How Coded-Pulse Techniques Extend Radar Range

Experimental system uses a wide transmitted pulse with low repetition rate and increases resolution by phase modulating the transmitted pulse carrier

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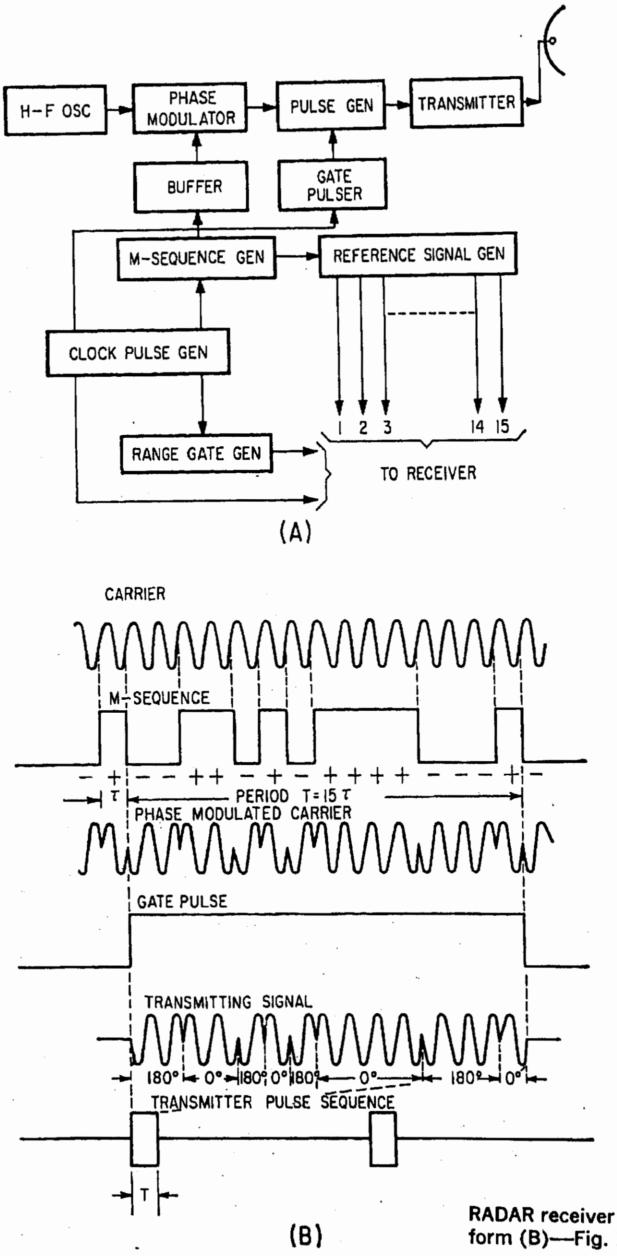


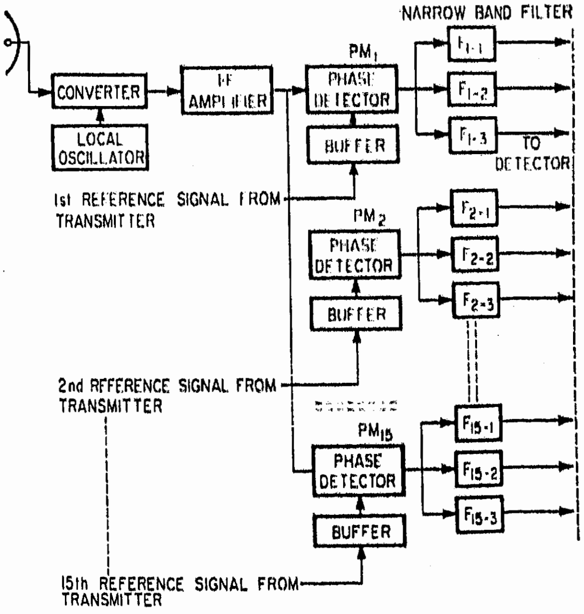
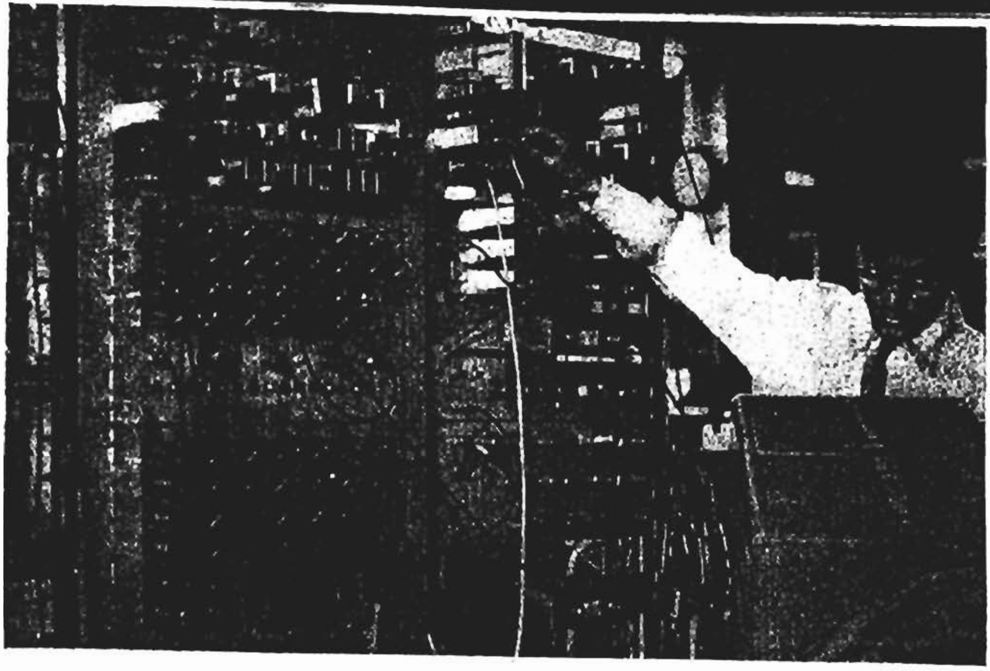


DIAGRAM of the receiving system including narrow-band filters—Fig. 2

RADAR receiver (A) and generation of the transmitted waveform (B)—Fig. 1



RESEARCH ASSISTANT adjusts the top stage of the coded-pulse radar receiver

INCREASING complexity of modern warfare has resulted in a need for sophisticated techniques for long-distance target detection. Simple radar systems have range limitations imposed by average radiated power, and resolution is limited by pulse length and beamwidth acquisition time.

During World War II, principal emphasis in the development of radar techniques and components was centered on increasing range and range resolution performance by higher transmitted peak power and reduced pulse length. As a result, the efficiency of high-power tubes is still often too low in terms of average power. While post-detection integration techniques have been developed to compensate for this inefficiency and extend radar range, they often lead to further losses in the use of total available average power.

Improved Performance—The chirp scheme,[2,3] which employs linear frequency modulation, represents one method with which desirable high-resolution properties may be secured with optimum equipment utilization. However, this technique, like conventional radar methods, possesses an inherent ambiguity in simultaneous determination of both the range and velocity of a moving target.[4]

To obtain improved long-range radar performance, not only must a wide pulse with large total power be employed, but the product of signal bandwidth or duration (time-bandwidth product) must be large. Moreover, the ambiguity function (radar response function) should be sharply defined and have low side-lobe level. In accordance with these requirements, a coded-pulse radar was proposed for long-range applications[6] and lab experiments were performed to demonstrate its principle.

Operation—The desired radar system had to provide both range and doppler information. The system designed utilizes a wide transmitted pulse with a low repetition rate. High resolution is accomplished by modulating the phase of the transmitted pulse carrier. Pseudo-random sequence is generated with a feedback shift register as a modulating signal.

A wide r-f pulse with width T is generated by a crystal oscillator, where the carrier pulse is phase modulated by a pseudo-random signal from a sequence generator. A block diagram of the transmitter is shown in Fig. 1A, while the signal waveforms appear in Fig. 1B. The top waveform in Fig. 1B is that of the unmodulated r-f pulse; the second the pseudo-random sequence derived from the sequence generator[1] that is similar to a feedback shift register; the third waveform represents the phase-modulated carrier; the fourth, the gate pulse; the fifth, the transmitted signal and the last waveform the transmitter pulse sequence.

At the receiver, the signal reflected from the target is phase modulated by a replica of the pseudo-random signal used in the transmitter as shown in Fig. 2. The first local reference signal (lrs) is the replica of the pseudo-random signal without delay. The second lrs signal is the replica with one unit of delay corresponding to one code element or one cycle of the feedback shift register. In the same manner, the n-th lrs signal becomes the replica of the pseudo-random signal with a delay of (n-1) units.

The demodulated signal is supplied to the filter bank, which consists of a number of narrow-band filters each having a bandwidth of $1/T$. For moving targets, the doppler effect produces a frequency difference between the transmitted and received pulse. Since doppler shift is not known beforehand, it is necessary to be prepared to process an echo that occurs anywhere within a wide bandwidth. The filter bank discriminates between the reflected signals and those from targets of different velocities. A number of local reference signals with different delays will discriminate between signals reflected from targets in different positions. The principle of velocity and position discrimination is shown in Fig. 3A and 3B.

The signal waveforms involved in the detection process are shown in Fig. 3A for a zero time difference between reflected signal and lrs signal. Here, the output of the phase modulator is a continuous wave without phase modulation. If there is no doppler shift, the output of the first filter in which signal appears indicates the presence of a target. The other channels yield only small outputs.

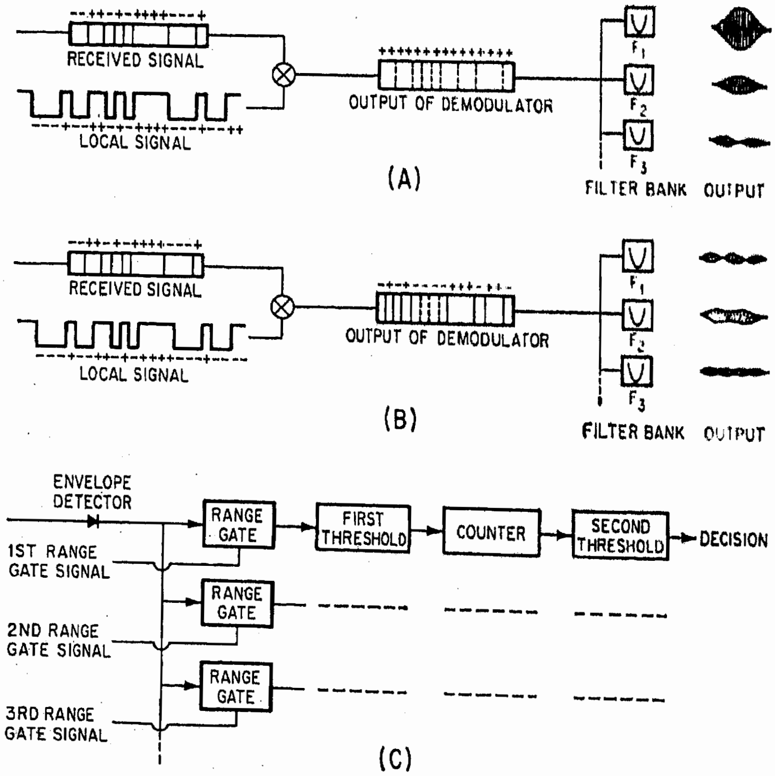
For nonzero time difference between reflected and local signals, the waveforms for detection appear in Fig. 3B. Here, the output of the phase modulator is a phase-modulated sinusoidal wave. Because the pseudo-random sequence is derived by the maximal length or M-sequence feedback shift register, the number of units with a plus-phase of the demodulated waveform is almost equal to that of the minus phase. Since the pluses and minuses cancel, none of the filter outputs builds up sufficiently. This is also explained by the fact that each filter in the bank has a narrow bandwidth.

Filter-bank outputs are fed to envelope detectors. To further extend target-detection range, the double-threshold method of detection was used as a means of post-detection integration.[6,7] Figure 3C illustrates the basic principle of this method.

The pseudo-random signal used to modulate the transmitted pulse has a period T that equals the transmitted pulse width. According to the theory of correlation detection, this prevents the unambiguous measurement of any delay time larger than T. Considering that the transmitted pulse length is T, this ambiguity is eliminated by the range gates that are inserted after the envelope detector. These gates have identical repetition frequency as the transmitted pulses and are arranged so that their time differences are equal to transmitted pulse width. Therefore, the output of the first gate indicates the existence of the reflected signal with a delay between T and $2T$ etc.

LONG RANGE THREAT

Modern aircraft and missiles operate at speeds so high that they must be detected at far greater ranges than necessary just a few years ago. While the coded-pulse radar technique described is not at present being commercially produced, the authors feel that their investigations into this technique demonstrate that it offers substantial radar range extension and image resolution increase. Moreover, they feel sure that research of this type will result in even greater improvements of the state of the art



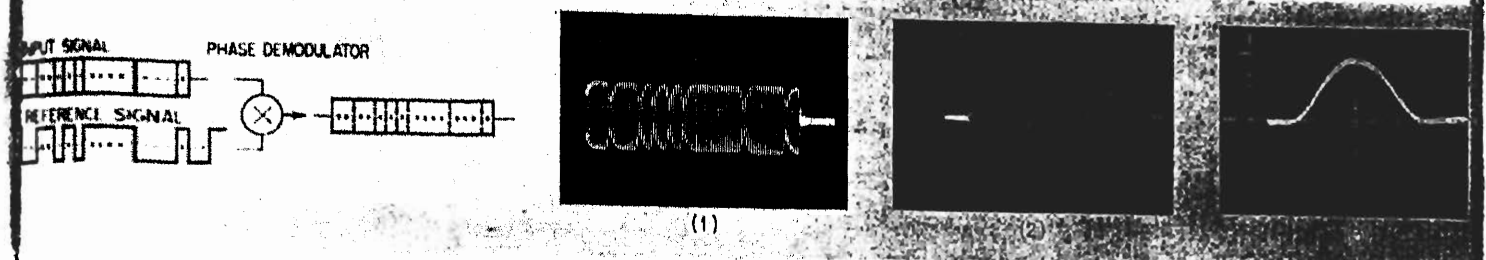
METHOD of correlation detection for zero delay (A), for nonzero delay (B), and the double-threshold detection scheme (C)—Fig. 3

Output—The first threshold detector quantizes the output of the envelope detector into 0 to 1. The succeeding counter integrates the number of 1's during a certain time interval. Should this number exceed the second threshold, the alarm signal will be obtained. The double-threshold method of detection makes possible the application of digital techniques to the detection process to stabilize the system by eliminating various external disturbances.

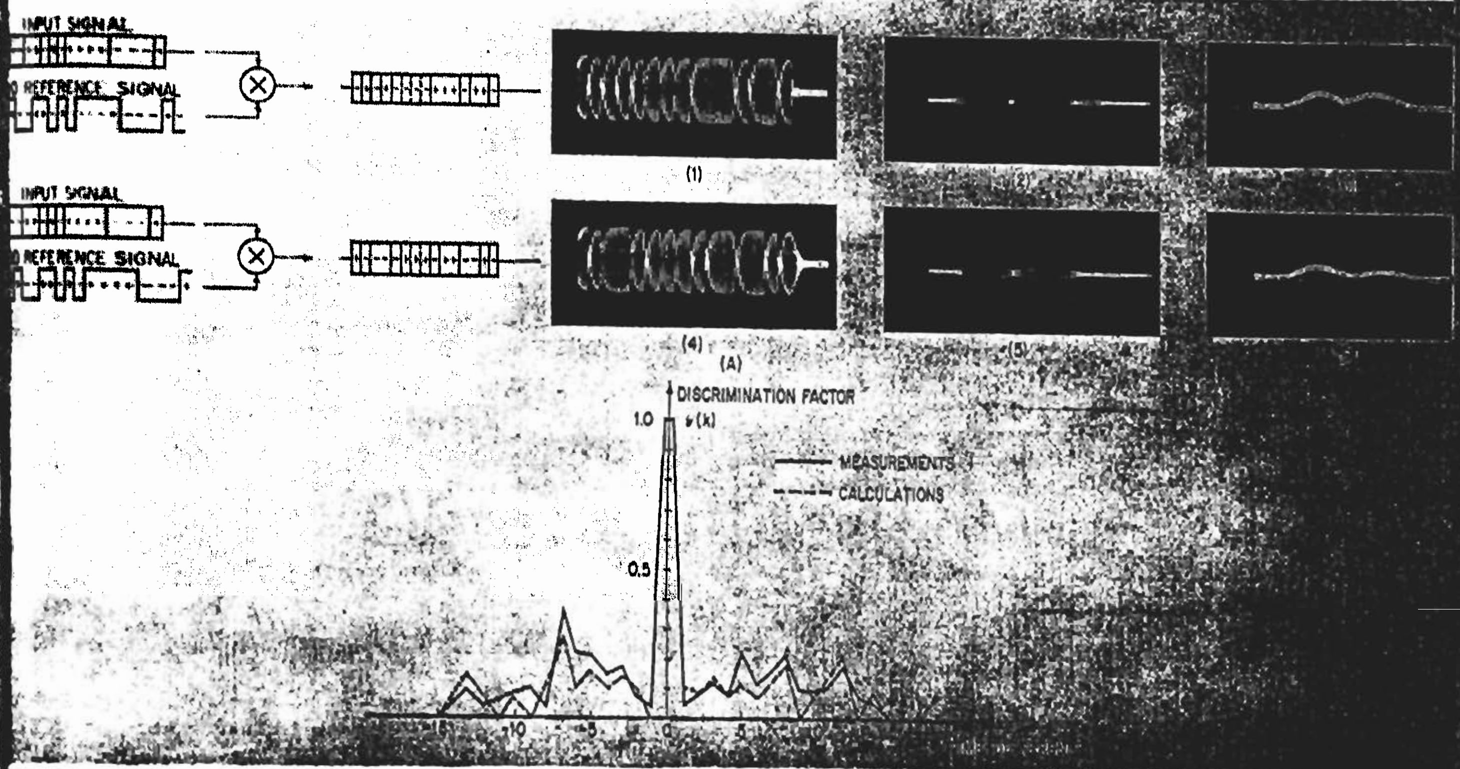
Figure 4 shows the waveforms involved in the detection process for zero time difference between reflected and local reference signals. In these photos, the lab model used a carrier frequency of 1.9 Mc, a pulse repetition frequency of 100 cps, a pulse width of 1 millisec and a pseudo-random sequence of 15 for modulation.

A fifth-order, maximally-flat-delay LC filter with a 3-db bandwidth of 760 cps and a center frequency of 100 kc was used for the narrow-band filter. According to results obtained, the doppler shift[8] of ±300 cps has negligible effect on the output amplitudes. Moreover, a doppler shift of ±600 cps gives 6 db attenuation and a shift of ±900 cps gives nearly zero output.

Waveforms for nonzero time difference between reflected and local signals are shown in Fig. 5A. They illustrate the incomplete buildup of the output waveform of a narrow-band filter. Observations made for each time difference between local and reference signals resulted in the ambiguity curve of Fig. 5B where the ordinate shows the relative amplitude of the narrow-band filter output. The unit k represents one cycle of the feedback shift register. From these results, the poorest discrimination factor is 0.3, while this factor is better than 0.2 over the wide range of k. The peak at the origin indicates the true coordinate of a single target, with the response falling off sharply from the origin. According to theory, the sharpness of the peak depends upon the bandwidth of the modulating signal. Increasing the maximal period of the



SCOPE PHOTOS showing the output of the phase modulator (1), output of the narrow-band filter (2) and the linear-detector output (3) for zero-delay correlation detection as in Fig. 3A—Fig. 4



WAVEFORMS corresponding to the detection scheme shown in Fig. 3B, where photos 1 and 4 show the output of the phase modulator, 2 and 5 are narrow-band filter outputs and 3 and 6 are linear detector outputs (A) and ambiguity diagram showing discrimination factor vs time difference (B)—Fig. 5

pseudo-random sequence derived from a feedback shift register results in an indefinite increase in peak sharpness. For a specific sequence with a length of 15, spurious peaks appear at $k = -7$, $k = 5$, etc. It seems logical that these peaks can be further decreased by employing a pseudo-random sequence with a larger maximal period. Furthermore, the magnitude of spurious peaks can be reduced in practice with post-detection integration of successive radar responses. In this case, the sharpness of the origin peak will also be increased.

The authors would like to emphasize that this work represents experimental results of the response of one specific system. However, they believe that proper waveform design can further improve the sharpness at origin and reduce the magnitudes of spurious responses.

REFERENCES

(1) D. A. Huffman: "The Synthesis of Linear Sequential Coding Network", Information Theory, The Third London Symposium, Sep. 1955.

(2) C. E. Cook: "Pulse Compression-Key to More Efficient Radar Transmission", *P.I.R.E.*, 48, 3, p 310, March, 1960.

(3) J. R Klauder, A. C. Price, S. Darlington and W. J. Albersheim: "The Theory and Design of Chirp Radars", B.S.T.J., 39, 4, p 745, July, 1960.

(4) J. R. Klauder: "The Design of Radar Signals Having Both High Range Resolution and High Velocity Resolution", B.S.T.J., 39, 4, p 809, July, 1960.

(5) K. Endresen and R. Hedemark: "Coincidence Techniques for Radar Receivers Employing a Double Threshold Method of Detection", *PIRE*, 49, 10, p 1561, Oct., 1961.

(6) W. Fishbein and O. E. Rittenbach: "Correlation Radar Using Pseudo-[illegible] Modulation", *IRE, Trans. on I.T.*, [illegible] 1961.

(7) J. V. Harrington: "An [illegible] the Detection of Repeated Signals [illegible] by Binary Integration", [illegible] *I.T.*, March, 1955.