated with eight reference pulses. The results of each correlation process for each received pulse is added to the previous until all eight pulses are processed. The result is shown as a peak of value 48 (value of 6 from each of 8 pulses) with no sidelobe responses. Although intermediate correlation results do produce sidelobes, the eight correlations combine with cancellations and result with zero sidelobes in the final sum.

A comparison of the use of group-complementary codes in a pulse train with the use of only one code word in a pulse train is seen in Figure 7. The first two traces show the pulse train encoded with the same code word and its autocorrelation, respectively. The last two traces show the pulse train with K group-complementary code pulses and its corresponding autocorrelation function. Notice that the sidelobes around each peak response have been eliminated and in fact have been eliminated for nearly twice the interpulse period (T) which is more than the unambiguous region of interest. Where ambiguous peak responses occur in the constant code case, they have been eliminated in the multiword case. However, sidelobes are seen to still occur at previous ambiguous intervals. The effect on PRF has been to effectively lower it by a factor of K and the new unambiguous interval is KT. The desired and significant feature is that no sidelobes are produced near the peak response for the principle unambiguous interval of T which covers the fundamental target range of interest.

The previous results have been for zero doppler targets. Consideration of both doppler and range are seen by examining the ambiguity response. Such is seen in Figure 8 where the square root of the function is plotted to emphasize the details. This response is for a train of 16 pulses processed in 16 point DFT, each pulse being encoded with a 15 bit maximal length sequence. The principle response is repeated along the doppler axis every PRF interval and along the range axis every interpulse interval. Responses are seen along the delay or range axis for near zero doppler and it is this out-of-range region where ground clutter sidelobes would add up to offer strong competition with a target at the central response. For comparison, the square root of the ambiguity surface for a group-complementary code pulse train is shown in Figure 9. Here, 15 pulses make up the pulse train before the group code is repeated. Each pulse is encoded with a different 15 bit code until the set repeats after 15 pulses. Notice the trough along the range axis which is due to the zero sidelobes at zero doppler.

The sensitivity of the group-complementary codes with bi-phase modulation to velocity or doppler is shown in Figure 10. Higher and higher velocity targets introduce phase shift in the return pulses which causes decorrelation or the realization of less gain in the correlation process. This is reflected as a loss in the figure, being about 10 dB when the closing velocity reaches about 2800 ms. For most air defense targets of interest, the combined missile and target velocity (for homing seekers) results in a loss on the order of 1 dB. The loss associated with land combat engagements is even less.

Many group-complementary code sets are possible since any of several operations upon an initial set will generate a new set. The zero sidelobe property still maintains whenever any of the following operations are performed separately or in combination on an original code matrix: (1) one or more columns may be truncated (making fewer phase intervals within the encoded pulse), (2) columns or rows may be interchanged, (3) one or more rows may be complemented (reverse phase in every interval of the pulse), and (4) one or more columns may be complemented. Such operations offer many permutations of an original matrix which could start with one unique maximal length code. The result being a very, very large set of group-complementary codes.

D. Conclusions

Complete range sidelobe cancellation over a range interval corresponding to the interpulse period is possible with group-complementary coded radar pulse waveforms. A very large set of group-complementary matrices may be generated from an initial matrix through simple matrix operations.

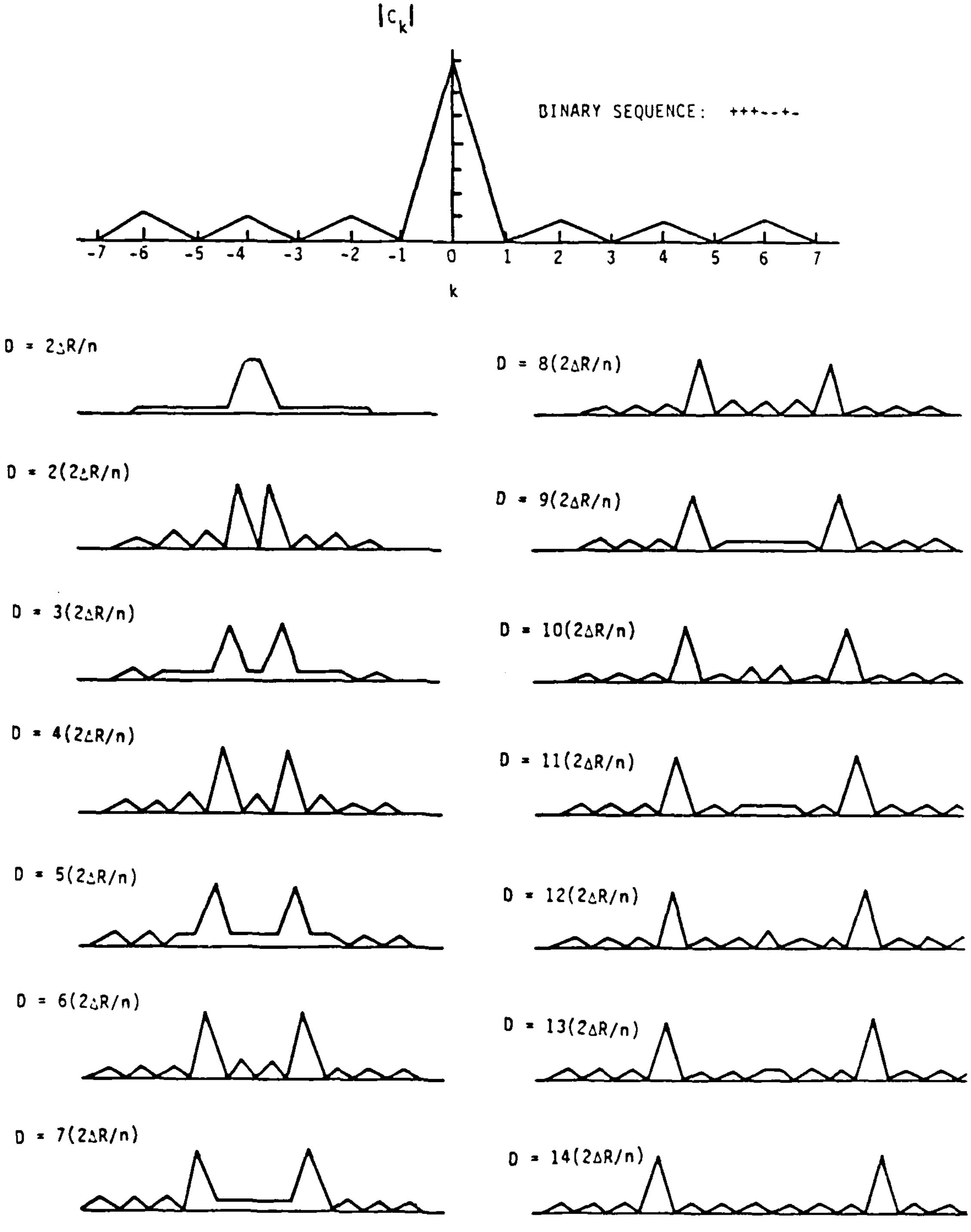


Figure 1. Binary sequence encoded pulse one/two target response.

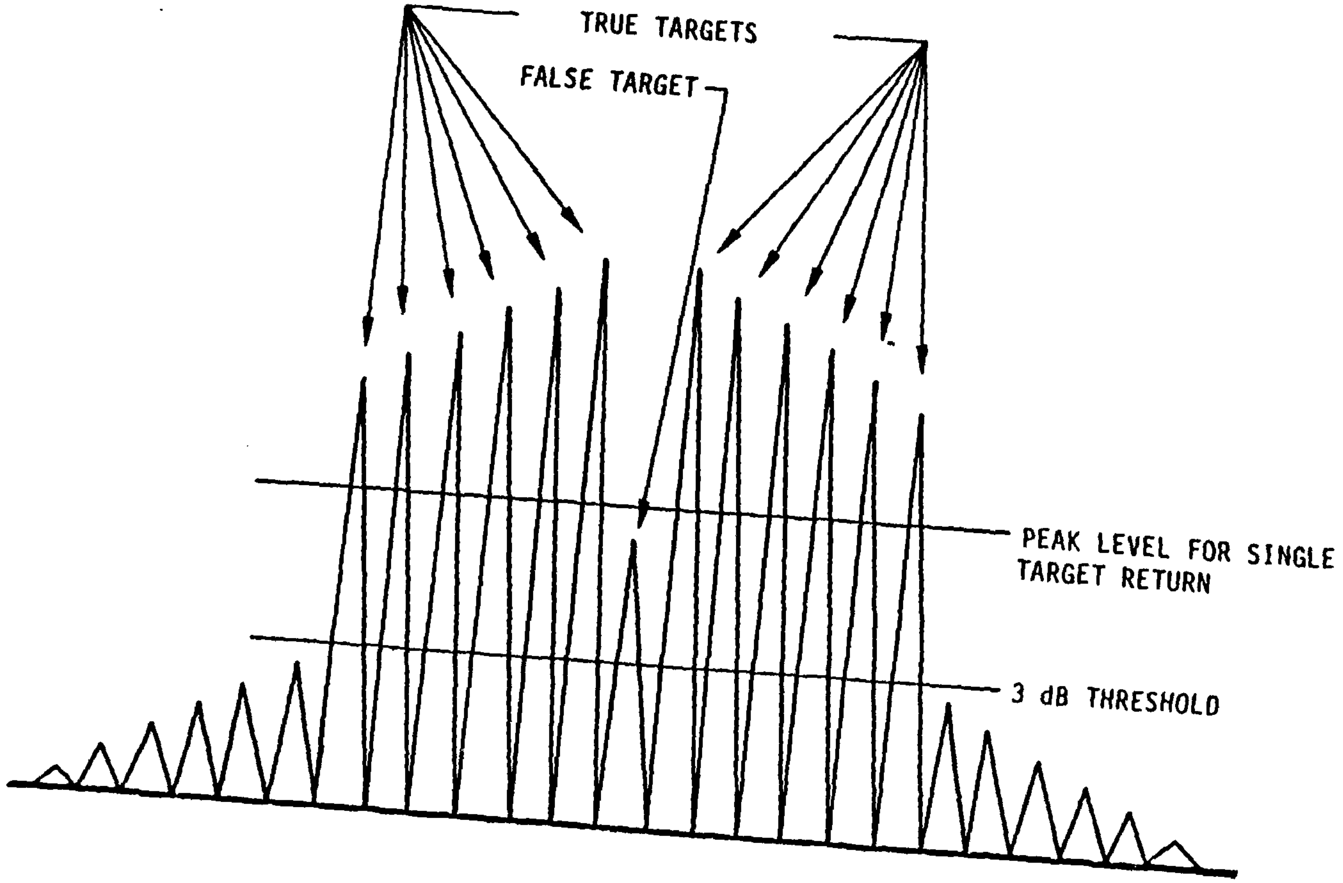


Figure 2. Correlation function for 12 targets.

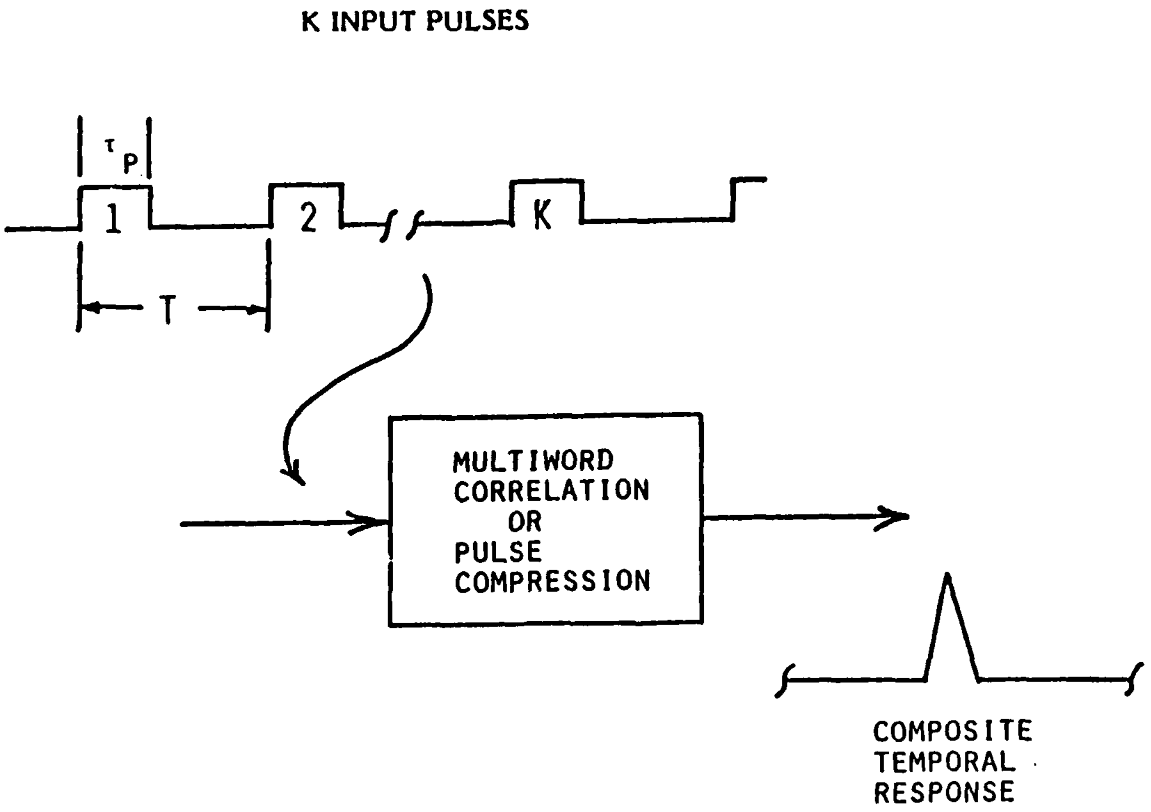
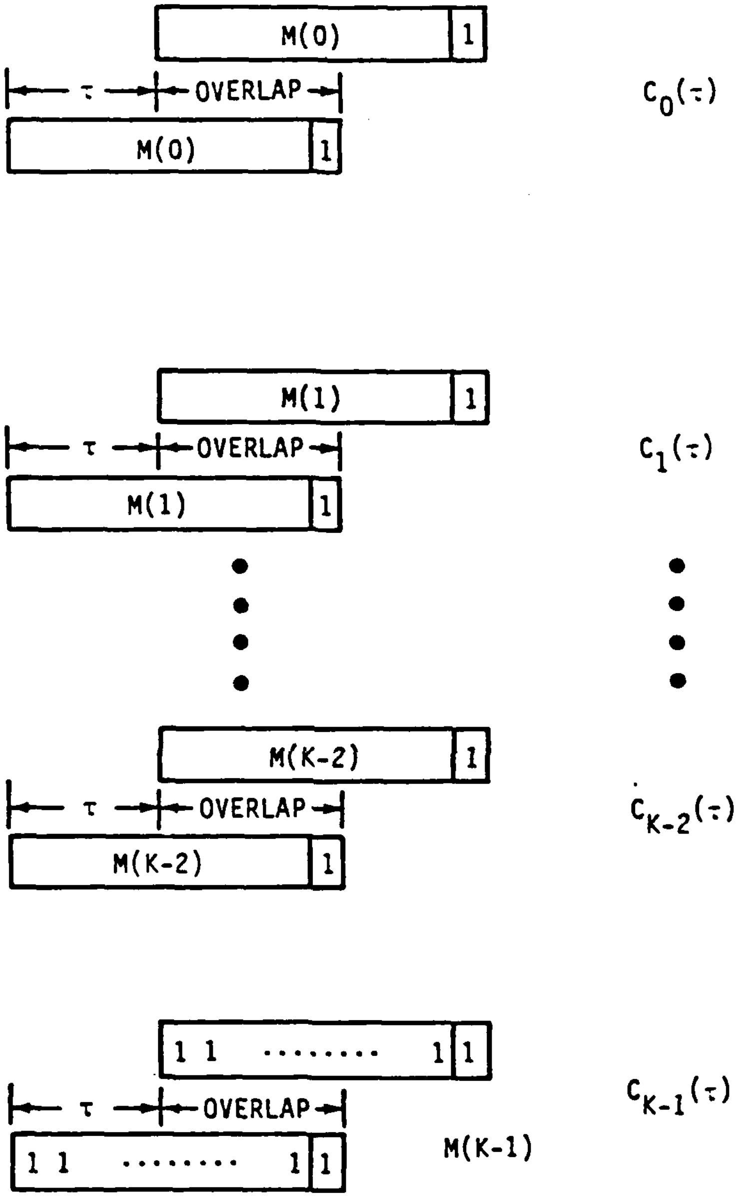


Figure 3. Multiword correlation or pulse compression process.



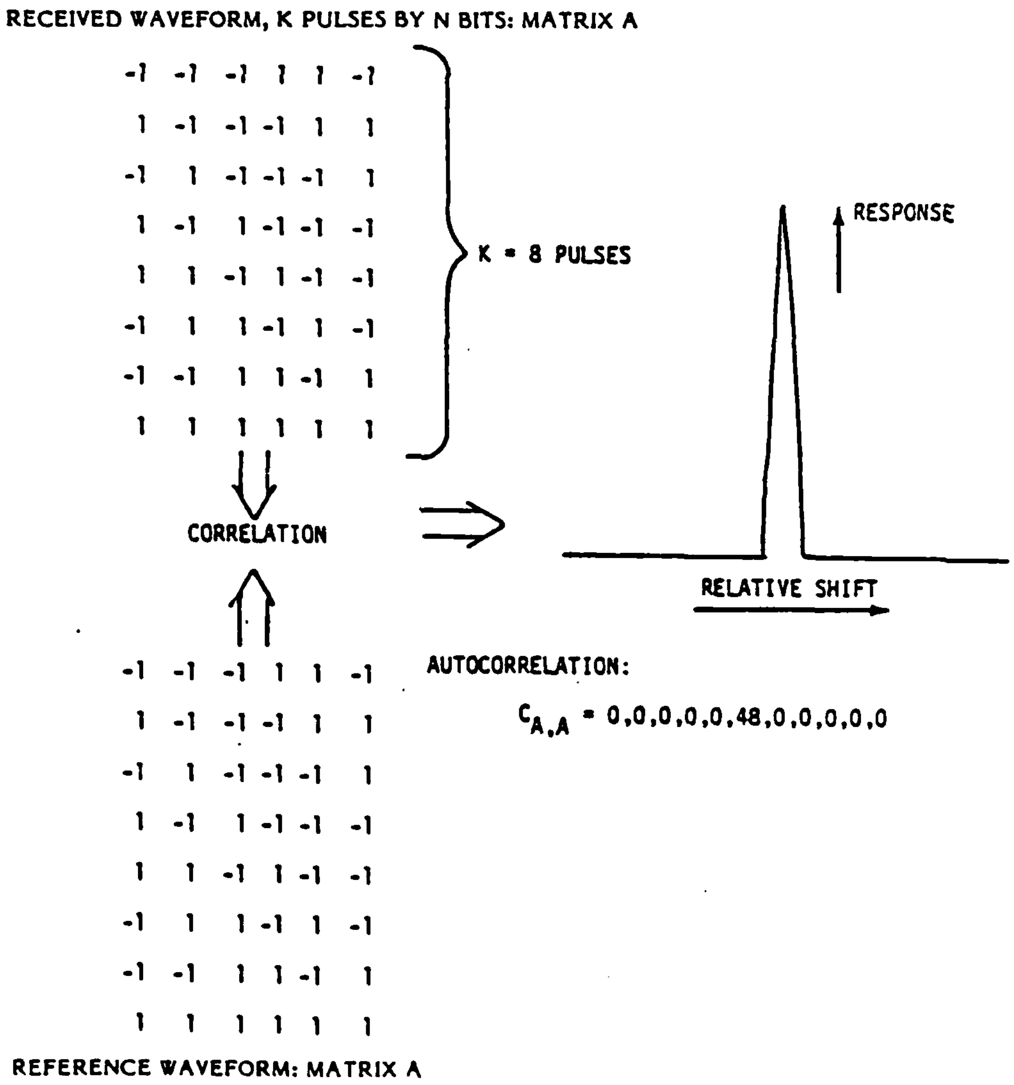
$$C(\tau) = \sum_{i=0}^{K-1} C_i(\tau)$$

Figure 4. Autocorrelation for a shift for group-complementary matrices.

$$K = N = 2^n, \quad n \text{ an integer}$$

$$K = 8 \left\{ \overbrace{\begin{matrix} -1 & -1 & -1 & 1 & 1 & -1 & 1 & 1 \\ 1 & -1 & -1 & -1 & 1 & 1 & -1 & 1 \\ -1 & 1 & -1 & -1 & -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & -1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 & -1 & -1 & -1 & 1 \\ -1 & 1 & 1 & -1 & 1 & -1 & -1 & 1 \\ -1 & -1 & 1 & 1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{matrix}}^{N = 8} \right.$$

Figure 5. Group-complementary code array - an example.

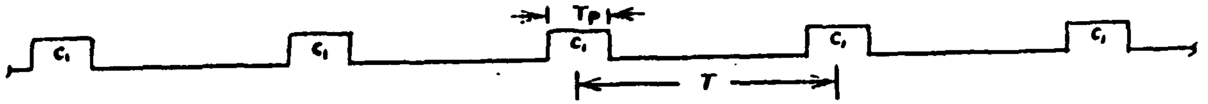


$$\begin{matrix} -1 & -1 & -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & -1 & 1 & 1 \\ -1 & 1 & -1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 & 1 & -1 \\ -1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{matrix}$$

$$\begin{matrix} -1 & -1 & -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & -1 & 1 & 1 \\ -1 & 1 & -1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 & 1 & -1 \\ -1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{matrix}$$

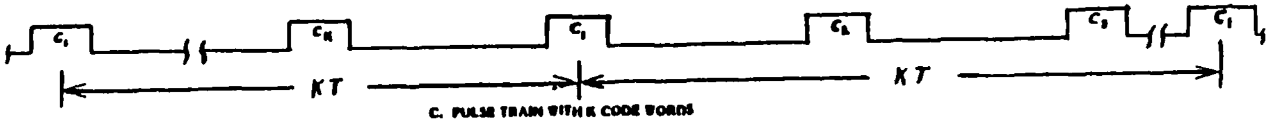
$C_{A,A} = 0,0,0,0,0,48,0,0,0,0,0$

Figure 6. Pulse compression using group-complementary binary codes with optimized autocorrelation properties.

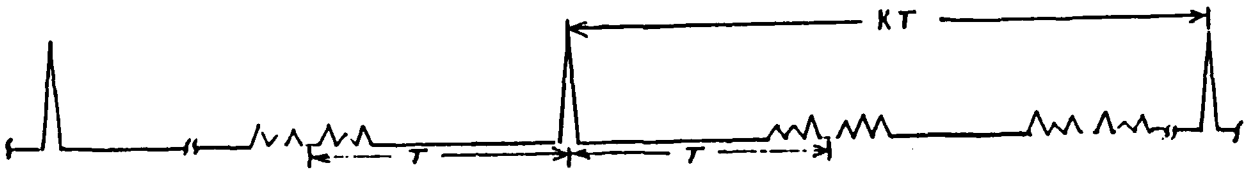


A. PULSE TRAIN WITH SAME CODE WORD C_1

B. AUTOCORRELATION OF WAVEFORM IN A.



C. PULSE TRAIN WITH K CODE WORDS



D. AUTOCORRELATION OF WAVEFORM IN C.

Figure 7. Autocorrelation of pulse train with one code word or group-complementary code words.

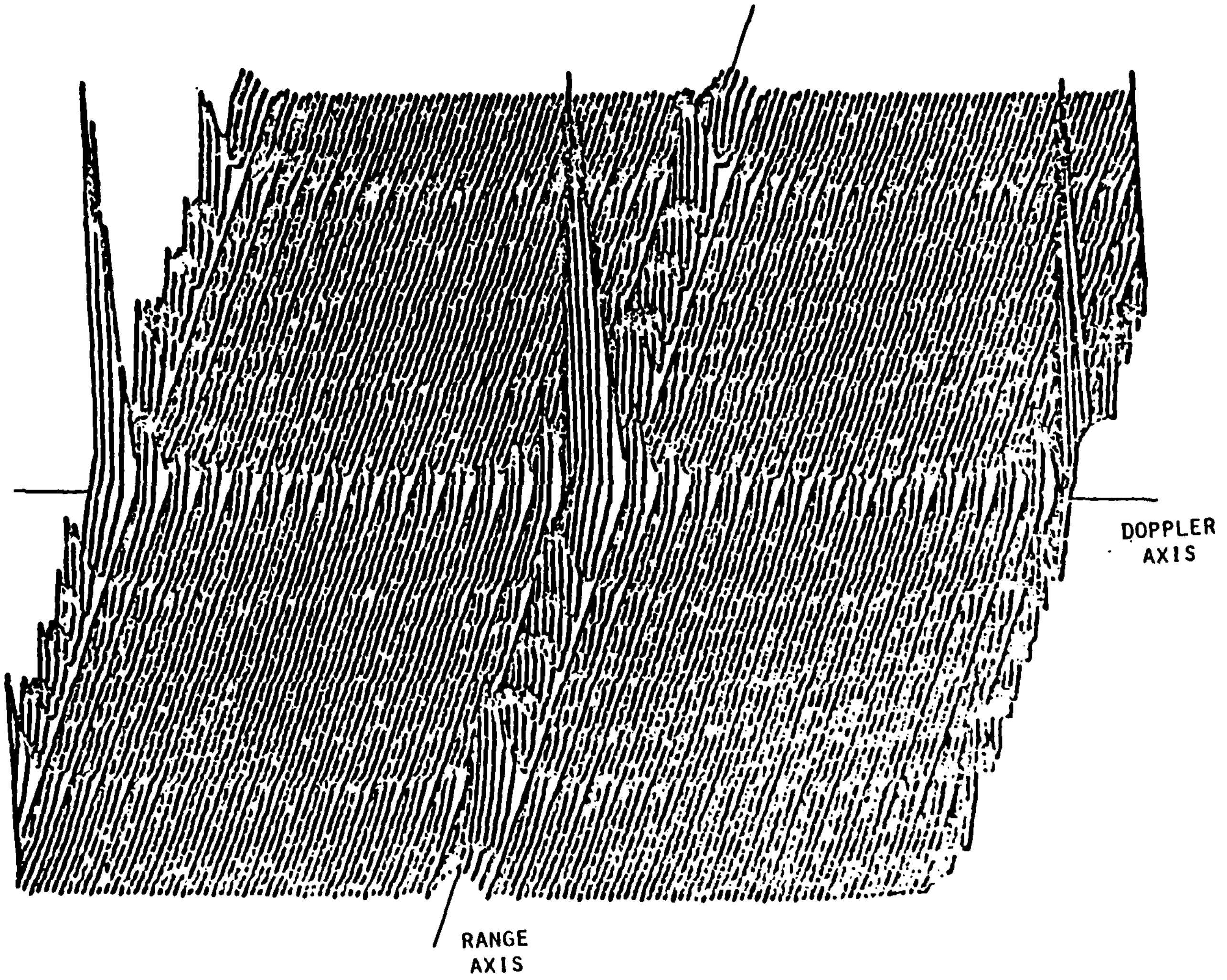


Figure 8. Square root of ambiguity surface for 16 pulse train (15 BIT M - sequence code).

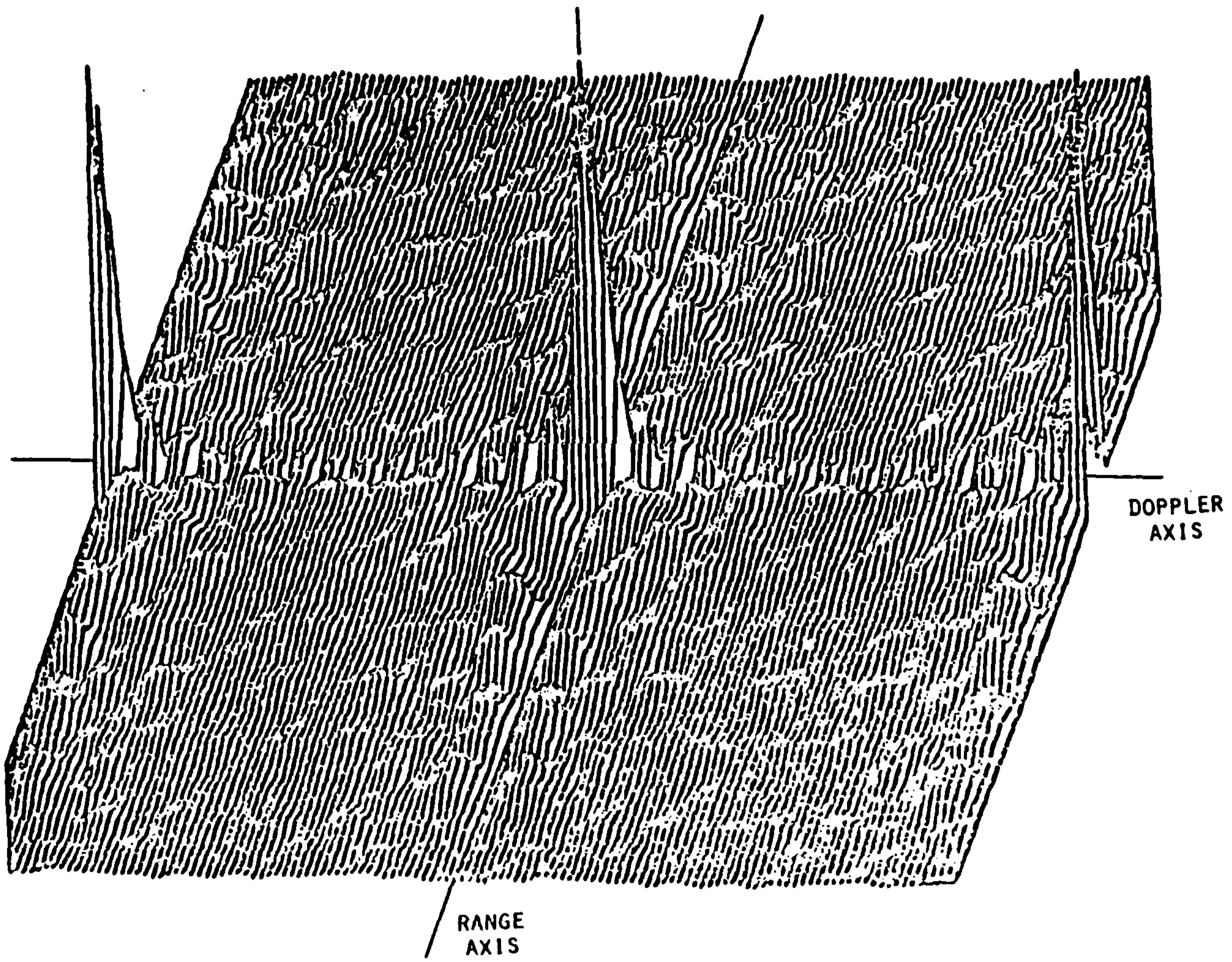


Figure 9. Square root of ambiguity surface for K = 16, N = 15 group-complementary code.

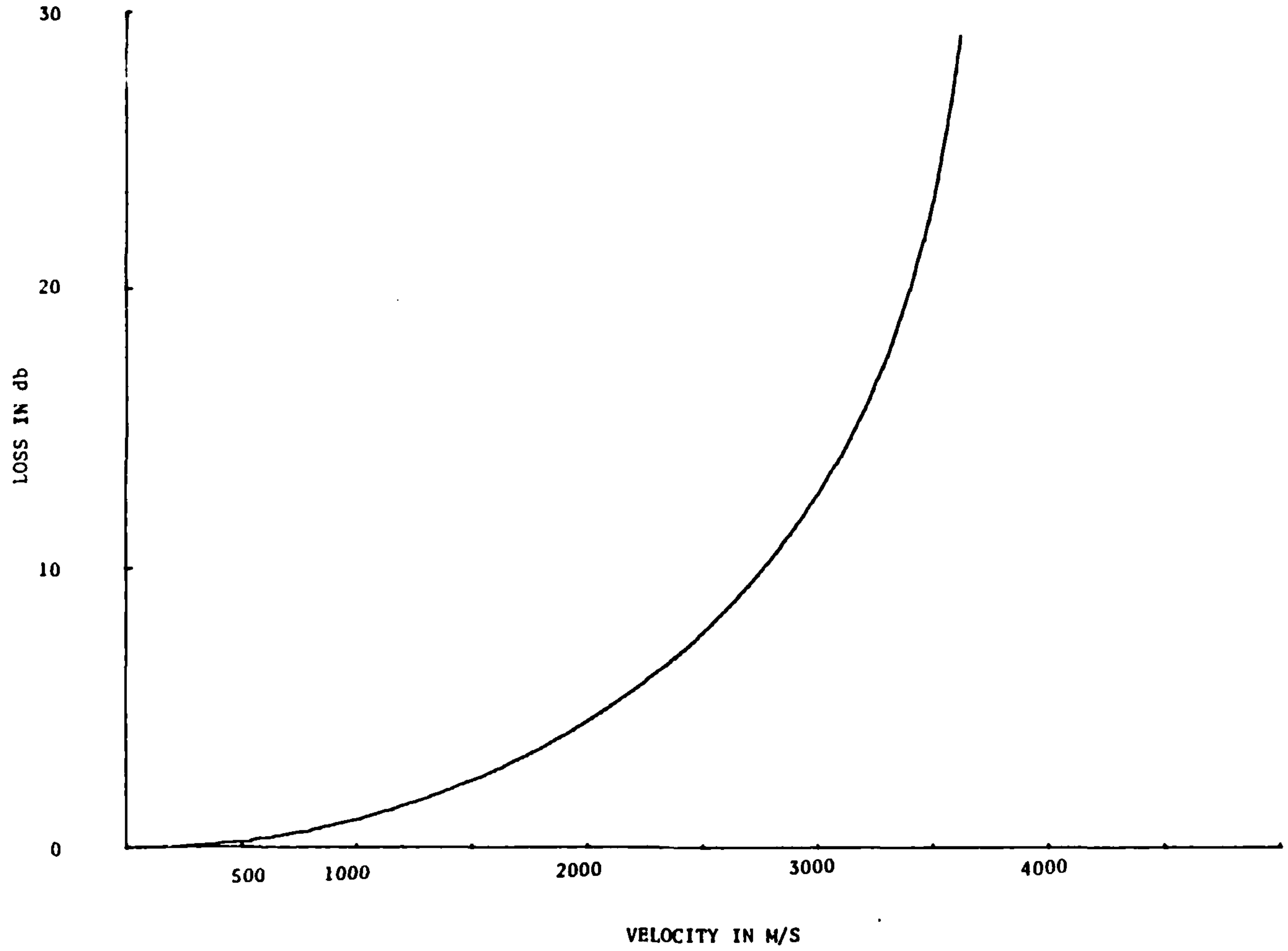


Figure 10. Group complementary code doppler sensitivity.

1. ONE OR MORE COLUMNS MAY BE TRUNCATED
2. COLUMNS OR ROWS MAY BE INTERCHANGED
3. ONE OR MORE ROWS MAY BE COMPLEMENTED
4. ONE OR MORE COLUMNS MAY BE COMPLEMENTED

Figure 11. Operations that produce new group complementary arrays from a Hadamard matrix.

II. GROUP-COMPLEMENTARY CODE SETS: AN UPDATE

A. Introduction

In a previous presentation, waveform coding work in the Advanced Sensors Directorate was discussed. Here, an update reflecting accomplishments since the last discussion is offered. Some review of the basic coding approach is necessary for completeness.

B. Group-Complementary Codes

Waveform coding in this work is for the purpose of achieving pulse compression while reducing time or range sidelobes. Reduced sidelobes help improve discrimination against unwanted, out-of-range signals such as ground clutter, therefore improving target detectability.

The technique being explored in this work is an extension of the complementary code concept introduced by Golay [3]. Golay's complementary series involves processing two coded pulses such that the time sidelobes of the combined pulses are eliminated. This approach has been extended to N pulses and is called group-complementary codes. Here a set of N pulses is transmitted, each pulse being bi-phase modulated with a pseudo-random-like code of K bits each. Each pulse is modulated/encoded with a different (K bits) code. The received pulses are cross-correlated with corresponding reference pulses (usually the same transmitted code) and the results are integrated to yield zero, time sidelobes. Figure 12 illustrates the cross-correlation of an 8 pulse set of 6 bit coded pulses with an identical reference set, and Figure 13 reflects the auto-correlation of two pulse trains, one with each pulse encoded the same and the second with each pulse coded uniquely. Greater details of this code work may be found in references 4 through 7.

C. An Update

The group-complementary coding approach has been implemented in hardware and preliminary results of laboratory and field testing are presented here.

From a previous exploratory development program there existed an RF active seeker suitable for modification to explore group-complementary code implementation. This X-band seeker uses intrapulse, bi-phase coding with selectable pulse widths, code rates, and code lengths. Figure 14 depicts the seeker's use in a short range, air defense role while the inserts show the hardware as used in captive flight testing. Having met the objective in the air defense program, the seeker hardware was available for modification to have a changing code word for each pulse. This modification was made for the 15 bit/pulse, 16 pulse case for several group-complementary code sets. Flexibility in comparing regular pseudo-random, 15 bit code performance with 15 bit group-complementary codes and group-to-group codes was afforded with the hardware modifications.

In the normal seeker configuration, the receiver output feeds each range gate correlator which in turn feeds a 16 point DFT. The DFT formation includes amplitude weighting which was by-passed for group-complementary code implementation to ensure uniform weighting which is required when each reference code word is identical to each transmitted code word. Spectral sidelobe control as well as range-time sidelobe control is realized in group-complementary codes by design of the proper reference code words for a given transmit set and desired sidelobe responses.

For performance assessment in a clutter free situation, a repeater target simulator was designed to accept a sample of the transmitted energy which in turn was delayed, doppler shifted and sent to the seeker receiver. This implementation was with waveguide and did not involve radiated signals. Figure 15 presents the correlator output for two code situations as the receiver range gate position is sweep in range steps over the simulated target. A target doppler of about 12 kHz was imposed on the delayed signal, putting the target about midway in the DFT filter bank. Figure 15a is the range response for one of the regular 15 bit PN codes of the seeker while 15b is a similar response for a 15 bit group-complementary code set (16 code words in the set). The peak range sidelobes in Figure 15a are about 20 percent of the center range position while the sidelobes in Figure 15b for the group-complementary set are in the instrumentation noise level.

Performance in clutter was assessed at a range facility where the 19 degree-beamwidth seeker was located about 10 feet above ground level and directed along a roadway with large trees on each side. A repeater target was placed about 980 meters in range remote to the seeker with a very small doppler offset such that both the target and ground clutter fell within the first doppler filter of the seeker. As the seeker range gate position was sweep out in range (for a fixed receiver AGC), the response of Figure 16 was obtained, again for two code situations. First, for the normal 15 bit PN seeker code in Figure 16a and second, the 15 bit group-complementary code in Figure 16b. Range increases from right to left and the sweep covers from 750 meters to 1,650 or 1,800 meters. Beyond this range the clutter profile reduces to near zero value because of the very low seeker grazing angle and terrain masking.

Clutter reduction from out-of-range positions is easily noted in Figure 16b. The target is located at 980 meters and provides a good return in both cases. In Figure 16b a response is also noted at 1,580 meters which appears to be a false target. Explanation of this response can not be made at this time since the seeker's transmitter failed as this unexpected return was being investigated. Another experiment to repeat the previous and assess further the group-complementary code performance is currently in preparation.

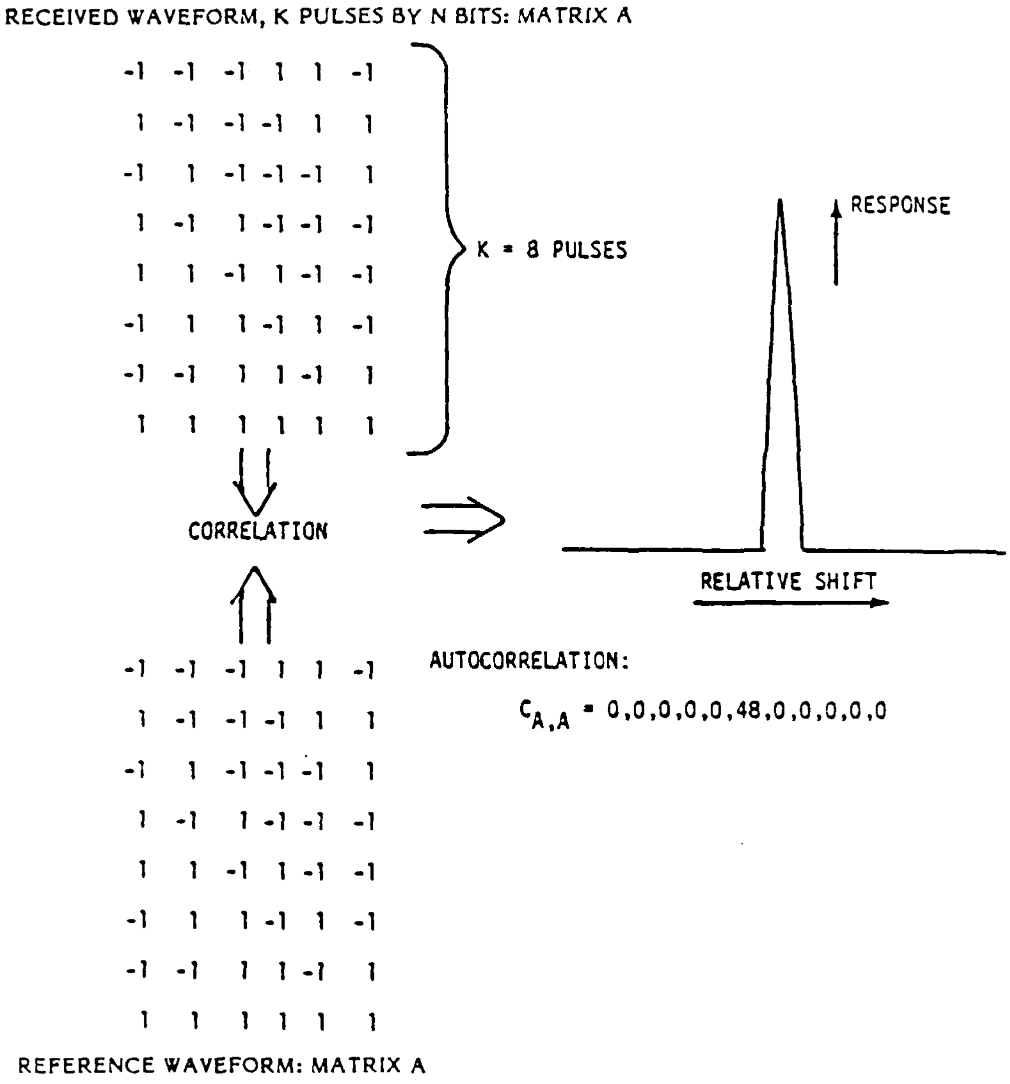
D. Future Plans

One further area of investigation and application of the group-complementary codes is also in the planning and analysis stages. This area involves polarization coding as opposed to phase coding of the carrier for pulse compression. The approach will use a concept developed by Georgia Institute of Technology and patented through the US Army Missile Laboratory. Figure 17 illustrates the basic concept in one configuration. Here two transmit chains (vertical and horizontal polarization) are encoded such that a plus or minus 90 degree phase relationship exists between the two. The two channels are combined in a dual polarization coupler to yield a circular polarized wave for transmission. Within the radiated pulse, the polarization will be right hand (RH) or left hand (LH) circular according to the PN coding.

The received signal will be decomposed into the vertical and horizontal linear polarized channels to be phase detected. The detected output will be unit values, plus/minus which correspond to the encoded pulse. This output is in turn cross-correlated with the transmitted code to yield a compressed pulse output. Odd bounce targets (reflectors) will provide strong negative correlation and even bounce returns will provide strong positive correlation while clutter should be a noisy correlation. The application of group-complementary codes in this concept should strongly reduce out-of-range sidelobe clutter and enhance target detectability as well as aid exploitation of target polarization characteristics.

E. Conclusions

Current work at the Research, Development, & Engineering Center, (formerly the Army Missile Laboratory) with pseudo-random phase coding of waveforms for pulse compression benefits has been presented. Results of recent laboratory and field experiments demonstrating the desirable features of group-complementary coding which significantly reduces out-of-range clutter has been included. Future plans were discussed and included a repeat, with further emphasis, of the previous clutter reduction experiments. Beyond verification of group-complementary coding benefits, analysis and experiments, through seeker hardware modification, are planned to achieve pulse compression with polarization encoding using group-complementary codes.



$$\begin{matrix} -1 & -1 & -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & -1 & 1 & 1 \\ -1 & 1 & -1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 & 1 & -1 \\ -1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{matrix}$$

$$C_{A,A} = 0,0,0,0,0,48,0,0,0,0,0$$

$$\begin{matrix} -1 & -1 & -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & -1 & 1 & 1 \\ -1 & 1 & -1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 & 1 & -1 \\ -1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{matrix}$$

Figure 12. Pulse compression using group-complementary binary codes with optimized autocorrelation properties.

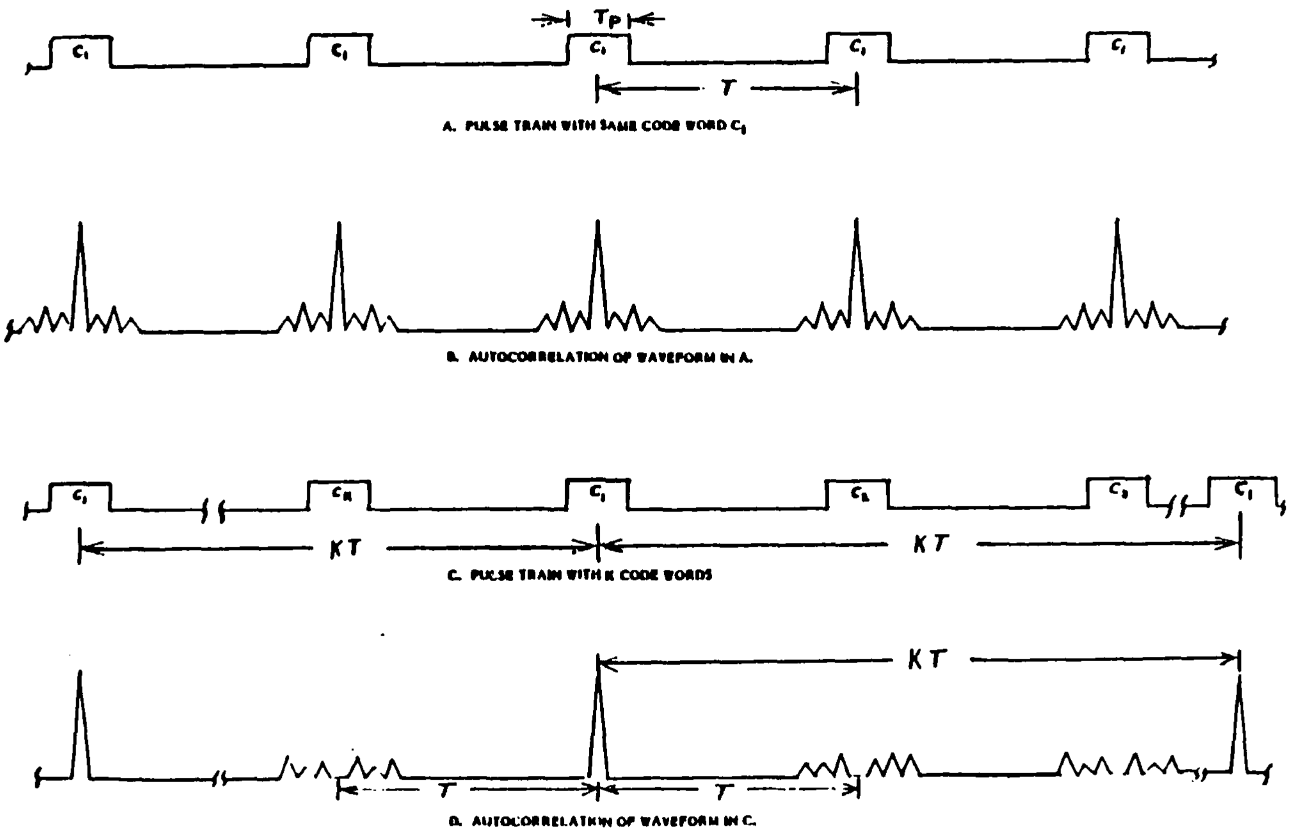


Figure 13. Autocorrelation of pulse train with one code word or group-complementary code words.

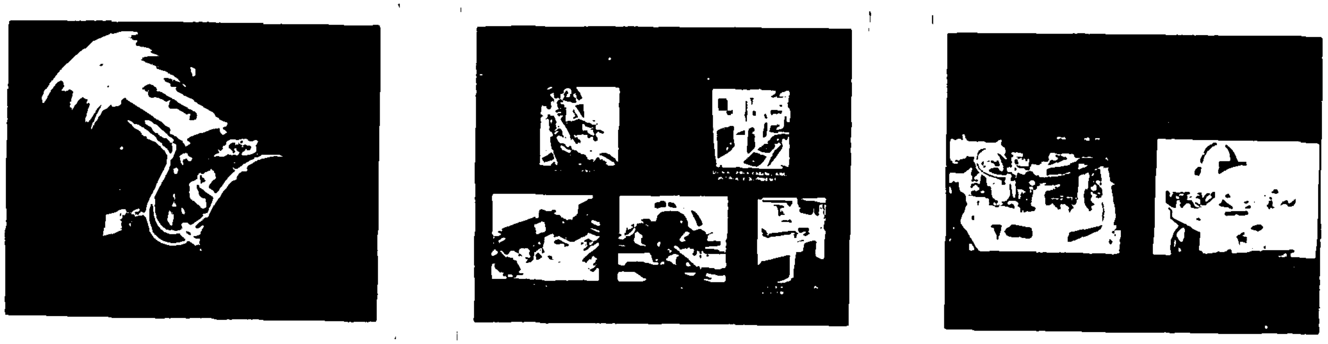
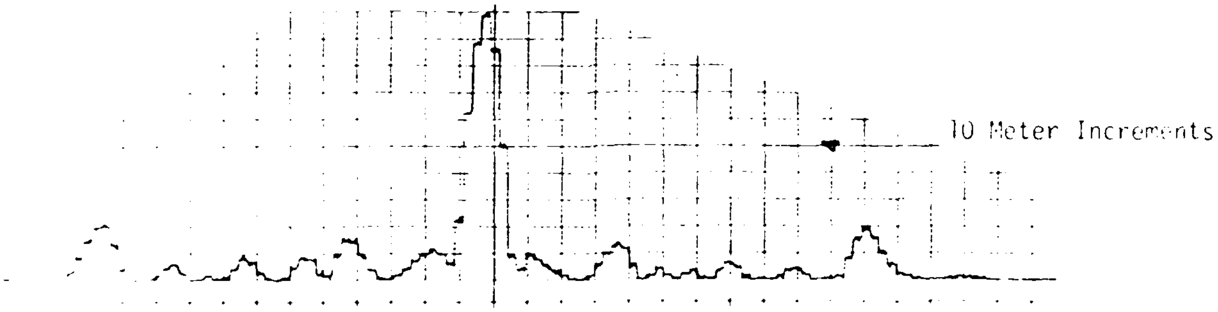
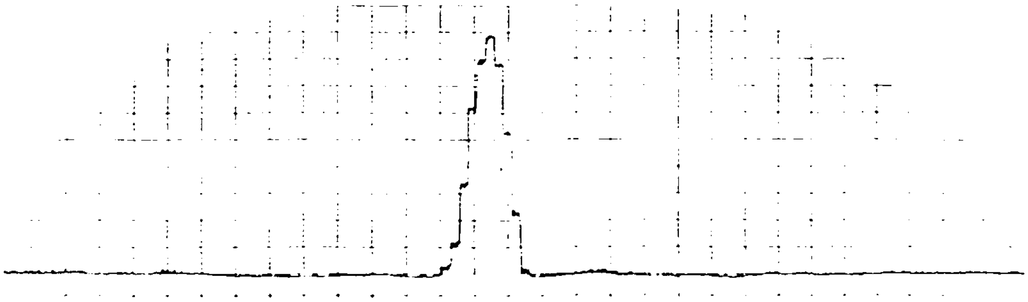


Figure 14. RF active seeker for air defense.

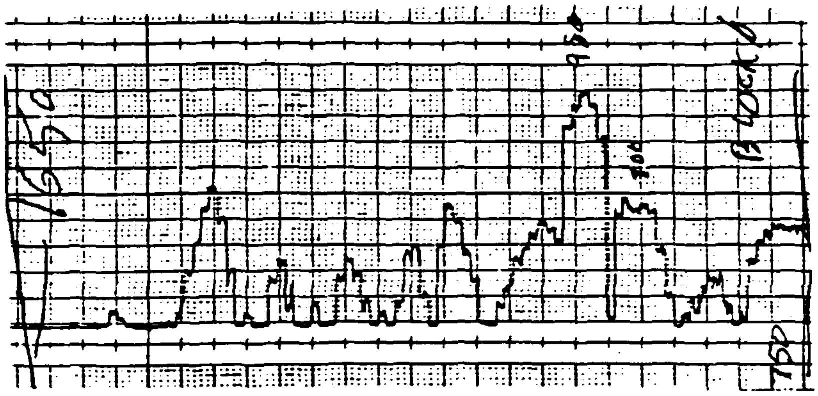


a. Regular 15 bit pseudo-random code.

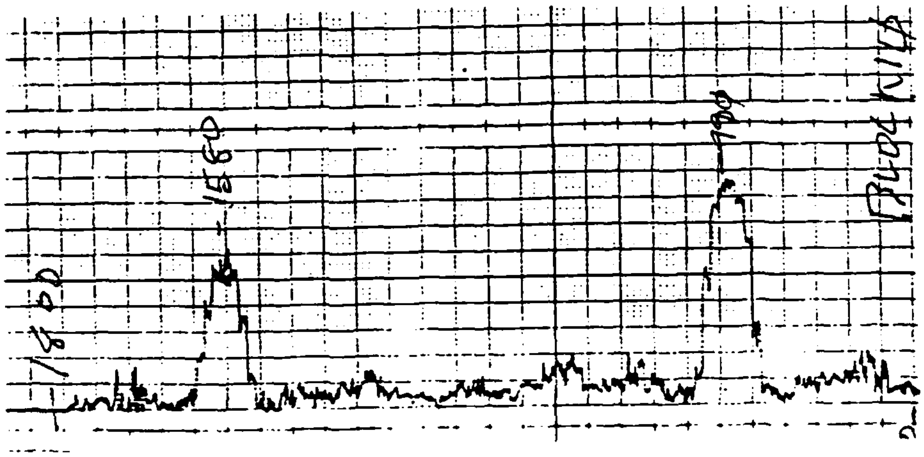


b. Group-complementary code set - 15 bit each.

Figure 15. Performance comparison of a good 15 bit PN code with a group-complementary code set (15 bit) - simulated target in the laboratory.



a. Regular 15 bit pseudo-random code.



b. Group-complementary code set - 15 bit each.

Figure 16. Performance comparison of a good 15 bit pseudo-random code with a group-complementary code set (15 bit) - remote repeater target in ground clutter.

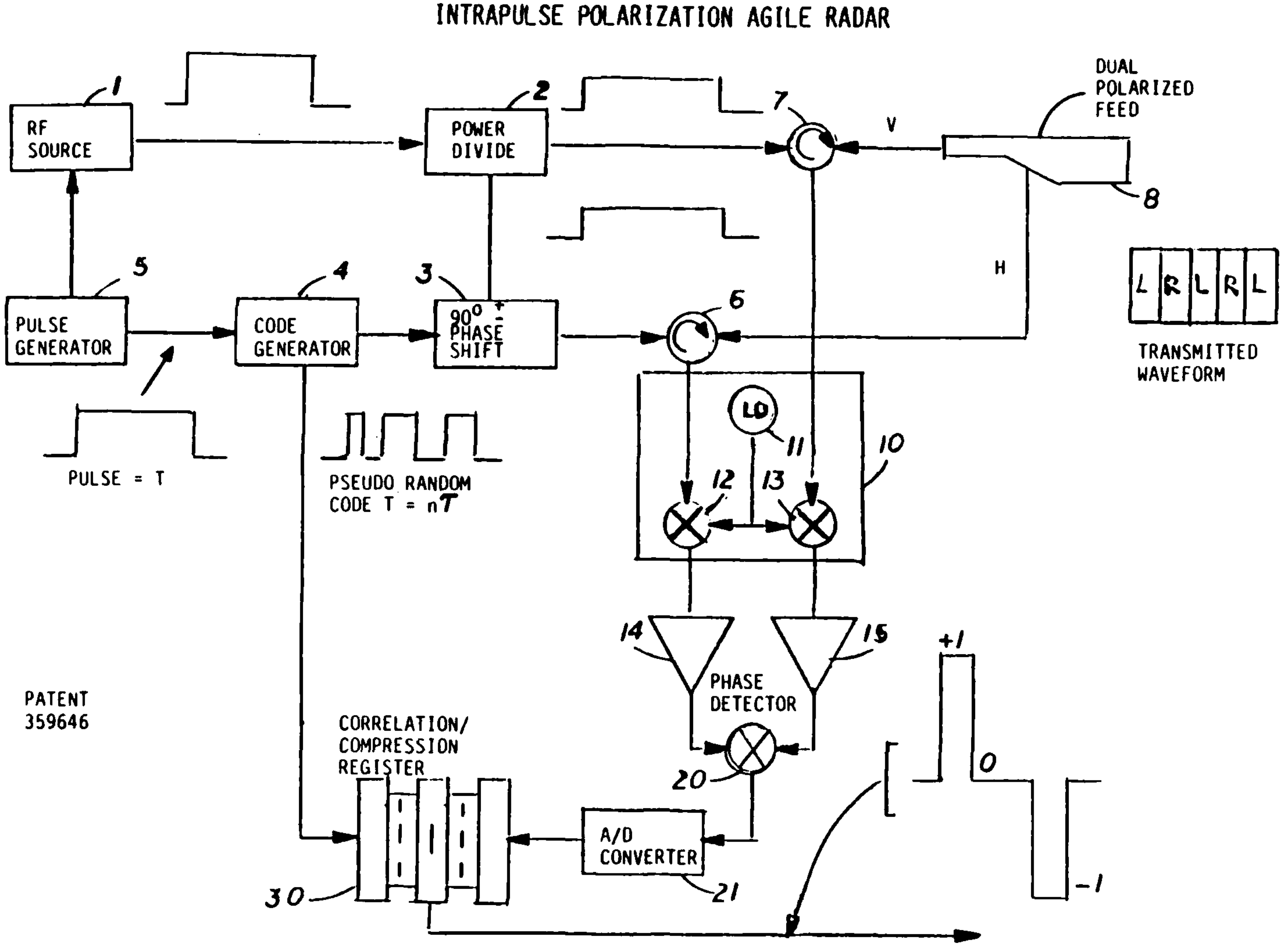


Figure 17. Intrapulse polarization agile radar.

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