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AN ELECTRONIC TARGET SIMULATOR FOR USE WITH OPERATIONAL RADAR SURVEILLANCE SYSTEMS

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FOREWORD

This report covers part of the research on human-engineering problems of air traffic control being conducted by the Laboratory of Aviation Psychology and the Department of Electrical Engineering of The Ohio State University, with Dr. Paul M. Fitts as Project Supervisor. The aim of this research is to establish psychological principles applicable to the design and operational use of future air traffic control equipment and procedures.

This work was initiated under contract No. AF 33(616)-43 with Dr. R. W. Queal, Jr. acting as Project Scientist. It is being continued under Contract No. AF 33-(616)-3612, Project 7192, Task No. 71596. Technical monitoring of this contract with The Ohio State University Research Foundation is performed by Dr. J. C. McGuire of the Aero Medical Laboratory, Directorate of Research, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. The research program is conducted in close liaison with the Air Traffic Analysis Branch, Test Engineering Division, Directorate of Flight and All Weather Testing, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, and the Air Traffic Control and Navigation Division, Headquarters, Air Research and Development Command, Detachment No. 1, Wright-Patterson Air Force Base, Ohio, in support of System 431L.

Mr. George Harter wrote most of the report and is responsible for most of the design contributions. He is now with Farnsworth Electronic Company, Fort Wayne, Indiana.

Mr. Peter Gain contributed chiefly to the design and evaluation work in adapting the basic OSU target simulator for operation with the electronic portion of the Device 15-J-1c and Air Force terminal area radars, and was in charge of constructing and testing the unit which was tried out at Wright-Patterson Air Force Base.

The authors wish to express sincere appreciation to Dr. P. M. Fitts for making this work possible and for his assistance and timely suggestions in the preparation of this report. Gratitude is also expressed to Dr. Earl A. Alluisi for his constructive editing, and to Mr. Conrad L. Kraft for his active liaison that maintained a continued interest in this project among operation, engineering, and research people.

ABSTRACT

An Operational Target Simulation (OTS) system for simulating targets and mixing them with "live" targets on operational PPI-type radar displays has been described. Three designs have been proposed. Each of the three was composed of an electronic target generator (of the type used in the OSU 30-target electronic radar ATC simulator) and the additional circuitry required to convert the rectangular-coordinate output signals of the target generator to polar-coordinate signals compatible with the video-type intelligence required for radar display. It was in the method used for the transformation of this information from rectangular to polar form that the three designs differed.

The first design makes use of a carrier system to facilitate an all-electronic coordinate transformation. It has the advantage of providing the possibility of packaging a small, self-contained, target simulator unit.

The second design makes use of analog-computer elements to achieve the necessary coordinate transformation. This design should be especially applicable to laboratory situations in which a standard analog computer is available, in which extreme versatility is important, and in which only a few simulated targets need be displayed.

The third design makes use of elements of the Moving Radar Targets Generator, Device 15-J-1c, to form an OTS system using the electronic target generator of the OSU-ATC simulator. Although not as efficient as the first or second designs, this third design has the advantage of making use of elements of the 15-J-1c that may be available at the present time. It could be used as an interim OTS system; it should provide adequate radar target simulation for ATC training and limited experimental purposes.

A prototype unit based on the third design was constructed and tried out using the operational AN/CPN-4 radar at the RAPCON Center, Wright-Patterson Air Force Base, through collaboration of the Directorate of Flight and All Weather Testing. These tests were successful.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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1. INTRODUCTION

A multi-target electronic radar simulator for use in air traffic control (ATC) studies has been designed and built at The Ohio State University (2, 3). Elements of the OSU-ATC simulator have been adapted to form an electronic target-simulation system that can be used to generate synthetic radar targets on operational radar plan position indicators (PPI's). This operational target simulation (OTS) system is described in this report.

Two major areas of radar ATC simulation are provided in the original OSU-ATC simulator (2, 3). First, moving target information is generated for as many as 30 simulated aircraft. Second, position information for each simulated target is displayed on a simulated PPI radar display.

The moving target information is generated for each simulated target by use of conventional electronic analog techniques providing independent control of aircraft flight characteristics such as speed, heading, turn rate, and altitude. The flight characteristics of each simulated aircraft are dynamically controlled, not preprogrammed with a fixed-course type of control.

The simulated PPI radar display, on which the position information is displayed, is a cathode ray tube (CRT) with an electrostatic deflection system. The design permits the use of a sweep-line generator, a wind-effect generator, a video-noise generator, target coding, and other components that either add to or degrade the information presented on the display.

The moving target information for each simulated target in the OTS system is generated in a manner similar to that of the OSU-ATC simulator. The target position information for each simulated target in the OTS system, however, is converted from a d.c. analog form (in which it is used in the OSU-ATC simulator) to the video-type intelligence required for display on an operational radar indicator. The principal advantage of this change is that the resultant OTS system can be used in conjunction with an operational radar surveillance system. "Live" radar targets may be supplemented with realistic synthetic (simulated) targets for purposes of both training and research in on-the-job situations of operational ATC centers.

2. THE OHIO STATE UNIVERSITY THIRTY-TARGET ELECTRONIC RADAR ATC SIMULATOR

The OSU-ATC simulator has been fully described elsewhere (2, 3); the brief description given below is intended to provide the background necessary for a full description of the OTS system.

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2.1 General Description

The OSU-ATC simulator displays moving aircraft blips on a simulated PPI display. The targets are individually controlled at target generator stations. Each station has facilities for the control of aircraft flight characteristics such as airspeed, altitude, position, heading, and rate of turn. Target position information for each simulated aircraft is fed into a single channel through a time-sharing switch to a CRT display. This display is located in a simulated ATC center that is remotely located with respect to the target generator stations. Several communication channels provide normal contact between controllers and pilots. The flights of up to 30 aircraft may be simultaneously simulated with the OSU-ATC simulator; the same principles of simulation could be used to permit the simulation of any number of aircraft.

The target generators of the OSU-ATC simulator were designed to allow simulation of aircraft flight characteristics over the following ranges:

a. Airspeed control.—Each target generator can provide an indicated airspeed between 100 and 600 kt. in the following discrete steps: 100, 125, 150, 175, 200, 250, 300, 400, and 600 kt. These airspeeds were chosen for use in a specific series of experimental studies; any desired values could be used. Furthermore, if less reliability could be tolerated in resetting specific airspeeds, a continuous rather than discrete choice of indicated airspeeds can be used.

b. Heading control.—The desired heading of a target can be presented on the control panel of that target's generator. The actual heading of the target as seen on the simulated radar display can then be changed upon command to any desired heading. Two standard rates of turn are provided for, and the operator selects which of the two is used in any given turn. An automatic stop mechanism is provided on the heading indicator to stop the turn when the desired new heading is reached.

c. Rate-of-turn control.—Standard rates of turn of 1.5 and 3.0 deg./sec. are provided for turns both to the left and to the right. If less accuracy could be tolerated in resetting specific rates of turn, a continuous rather than discrete choice of rates can be used.

d. Altitude control.—There is on each target generator a manually-operated altitude control for each simulated target. The effect of altitude on a two-dimensional display is to alter the apparent velocity of aircraft, giving a discrepancy between ground speed and indicated airspeed. The altitude controls used with the OSU-ATC simulator are calibrated for a continuous range of altitudes from 0 to 40,000 ft.; this range was selected for use in a specific series of experimental studies and could be changed to any desired value. If desired, the manual control of altitude could be replaced with a continuous rate-of-climb and rate-of-descent generator.

e. Initial position control.—The simulated targets may be positioned individually at any place within the maximum simulated radar range at any time. This is accomplished by use of an initial position control that provides for an east-west position and a north-south position in terms of indicated distance from the center of the simulated PPI display.

2.2 Theory of Target Generation

The OSU-ATC simulator provides position information for each simulated target as a function of time. The schematic diagram of Fig. 1 indicates the functions performed by each target generator. The input variables are airspeed, heading angle, turn rate, altitude, and wind velocity. The target generator operates on these variables to produce outputs proportional to the X (east-west) and Y (north-south) position of the target in a rectangular coordinate system. Thus, although the basic inputs to the generator, airspeed and heading angle, are in polar form, the outputs, X and Y, represent target position in rectangular form.

The conversion from polar to rectangular coordinates required of each target generator is schematically diagramed in Fig. 2. Airspeed (V) and heading angle (θ) are the input variables that define the velocity vector of the simulated aircraft. The rectangular components, V_x and V_y, of the velocity vector are defined by the following equations:

$$V_x = V \cos \theta \tag{1}$$

$$V_y = V \sin \theta \tag{2}$$

These rectangular component velocities are used to generate target position (X, Y) as a function of time. This can be accomplished by single integrations as shown by the following equations:

$$X = \int_0^t V_x \, dt \tag{3}$$

$$Y = \int_0^t V_y \, dt \tag{4}$$

Thus a resolver and two integrators can be used to convert the velocity vector of an aircraft, which varies as a function of time, into rectangular position information.

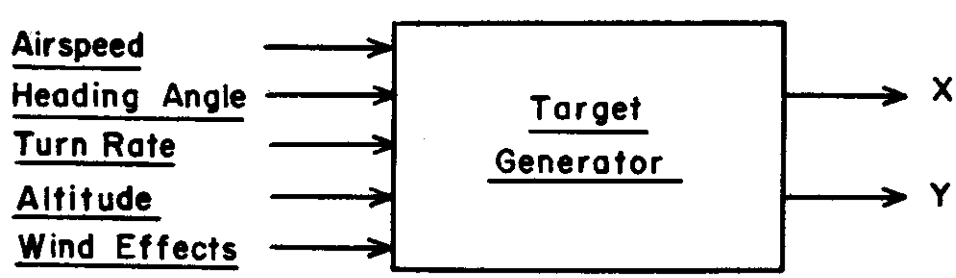

Fig. 1. Target generation functions.

A block diagram of the OSU target simulator is shown in Fig. 3. The symbols used in the diagram are defined as follows:

- S - LaPlacian operator
- V - indicated airspeed of the aircraft
- K_a - altitude bias function, or ratio between ground speed and indicated airspeed of the aircraft
- θ - heading angle
- V_{wx} - component of wind velocity in X-direction
- V_{wy} - component of wind velocity in Y-direction

Target position, it is seen, is generated as a function of indicated airspeed, altitude, heading angle, wind velocity, and time. Another input, turn rate $\dot{\theta}$, influences the instantaneous value of the heading angle.

2.3 Target Generator Design

Standard d.c. analog techniques are used to generate position information as a function of time for each simulated target. A simplified diagram of an OSU-ATC simulator is shown in Fig. 4. The required integrations are performed by two high-gain operational amplifiers. Drift voltage effects, common to this type of integrator circuit, are reduced by means of balance amplifier circuits. The resistor-capacitor input and feedback components are designed so that the integrator output voltages are proportional to the time integral of the integrator input voltages.

A voltage, E_V, proportional to the simulated aircraft ground speed, is developed across the sine-cosine potentiometer, R_{sc}. R_{sc} is wound non-linearly so

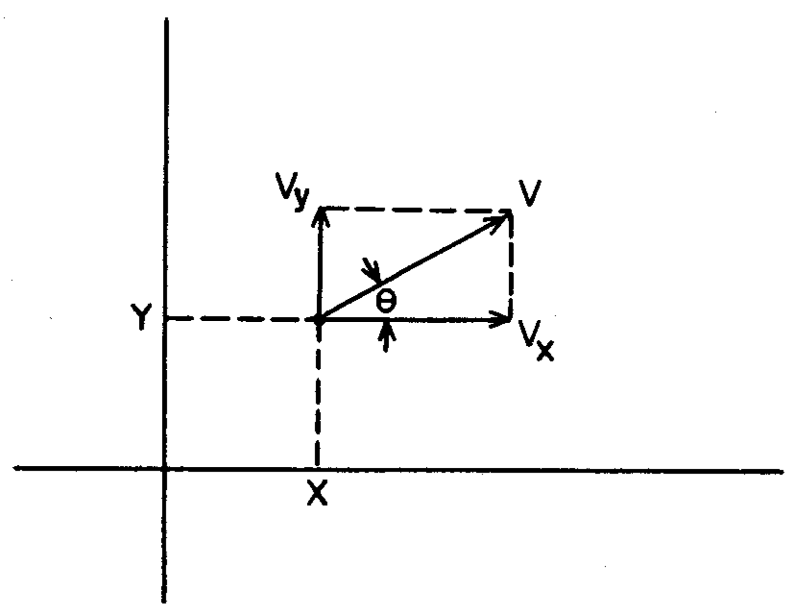

Fig. 2. Conversion from polar to rectangular coordinates.

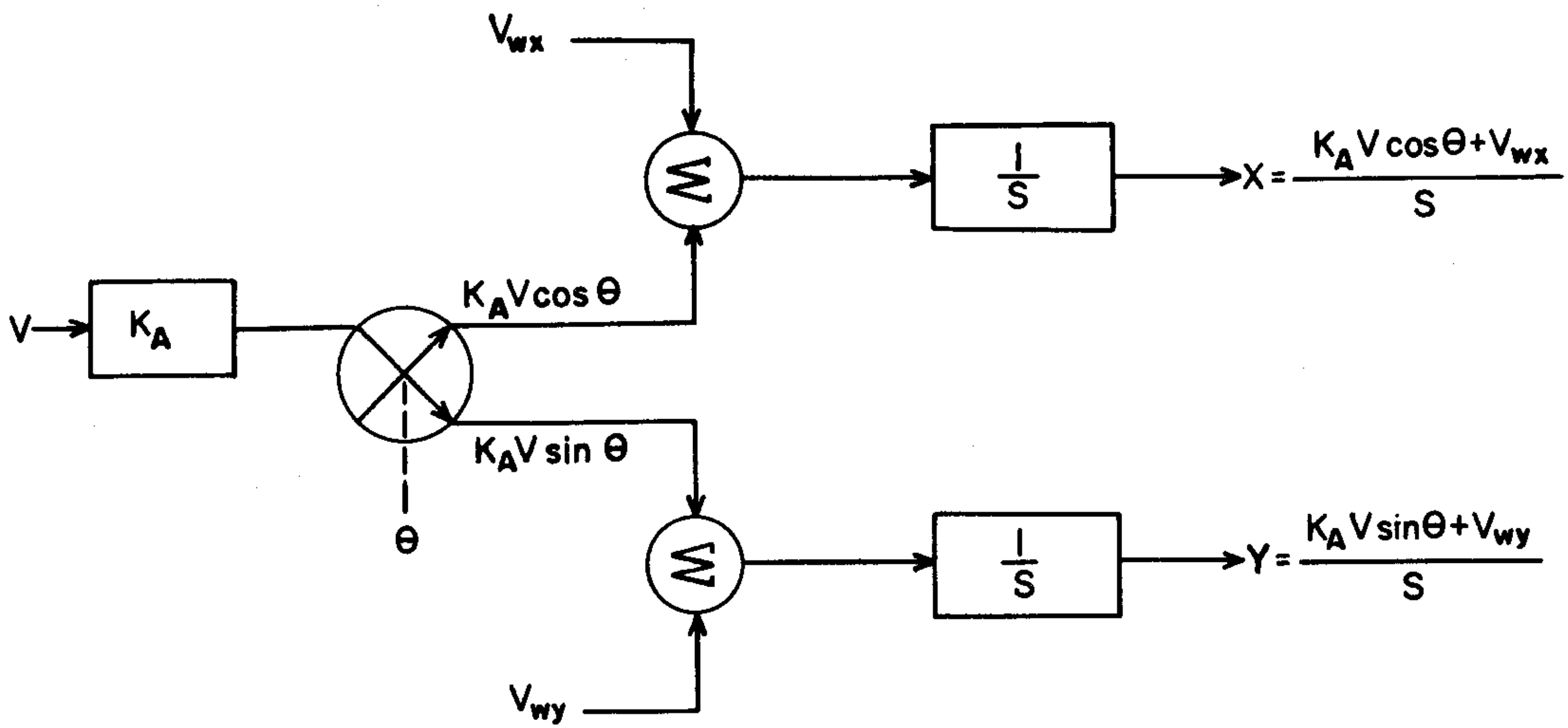

Fig. 3. Block diagram of the electronic target generator used in the OSU-ATC simulator.

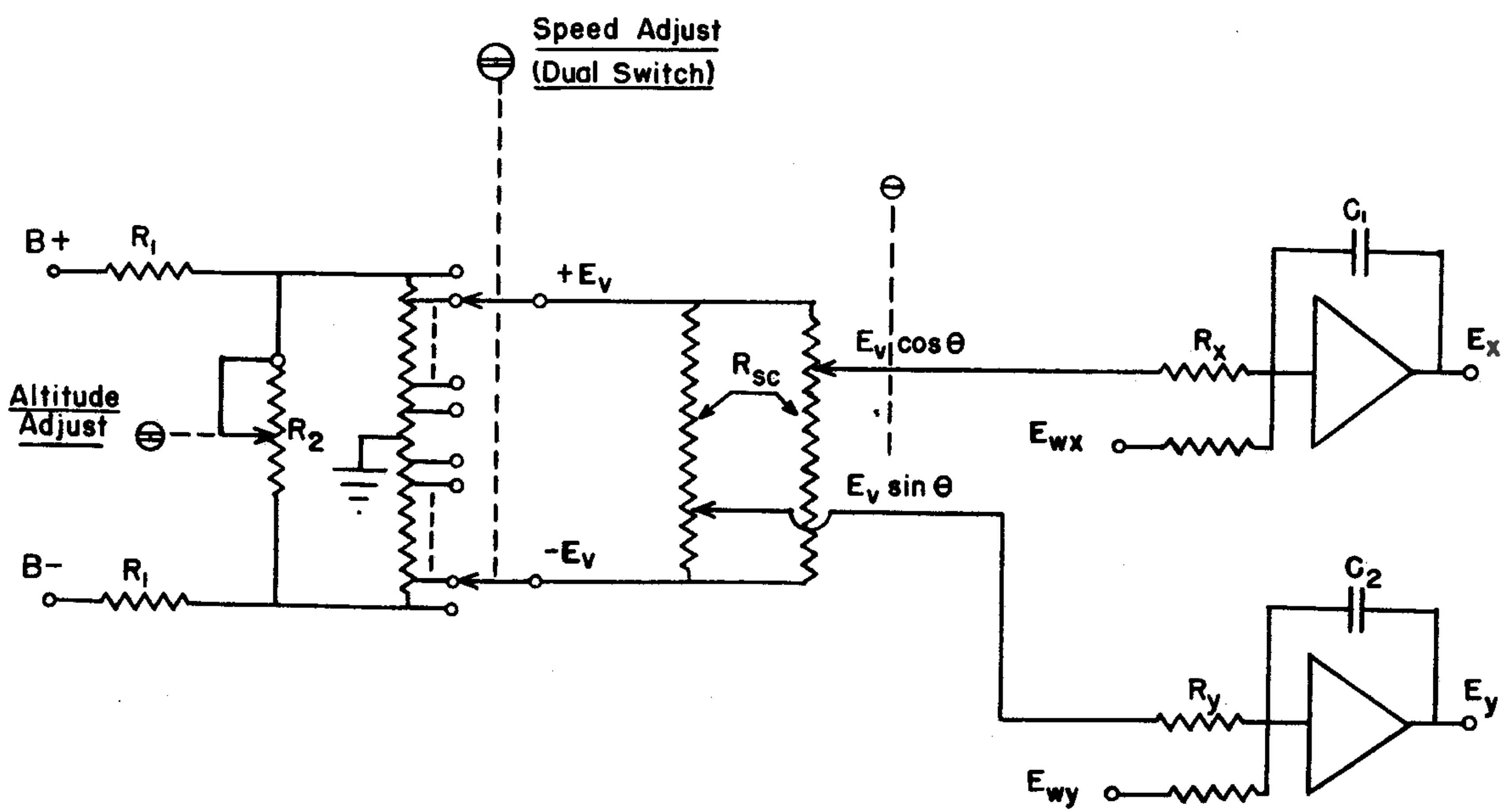

Fig. 4. Circuit diagram of the target generator used in the OSU-ATC simulator.

that the two outputs are respectively proportional to the sine and cosine of the potentiometer shaft position (θ). When these outputs are connected to the proper integrator through resistors R_x and R_y, the instantaneous outputs of the integrators represent the instantaneous position of the simulated target.

The resistor string connected to the speed-adjust switch provides for a wide range of aircraft velocities. This switch permits the use of different voltage inputs to the integrators; this, in turn, provides variation in the rate-of-change of E_x and E_y. Balanced positive and negative potentials must be applied to the terminals of the speed-adjust switch to provide both increasing and decreasing values of E_x and E_y. The total voltage across this switch is proportional to the maximum possible ground speed of the aircraft. Since the speed-adjust switch is calibrated for airspeed only, an altitude potentiometer (R_2) is used to convert airspeed to ground speed.

Wind velocity potentials, E_{wx} and E_{wy}, are inserted into the integrators in parallel with the normal control velocity potentials to make the output rate-of-change of E_x and E_y proportional to both wind velocity and commanded airspeed.

Heading information is inserted into the system by controlling the sine-cosine shaft position (θ). This shaft may be commanded to any angle but can turn at only two standard rates of 1.5 and 3.0 deg./sec.

3. AN OPERATIONAL TARGET SIMULATION (OTS) SYSTEM FOR SIMULATING TARGETS ON A PPI DISPLAY

The OTS system described below uses the same basic method of target generation as is used in the OSU-ATC simulator (see Section 2.3, above), but makes use of different additional circuits to adapt the output signal to a form acceptable to conventional, operational PPI radar displays. These additional circuits are described in this section.

3.1 General Discussion

The target generation system of the OSU-ATC simulator provides target position information in rectangular coordinates as a function of time. The outputs of each generator are two d.c. voltages proportional to the X and Y position of that target within the normal radar range of the simulated radar set. As such, these d.c. outputs cannot be used directly in presenting simulated targets on an operational PPI display. The two potentials must first be transformed into a video form of intelligence which can be accepted by the radar indicator. During this transformation, the intelligence contained in the two d.c. voltage levels should be maintained at the same level of accuracy that was obtained during the initial generation of the target.

The transformation of target position information from d.c. to video form may be considered in two steps. The first step involves a transformation at, or near, the d.c. level from rectangular to polar coordinates. The second step consists of transforming the resultant d.c. polar intelligence to a video form acceptable for presentation on a PPI display, i.e., to a form that is compatible with the video information obtained from a normal radar return.

The rectangular-to-polar transformation may be performed by using one of the following two methods:

a. Electronic transformation by use of a carrier voltage.
b. Electro-mechanical transformation by use of a d.c. analog computer.

The first method uses the simulation equipment more efficiently. The second method is of more interest in laboratory work because of the commercial availability of suitable analog computer installations. Both of these techniques for coordinate transformation will be considered in this report. The advantages and disadvantages of each will be discussed after their requirements have been more thoroughly considered.

Except for certain subtle differences that will be independently discussed, the requirements for conversion of d.c. to video intelligence are about the same regardless of the method used for coordinate transformation.

3.2 Target Simulation Using Electronic Coordinate Transformation (Carrier System)

3.2.1 Theory of operation.

3.2.1 (a) Rectangular-to-polar coordinate transformation.—The normal vector representation of a target position with respect to the radar set is shown in Fig. 5. The OSU-ATC simulator uses conventional analog techniques to generate two d.c. potentials that are proportional to the X and Y vectors shown in the figure. These vectors define the exact position of a single target in rectangular coordinate form. The normal PPI presentation, however, defines target position in terms of range from the radar set (R) and bearing angle (θ). Thus, the intelligence contained in the X and Y vectors must be transferred to the new set of variables, R and θ. This requires a rectangular-to-polar transformation.

Since it would be impractical to attempt a strictly electronic transformation of the two d.c. target potentials, the intelligence contained in those potentials must first be transferred to a pair of sinusoidal carrier potentials. Hence, two

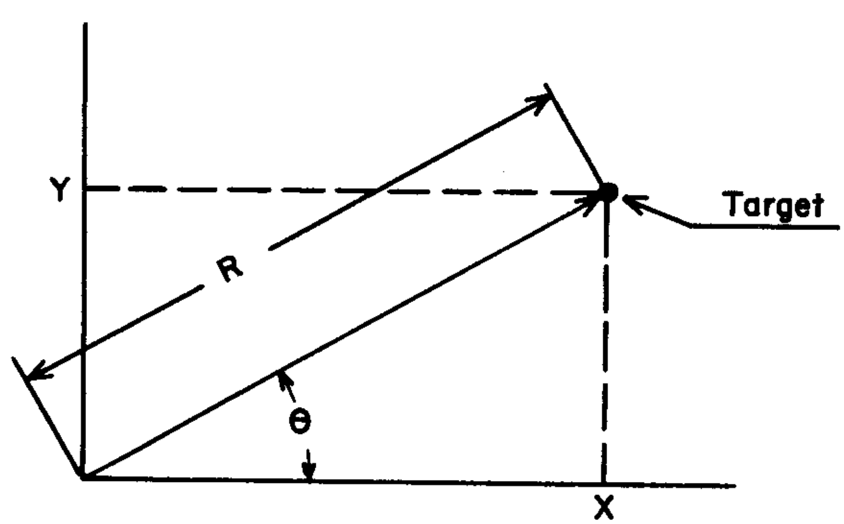

Fig. 5. Vector representation of target position.

sinusoidal signals are produced; the amplitudes of these two signals are proportional to the generated d.c. target voltages as shown in Fig. 6A and B. The carrier frequency should be in the neighborhood of 1000 cps. Notice that the amplitude of each sinusoidal signal is proportional to either the X or Y generated target position.

A rectangular-to-polar transformation is obtained by quadrature addition of the X and Y signal carriers. This is facilitated by providing a 90-deg. phase angle difference between the two carriers as shown in Fig. 6B. The normal Y-carrier signal is indicated by the dashed curve and the phase-shifted carrier by the solid curve. The coordinate transformation process is then completed by adding the two solid curves of (A) and (B). This results in the sinusoidal signal of Fig. 6C; the amplitude of this signal is proportional to target range (R), while the relative phase is proportional to the target bearing angle (θ).

A more rigorous description of this coordinate transformation scheme can be shown mathematically. The two signals representing target position may be defined as follows:

$$E_1 = X \sin wt \tag{5}$$

$$E_2 = Y \sin (wt + \pi/2) = Y \cos wt \tag{6}$$

Then

$$E_1 + E_2 = X \sin wt + Y \cos wt \tag{7}$$

$$E_1 + E_2 = R \sin (wt + \theta) \tag{8}$$

where

$$R = \sqrt{X^2 + Y^2} \tag{9}$$

$$\theta = \tan^{-1} Y/X \tag{10}$$

From these equations, it should be obvious that the amplitude of the signal shown in Fig. 6C is proportional to the range of the simulated target. Likewise, the phase angle of the summed signal relative to the unshifted carrier is equal to the bearing angle (θ) of the simulated target. Target position information is now available in polar coordinate form.

3.2.1 (b) Conversion from d.c. video intelligence.—The simulator requires two sources of reference information from the radar system. The first source is the radar pulse which references initiation of the sweep-like sawtooth on the radar indicator. This information is required so that a simulated range pulse may be generated at the proper time. The second source of information is an instantaneous indication of the scanning radar antenna position. This is required so that the range pulse may be applied when the sweep line corresponds to the bearing angle of the simulated target.

A new angle $\phi(t)$ will be defined as the instantaneous angular position of the scanning radar antenna. Since the sweep line on the PPI indicator is servo-locked to the antenna position, the angle $\phi(t)$ is represented by the instantaneous position of this sweep line. The simulator requires that a sinusoidal voltage

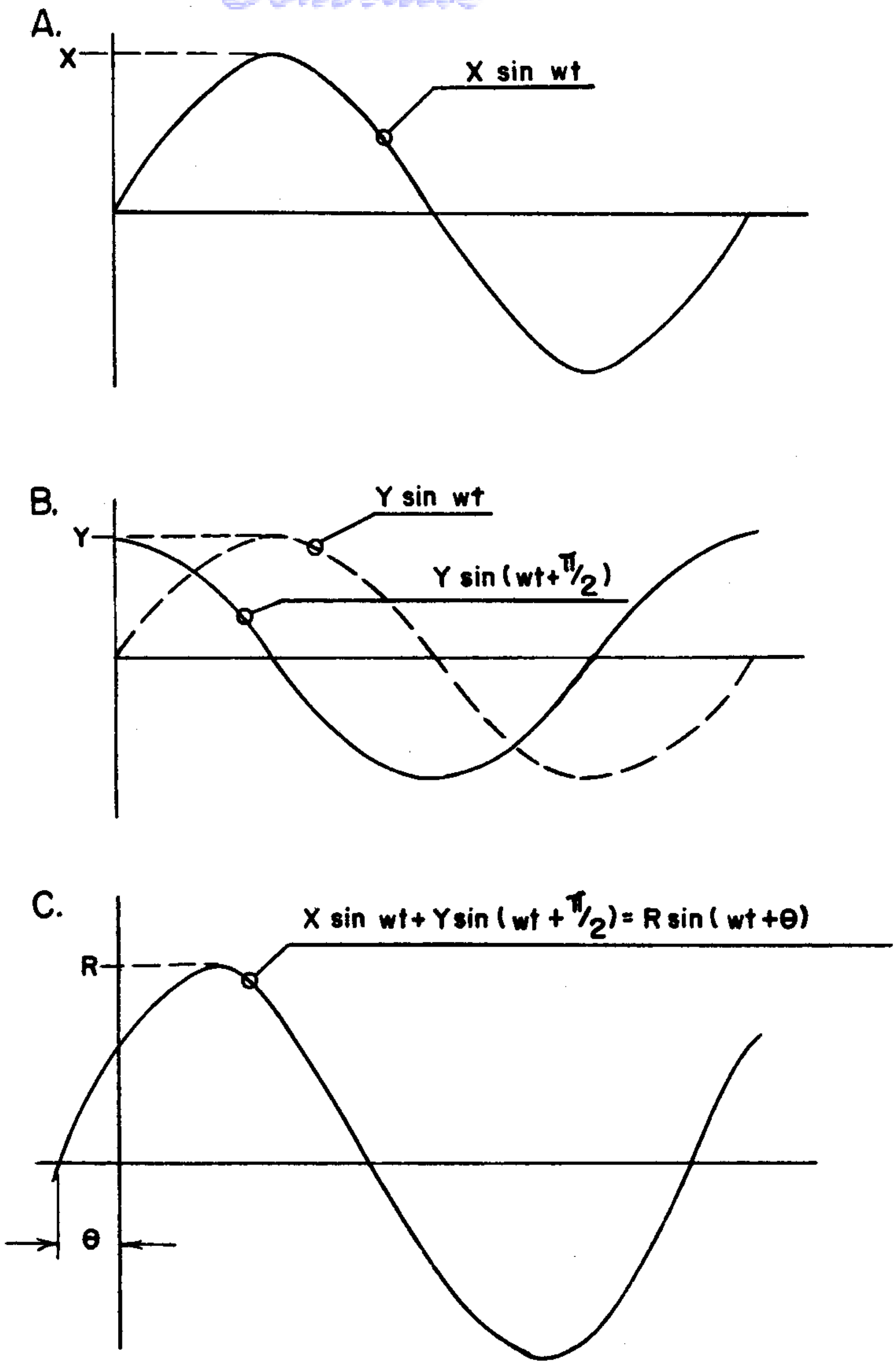

Fig. 6. Transformation curves.

of the carrier frequency be generated, the phase of which is proportional to the antenna angle $\phi(t)$. This can be accomplished by use of a single resolver geared directly to the rotating antenna. The output of the resolver can be represented by the equation:

$$E_o = E_m \sin [wt + \phi(t)] \qquad (11)$$

The same frequency (w) must be used to excite the antenna resolver as was used for the carrier of the two simulated target position potentials in the previous section. When angle $\phi(t)$ is equal to the simulated target bearing angle θ, it can be seen that the two sinusoidal voltages of equations (8) and (11) have a common phase relation. A simple phase-angle comparison of these two sinusoidal signals may be used to determine the proper time for application of simulated range pulses to the radar indicator.

A graphical description of the previous discussion is presented in the form of timing waveforms in Fig. 7. The sinusoid of graph A represents the result of quadrature summation as specified by equation (8). The phase of this signal is proportional to the bearing angle θ of the simulated target. The sinusoid of graph B represents the antenna resolver output as specified by equation (11). The phase of this signal is proportional to the instantaneous antenna angle $\phi(t)$ and is shown at the particular instant of time when $\phi(t)$ is equal to θ. The angle θ is considered constant in this discussion since it assumed that the target bearing will change slowly with respect to the antenna angle $\phi(t)$.

Reference pulses are generated as each of the sine waves in parts A and B of Fig. 7 pass through zero potential. These are shown superimposed over the signal in graphs A and B. When these two reference pulses are found to be timewise coincident, a bearing angle gate is generated as shown in Fig. 7C. It should be noted that the gate also corresponds to the period of time when the PPI sweep line is passing over that position on the indicator where the simulated target should appear. This gate is used to enable the application of video range pulses to the PPI indicator.

The range of the simulated target is represented by the amplitude of the sine wave of equation (8). This must first be rectified and filtered before it can be used for generation of simulated range pulses. The resulting range signal after rectification is shown in Fig. 7D. Superimposed on the same graph are a number of range sweep sawteeth. The peak value of these sawtooth waveforms is proportional to the maximum range of the radar set R_{max}. The amplitude of the simulated range voltage is compared with the varying sawtooth amplitude during each sweep period. At that instant when the two voltages are coincident, video range pulses are generated to be used for intensification of the indicator range sweep line. However, the range pulses are not allowed to pass to the PPI indicator except during the period of the bearing angle gate. The appearance of the "enabled" pulses as shown in Fig. 7E provides an accurate video representation of the simulated target both in range and bearing. The gate width τ can be varied to simulate as many radar returns from the synthetic target as desired. The example of Fig. 7 shows the simulation of only two returns per target.

3.2.2 Design of the carrier-type OTS system.—A block diagram showing all the circuits required for the simulation of a single radar target on a PPI display is presented in Fig. 8. The basic OSU-ATC simulator target generation system is represented by those blocks enclosed by the dashed lines on the left. Only the

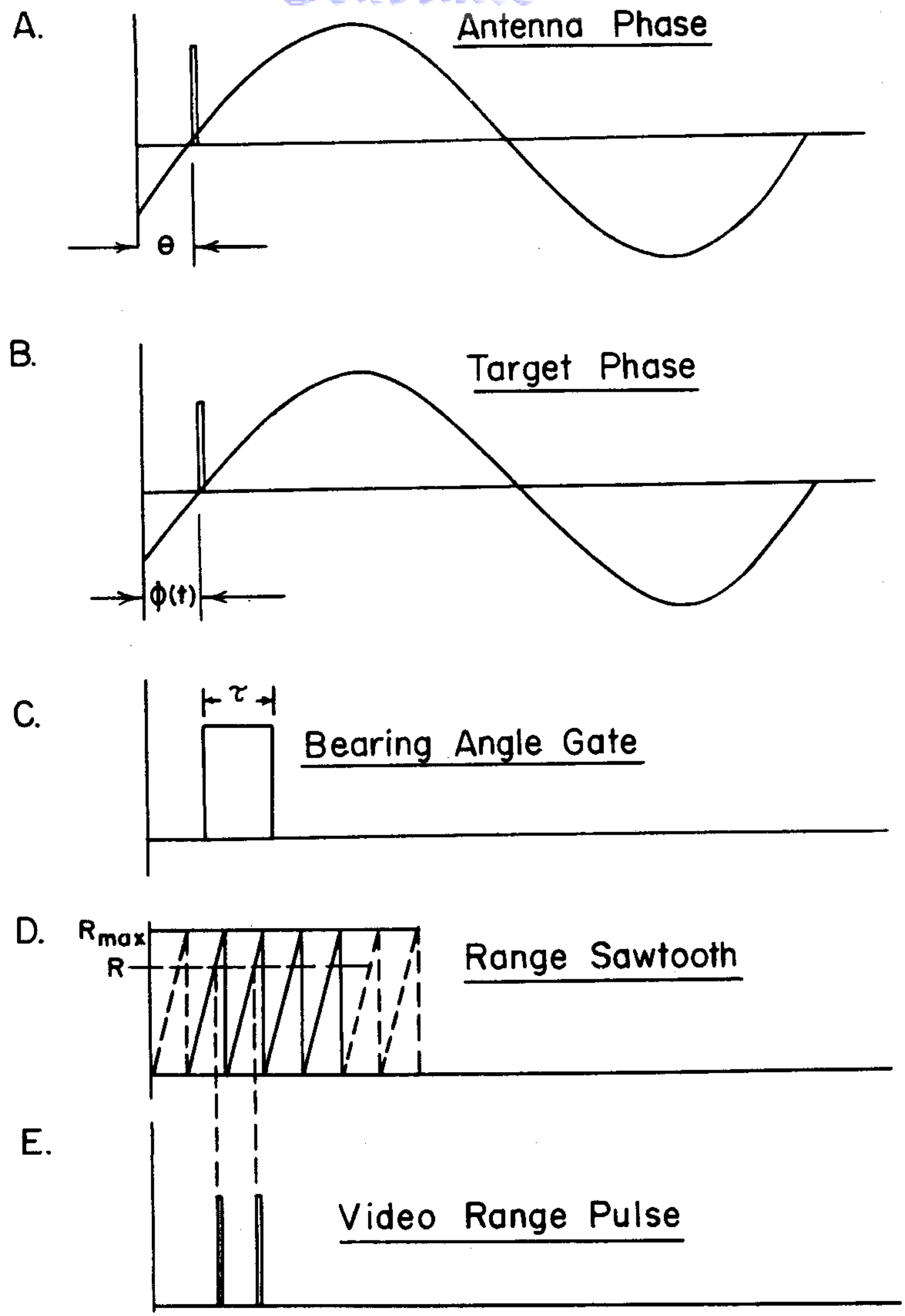

Fig. 7. Timing waveforms for generation of video range pulses.

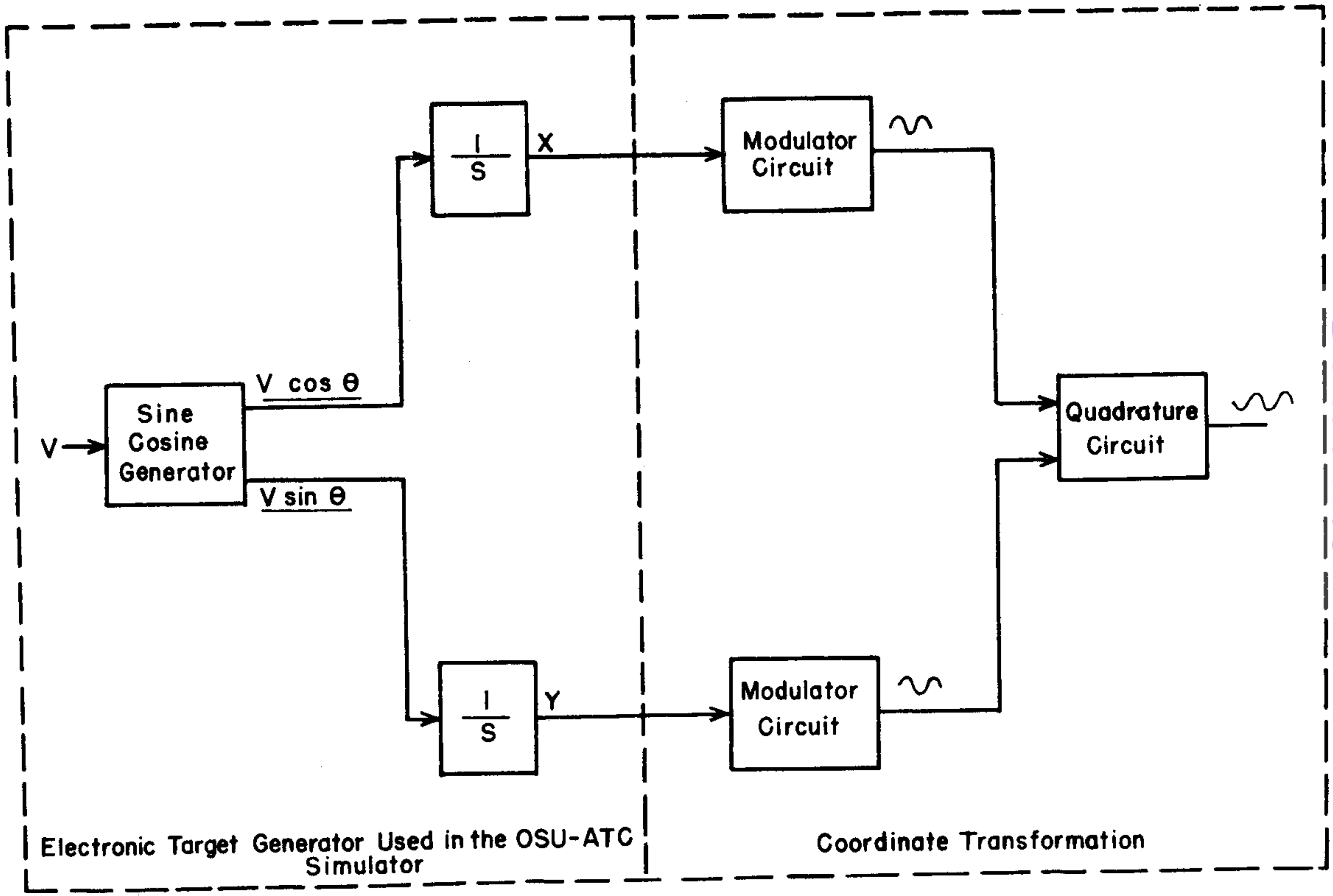

Fig. 8. Rectangular-to-polar coordinate transformation using carrier voltage.

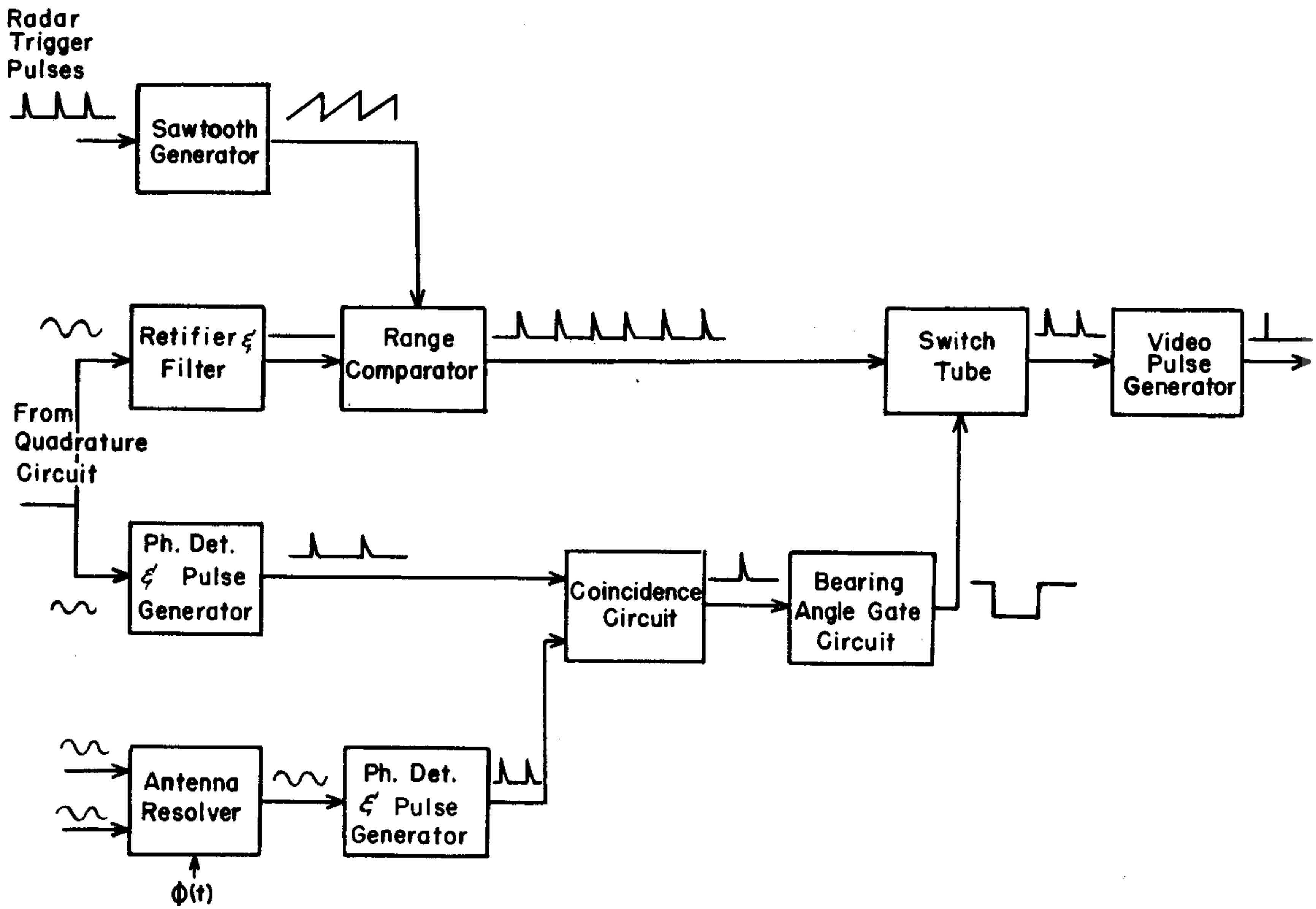

Fig. 9. Generation of video range pulses from quadrature output signal.

sine-cosine generator and two integrators are shown because a more complete description of the target generator unit was presented in section 2.3 of this report. The desired aircraft velocity (V) is resolved about the heading angle (θ) into X and Y components of velocity as was shown earlier in equations (1) and (2). The component velocities are then individually integrated to obtain the X and Y position vectors of the target as a function of time.

The remaining blocks of the diagram are those required to produce the functions described in parts (a) and (b) of section 3.2.1 The d.c. output potentials of each target integrator are fed into a modulator that operates at a standard reference frequency. This reference should be about 1000 cps for satisfactory resolution of target bearing angles and for proper response to extremely fast-moving targets.

A standard quadrature amplifier circuit is then used to produce the function previously described by equation (8). The two modulator outputs are first shifted 45 deg. in opposite directions so as to provide a 90-deg. phase difference between the two signals. They are then summed to provide a single output; the amplitude of this output is proportional to range and the phase is proportional to the bearing of the simulated target. This entire operation can be performed with a simple RC summing network operating into the grid of a vacuum tube.

The output sinusoid from the quadrature circuit contains both range and bearing information. It must be used, therefore, in two sets of circuits so that both forms of intelligence can be extracted from the carrier. Range information is obtained by routing the signal through a rectifier and filter network as shown in Fig. 9. The resulting signal is a positive d.c. voltage, the magnitude of which is proportional to the range of the simulated target.

A radar system trigger from the PPI display is used to trigger a sawtooth generator in the simulator. This is the same trigger that is used in the indicator to trigger the range sweep sawtooth. A range comparator is then used to compare the level of the d.c. target range potential with each sawtooth voltage waveform. When the two are coincident voltagewise a sharp output voltage pulse is generated. Input and output waveforms of this comparator were shown schematically in Fig. 7D and E.

A resolver must be either mechanically- or servo-locked with the instantaneous position of the scanning radar antenna. The input windings of the resolver are energized by two sinusoidal reference signals that have been shifted so as to be 90 deg. out of phase with each other. The phase of the output signal from the resolver then varies with the antenna bearing angle as specified by equation (11).

The resolver output is passed through a phase detector circuit which produces a pulse each time the resolver signal passes through zero potential in a positive direction. A similar circuit is used to generate a pulse each time the target bearing angle signal passes through zero in the same direction. These two pulses are continuously applied to a coincidence circuit that provides a sharp output pulse only when the two bearing angle pulses are timewise coincident. Coincidence occurs only when the sweep line on the PPI display passes over the position where the simulated target should appear.

The output pulse of the coincidence circuit is used to trigger a bearing angle gate with a waveform as was shown in Fig. 7. The width of the gate can be varied to simulate any number of radar returns from the simulated target.

A switch tube is used to pass the range comparator pulses to a pulse generator only during the period of the bearing angle gate. In this manner, one or more radar returns can be simulated by merely varying the width of the gating period. The output of the video pulse generator is fed back to the PPI display, summed in with other simulated and live radar returns and used to intensify the range sweep line at the proper time.

3.3 Target Simulation Using Electro-Mechanical Coordinate Transformation (Analog Computer System)

3.3.1 Theory of operation.

3.3.1 (a) Rectangular-to-polar coordinate transformation.—The normal vector representation of a target position with respect to the radar set is shown in Fig. 10. The operational equations which must be satisfied during the transformation are as follows:

$$R = X \cos \theta + Y \sin \theta \tag{12}$$

$$X \sin \theta = Y \cos \theta \tag{13}$$

In these equations θ is defined as the bearing angle of the target with respect to the radar set. The angle $\phi(t)$ will be defined again as the instantaneous angular position of the scanning radar antenna. Since the sweep line on the PPI display is servo-locked to the antenna position, the angle $\phi(t)$ is represented by the instantaneous position of this sweep line.

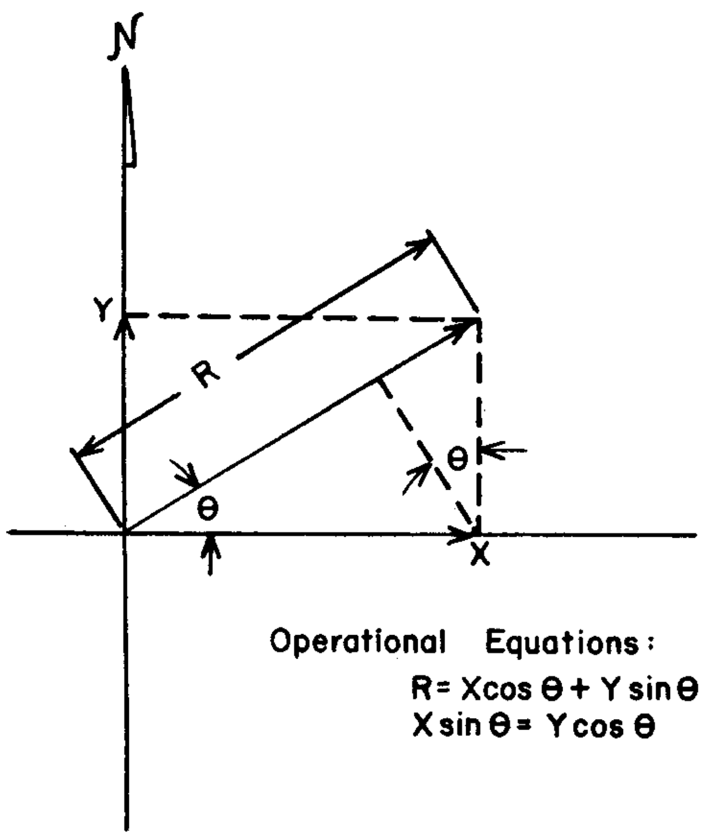

Fig. 10. Vector representation of target position.

Now a new set of operational equations will be defined as follows:

$$M_{(t)} = X \cos \phi(t) + Y \sin \phi(t) \qquad (14)$$

$$N_{(t)} = X \sin \phi(t) - Y \cos \phi(t) \qquad (15)$$

In these equations, $M_{(t)}$ and $N_{(t)}$ are sinusoidally varying functions with the same frequency as that of the rotating antenna. The values of X and Y are the same as in equations (12) and (13) and, thus, are the rectangular representations of the simulated target. They are considered as constants in these equations since it is assumed that the target will move very slowly with respect to the sweep line.

Diagramatic representations of equations (14) and (15) are presented in Fig. 11. It can be seen that:

$$M_{(t)} = X \cos \phi(t) + Y \sin \phi(t) = R \cos [\phi(t) - \theta] \qquad (16)$$

$$N_{(t)} = X \sin \phi(t) - Y \cos \phi(t) = R \sin [\phi(t) - \theta] \qquad (17)$$

Thus, when $\phi(t)$ is equal to θ,

$$M_{(t)} = R \cos [\phi(t) - \theta] = R \qquad (18)$$

$$N_{(t)} = R \sin [\phi(t) - \theta] = 0 \qquad (19)$$

These relations are used to obtain the values of R and θ corresponding to the generated functions X and Y. It should be obvious that at the instant of time when the function $N(t)$ is equal to zero, the value of $\phi(t)$ corresponds to the bearing angle θ of the simulated target. At the same time the value of the function $M(t)$ is directly proportional to the radar range of the simulated target (R). Thus, equations (16) and (17) define trigonometric relations that can be used to transform X and Y positional values into range (R) and bearing angle (θ) information for a simulated target.

3.3.1 (b) Conversion from d.c. to video intelligence.—A set of typical waveforms used for coordinate transformation is presented in Fig. 12. The short section of a sinusoidal waveform shown in Fig. 12A is a schematic representation of equation (17). The value of the function, $R \sin [\phi(t) - \theta]$, passes through zero when the antenna angle $\phi(t)$ is coincident with the target bearing angle θ. This zero crossover is used to initiate a bearing angle gate as shown in Fig. 12B.

It should be noted that the gate is initiated when the search antenna is radiating in the exact direction of the simulated target bearing angle. The appearance of this gate also corresponds to the period of time when the PPI sweep line is passing over that position on the indicator where the simulated target should appear. It only remains to intensify the sweep line during this gate interval at a range value corresponding to the simulated target!

The short section of a sinusoidal waveform shown in Fig. 12C is a schematic representation of equation (16). The value of the function, $R \cos [\phi(t) - \theta]$, is proportional to the range of the simulated target when $\phi(t)$ is coincident with θ. Superimposed on the same graph are a number of range sweep sawteeth. The peak value of these sawteeth waveforms is proportional to the maximum range of the

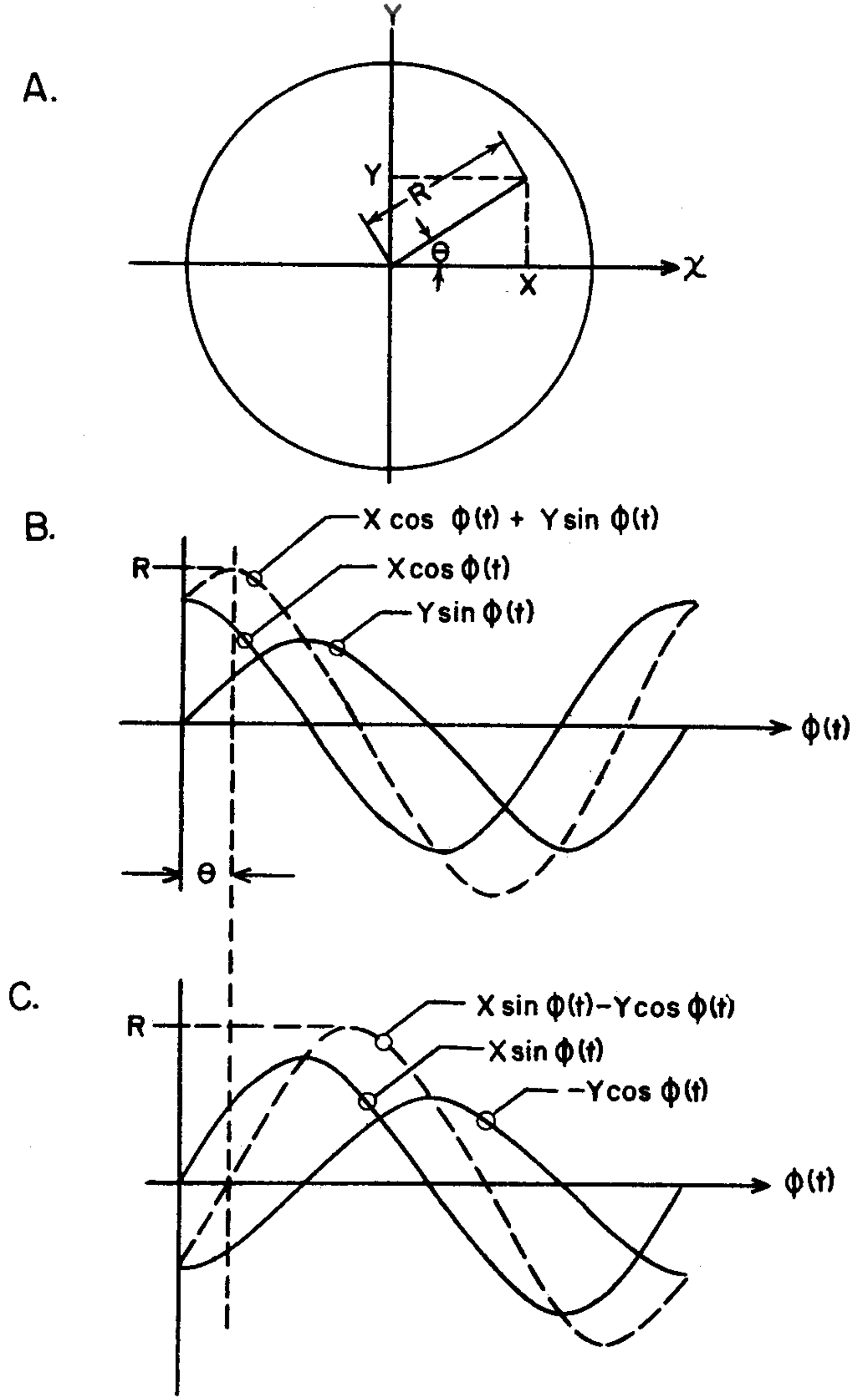

Fig. 11. Operational waveforms for coordinate conversion.

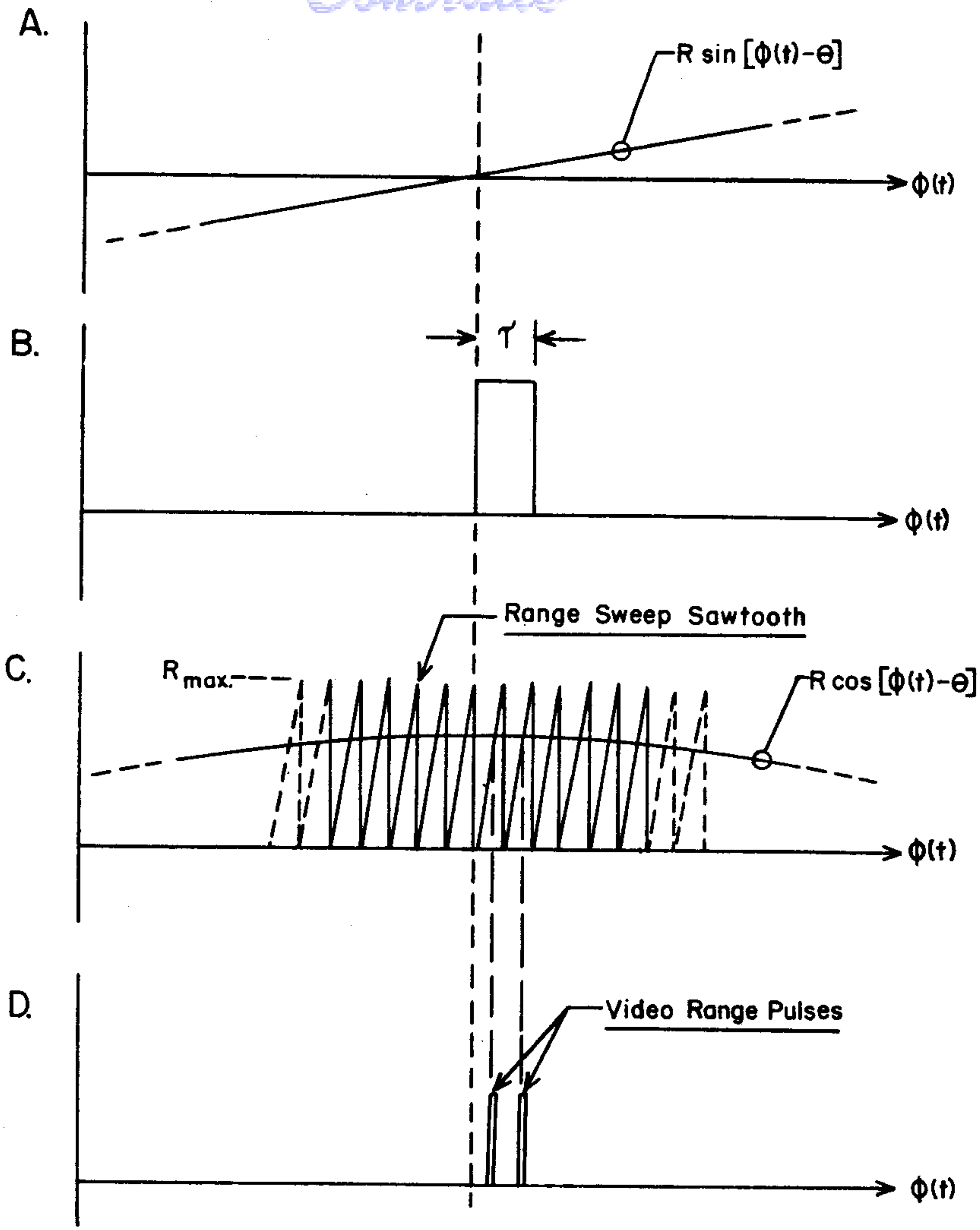

Fig. 12. Typical transformation waveforms.

radar set, R_{max}. During the bearing angle gate period τ the amplitude of the range function, $R \cos [\phi(t) - \theta]$, is compared with the varying sawtooth amplitude. When the two are coincident, video range pulses are generated to be used for intensification of the range sweep line. The appearance of these pulses as shown in Fig. 12D provides the required range information on the simulated target. The gate width (τ) can be varied to simulate as many radar returns from the synthetic target as desired. The example of Fig. 12 shows the simulation of only two returns per target.

The procedure just discussed provides range and bearing information for a synthetic target in a form that can be used directly with a PPI display. It should be noted that the primary source of positional information was present in the form of rectangular coordinates. The sinusoidal waveforms used in Fig. 12A and C were derived from the original X and Y positional values as indicated in equations (16) and (17). These equations describe the modulation and summing procedures required for proper coordinate transformation.

3.3.2 Design of the analog-computer-based OTS system.

3.3.2 (a) Coordinate transformation system.—A generalized block diagram of the rectangular-to-polar coordinate transformation system is shown in Fig. 13. The basic target generator used in the OSU-ATC simulation system is represented by those blocks enclosed by the dashed lines on the left. The remaining blocks of the diagram are those required to produce the functions described in section 3.3.1(a). The position vectors X and Y are resolved by the antenna sweep angle (ϕ) into vectors parallel and perpendicular to the sweep line on the indicator. These resulting vectors are summed in the manner shown to produce functions previously described by equations (16) and (17). These are the two functions used to provide the range and bearing information concerning the simulated target.

The coordinate transformation equations (16) and (17) can be generated by standard d.c. analog computer elements as shown in Fig. 14. The inputs to this system are d.c. voltages proportional to the X and Y position vectors of the target and a shaft angle representing the sweep line bearing angle $\phi(t)$. Two inverter amplifiers are required to provide balanced positive and negative potentials across the sine-cosine potentiometers for each simulated target. Since any unbalance of the d.c. amplifiers will add to system errors, they should be provided with chopper stabilization.

3.3.2 (b) Conversion from d.c. to video intelligence.—The output functions of the coordinate transformation circuits are two d.c. voltage levels modulated at the range sweep frequency. The bearing angle function, $N_{(t)}$ of equation (17), is at zero level when the sweep line is directly over the simulated target position of the indicator. This zero output then dictates when the target should appear and should initiate a series of simulated radar returns.

The sinusoidal waveform which represents the range function, $M_{(t)}$ of equation (16), is 90 deg. out of phase with the bearing angle function. Thus, when $N_{(t)}$ is zero, the value of $M_{(t)}$ is at a maximum level and is proportional to the range of the simulated target.

The circuits required to convert the range and bearing functions into video range pulses are indicated by the block diagram of Fig. 15. A voltage comparator is used to compare the bearing angle function with a zero reference. The output

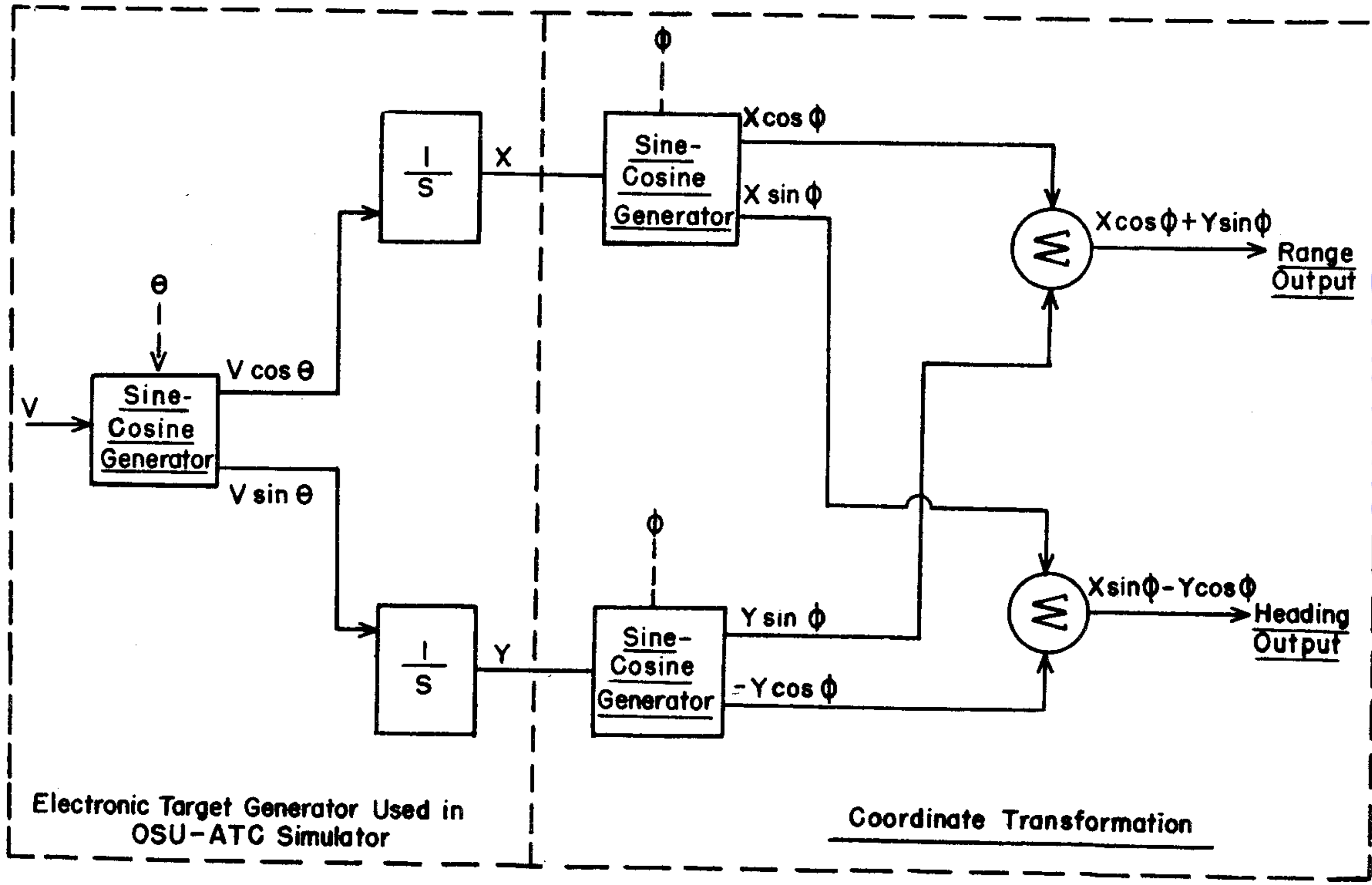

Fig. 13. Block diagram for rectangular-to-polar coordinate transformation.

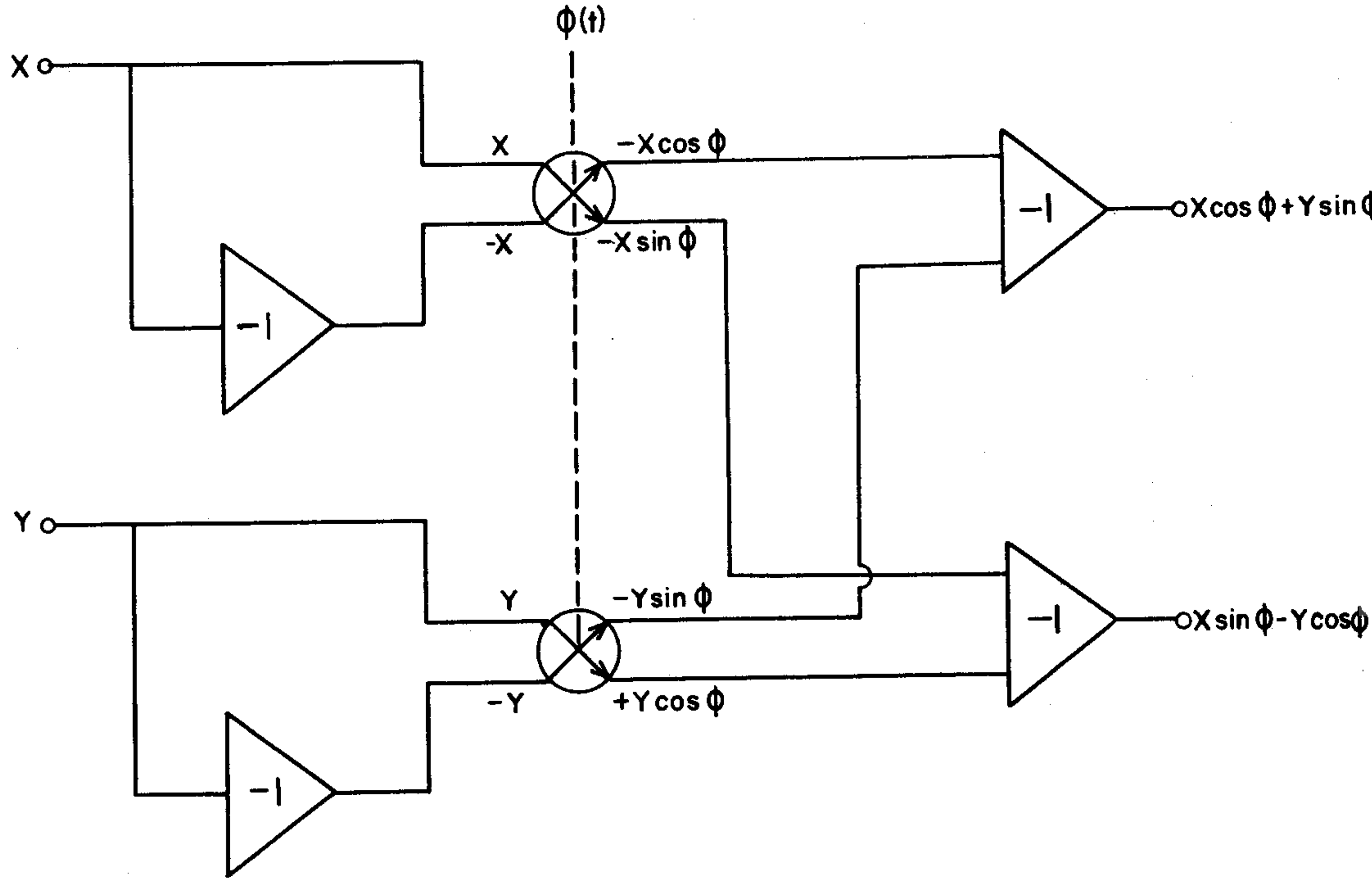

Fig. 14. Coordinate transformation using d.c. analog computer elements.

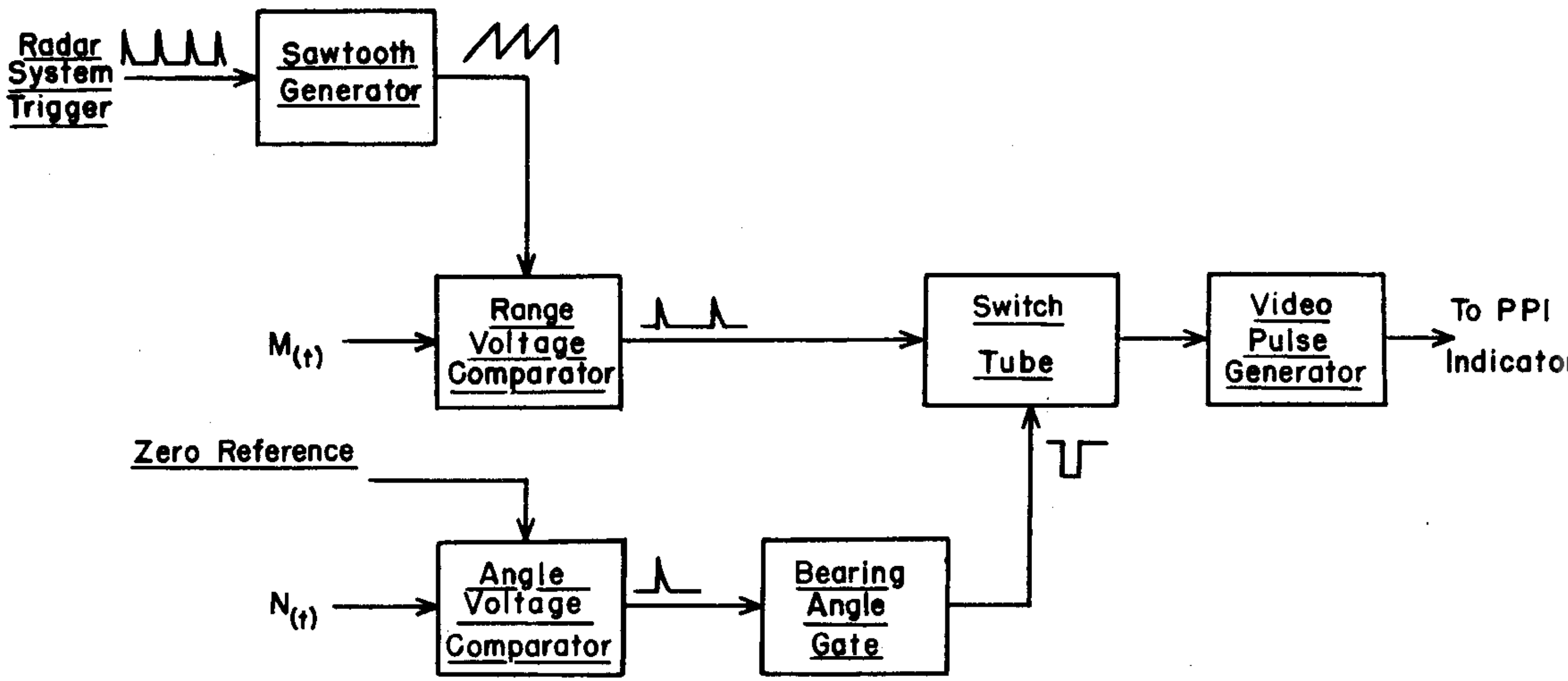

Fig. 15. Block diagram of d.c. to video conversion system.

of this circuit is a sharp voltage pulse at the instant when $N_{(t)}$ passes through zero. This comparator need only operate when $N_{(t)}$ approaches zero from a negative-to-positive direction as was shown in Fig. 12A. When $N_{(t)}$ passes through zero in the reverse direction, the range output will be negative and thus cannot provide a range output pulse.

The output pulse of the angle comparator is used to trigger a bearing angle gate with a waveform as was shown in Fig. 12B. The width of this gate can be varied to simulate any number of radar returns from the simulated target.

A radar system trigger from the PPI display is used to trigger a sawtooth generator in the simulator. This is the same trigger that is used in the indicator to trigger the range sweep sawtooth. A range comparator is then used to compare the level of $M_{(t)}$ with each sawtooth voltage waveform. When the two are coincident voltage-wise, a sharp output pulse is provided. Input and output waveforms of this comparator were shown in Fig. 12C and D.

A switch tube is used to pass the range comparator pulses to a video pulse generator only during the period of the bearing angle gate. In this manner, more radar returns can be simulated by merely varying the width of the gating period. The output of the video pulse generator is fed back to the PPI display, summed in with other simulated and live radar returns, and used to intensify the range sweep line at the proper instant of time.

3.4 Target Simulation Using Elements of the Moving Radar Targets Generator, Device 15-J-1c.

3.4.1 Discussion.—A moving target simulator available at many ATC installations is the Moving Target Generator 15-J-1c, developed by the Naval Training Devices Center (7). This device, commonly referred to as the 15-J-1c, provides realistic radar signals representing moving aircraft or naval ships that are displayed on conventional radar indicators. Up to 30 targets can be used, with an individual control of target speed, heading, and initial position available at each of the 30 operating stations.

The basic dynamic target information is gènerated by a mechanical computer assembly. This assembly, employing ball and disc integration, drives a set of potentiometers to obtain electrical signals proportional to the range and bearing of each simulated target. The actual position information is generated in rectangular coordinates. Electronic quadrature, comparator, and time coincidence circuits allow these signals to be resolved into video components that can be displayed on a conventional PPI radar display. Since no alterations are made to the radar indicator, the simulated target position information can be displayed simultaneously with live target information.

This device was designed for application as a training aid for Naval Combat Information Centers. Thus, the design criterion was the generation and display of simulated moving targets that resemble closely the display of live targets. The simulator was not designed to produce flight paths to meet the high linearity requirements of training and experimentation in ATC centers. The principal feature of the 15-J-1c in the area of air traffic control is its adaptability for the presentation of simulated targets on a live target display.

The 15-J-1c has several major disadvantages that limit its applicability to ATC situations. These disadvantages include the following:

(a) A cumbersome and lengthy adjustment procedure that must be followed before using the simulator.

(b) Target generators employing ball and disc integration that provide relatively inaccurate control of target motion.

(c) A target generator control panel that makes for inefficient use of "pilot" personnel and leads to frequent control errors.

The first-mentioned disadvantage is designed into the 15-J-1c control circuits and can be improved only by a redesign of the unit. The last two characteristics can be remedied by replacement of the existing mechanical target generator with an electronic generator such as that used in the OSU-ATC simulator. This section of the report will be devoted to a discussion of adapting the target generators of the OSU-ATC simulator for use with the 15-J-1c in forming a third type of OTS system.

3.4.2 Description of the 15-J-1c simulator.—A simplified block diagram of the 15-J-1c simulator is presented in Fig. 16. Only a brief description of the device will be presented here to facilitate later discussions concerning its possible use in forming an OTS system with a target generator from the OSU-ATC simulator. The following general theory of operation appears elsewhere (7) with a more complete description of the device.

> The target generator's N-S and E-W output shafts rotate in accordance with the desired motion of the target. Their instantaneous positions are always proportional to the N-S and E-W coordinates of the target's position, measured with respect to system origin. Precision potentiometers, coupled to the N-S and E-W output shafts, are energized with a balanced a.c. voltage obtained from the Power Amplifier, Chassis 421. The arms of the potentiometers then deliver two identically phased a.c. voltages which are proportional respectively to the N-S and E-W coordinates of the target position.
>
> The N-S and E-W voltages are combined in the Quadrature Circuit and amplifier which adds them as if they differed in phase by 90 deg. The result is a single a.c. voltage which contains the essential target position information. The amplitude of this voltage is proportional to the range of the target.
>
> In the Range Pip Circuit the range information is extracted by amplifying, detecting, and filtering the a.c. voltage obtained from the Quadrature Circuit producing a d.c. voltage proportional to the target range. This d.c. range voltage is converted to a time delay by a voltage controlled delay circuit, which is initiated by the synchronizing trigger. The result is a range delayed video pulse occurring on each sweep of the radar regardless of the azimuth of the target. However, the Azimuth Gate Circuit allows the range pip to pass only when the target azimuth coincides with the antenna azimuth.
>
> The radar and IFF antennae are represented by two blocks (in Fig. 16) but the operation of both is very similar. The Antenna Azimuth yields a gate constant in amplitude but varying in phase to represent the angular position of the simulated antenna electrically. When the antenna azimuth

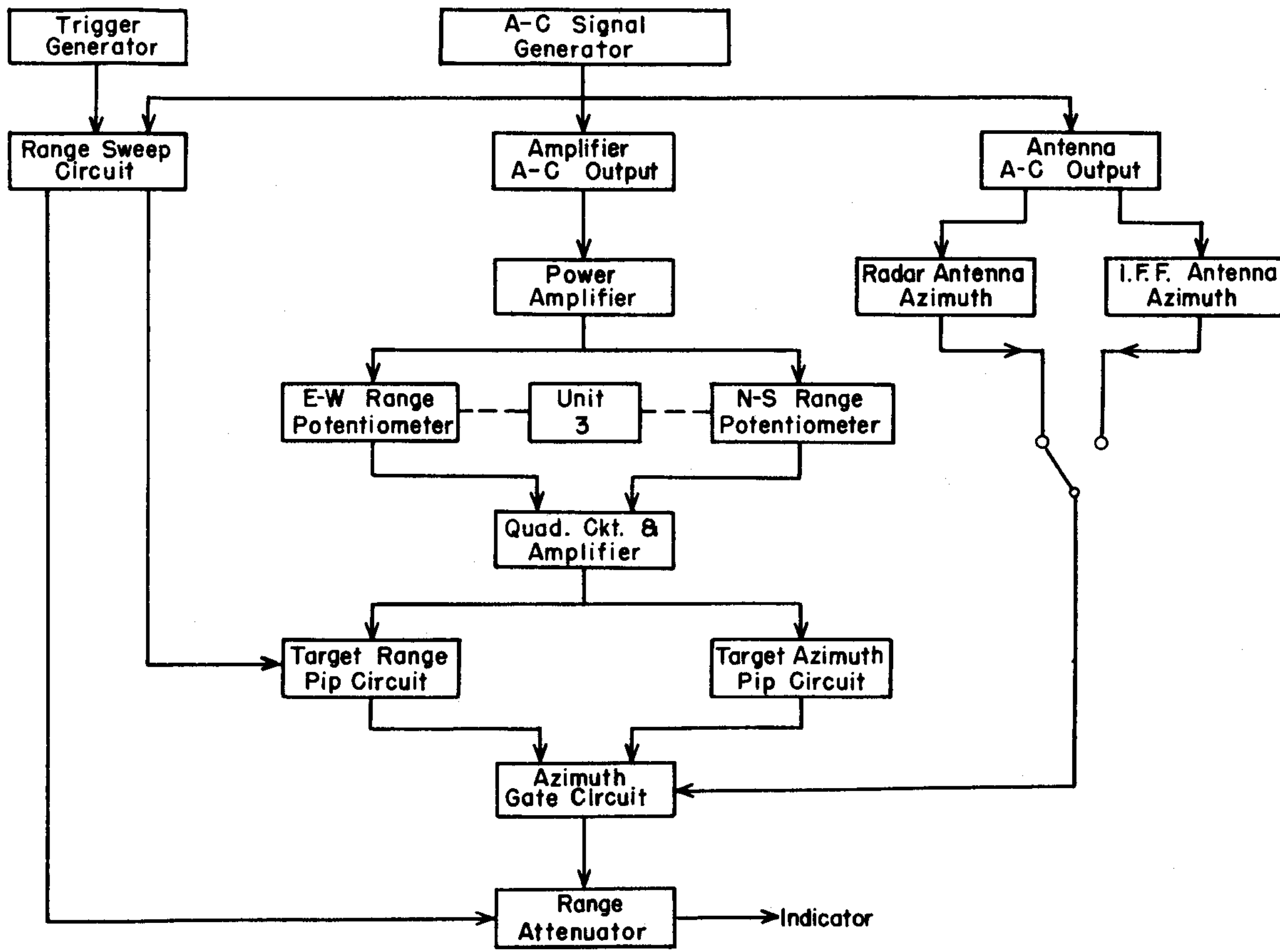

Fig. 16. Simplified block diagram of the 15-J-1c simulator.

is the same as the target azimuth (i.e., when the antenna gate phase is the same as the target azimuth gate phase) the Azimuth Gate Circuit permits the range pips to go on to the Range Attenuator Circuit. The width of the coincidence region is controlled by varying the width of the antenna gate. By this means the antenna azimuth width of the target pip is made to agree with the antenna beam width of the chosen radar.

The Range Attenuator Circuit serves to attenuate the pip in proportion to its range if desired. The pip is then transmitted to the indicator where it will appear as a target of known range and azimuth.

It should be noted that the electronic portion of the 15-J-1c simulator performs the same general types of functions as were required for the carrier-type OTS system described in section 3.2 of this report. The principal difference between the two simulator units is the method used in generating the primary target position information. The all-electronic carrier-type OTS system described in section 3.2 makes use of operational amplifiers to provide the required integration function. The 15-J-1c makes use of a ball and disc type of mechanical integrator. Because the operational amplifiers can provide the more linear integration, they are more satisfactory for ATC simulation problems than are the mechanical integrators. Drift problems that are inherent to the electronic integrator can be minimized by use of chopper stabilization techniques, high-quality integrating capacitors, and power supplies with a high degree of stability.

3.4.3 Combination of the 15-J-1c simulator with the electronic target generator used in the OSU-ATC simulator.—The design of the 15-J-1c simulator is such that it can easily be adapted for use with the electronic target generators used in the OSU-ATC simulator. A simplified block diagram showing a combination of the two units is presented in Fig. 17. The original E-W and N-S range potentiometers and mechanical drive units have been replaced by E-W and N-S units of the electronic target generators and associated modulator circuitry. The output of each target generator is a d.c. voltage proportional to either the E-W or N-S range of the target. Simple modulator units convert the available d.c. outputs to a.c. signals that can be used by the 15-J-1c quadrature circuit.

The output of each modulator circuit is an a.c. voltage proportional to either the N-S or E-W target range. A standard carrier voltage from the power amplifier is used so that the quadrature circuit can provide a target azimuth signal with the proper frequency and phase characteristics. The modulator units can be designed to provide outputs identical to those which are available at the outputs of the E-W and N-S range potentiometers of the unmodified 15-J-1c unit. Thus, the quadrature circuit will perform in exactly the same manner regardless of whether the mechanical integrator units of the 15-J-1c simulator or the electronic target generators of the OSU-ATC simulator are used.

The 15-J-1c is packaged in such a manner as to facilitate easy replacement of the mechanical integrators by the electronic target generators. Cabling connections between the several units of the 15-J-1c are shown in Fig. 18. The mechanical integrator units are contained in the block entitled "six target generator unit." This is the block that would be replaced by the electronic target generators and associated modulator circuits. A single 15-conductor cable is used to interconnect the target generator unit with the target signal unit. The same cable could be used to couple from one to six electronic target generators to the 15-J-1c simulator. With

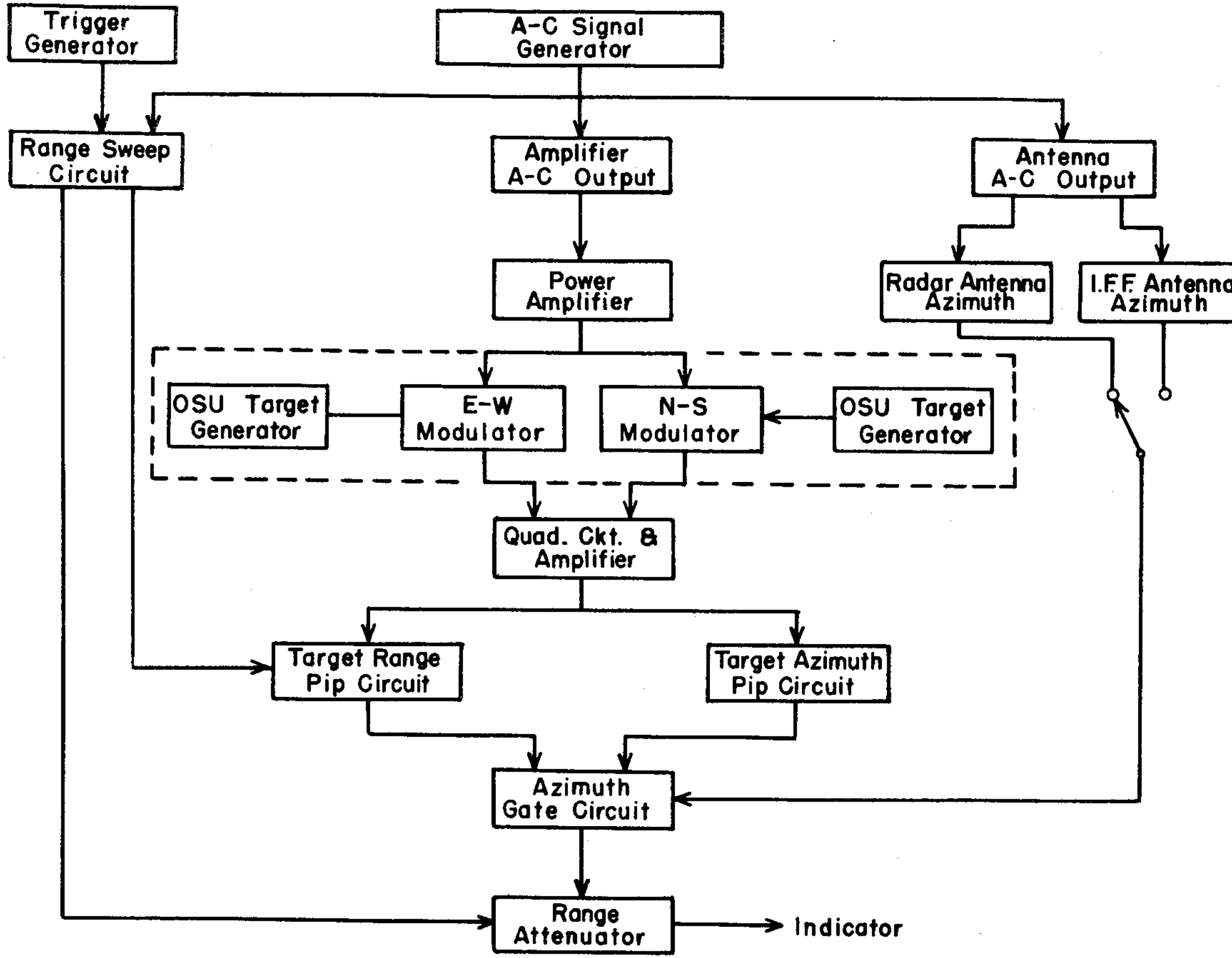

Fig. 17. Simplified block diagram of a 15-J-1c simulator modified to accept signals from an electronic target generator of the type used in the OSU-ATC simulator.

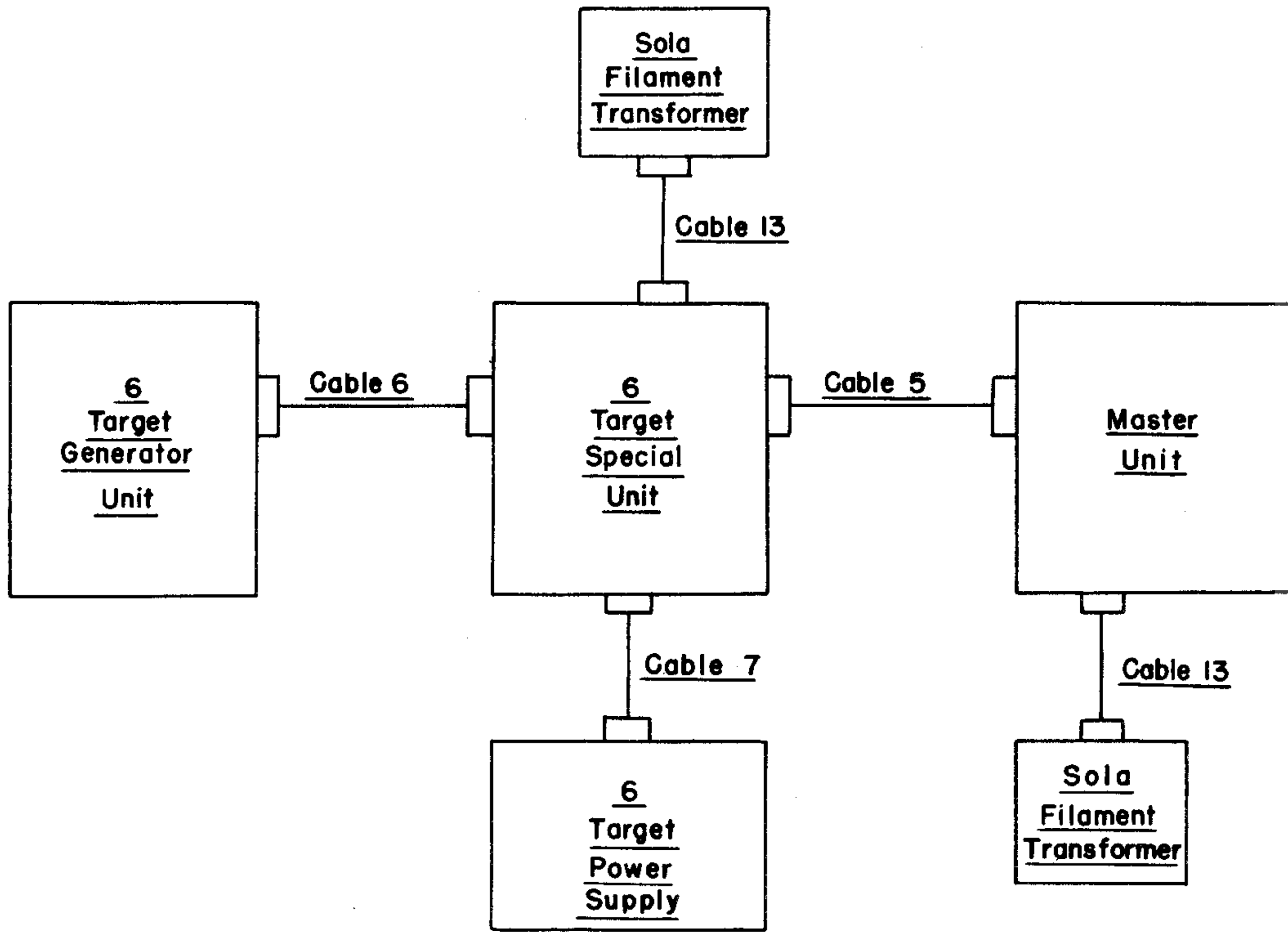

Fig. 18. Packaging and cabling connections for the 15-J-1c simulator.

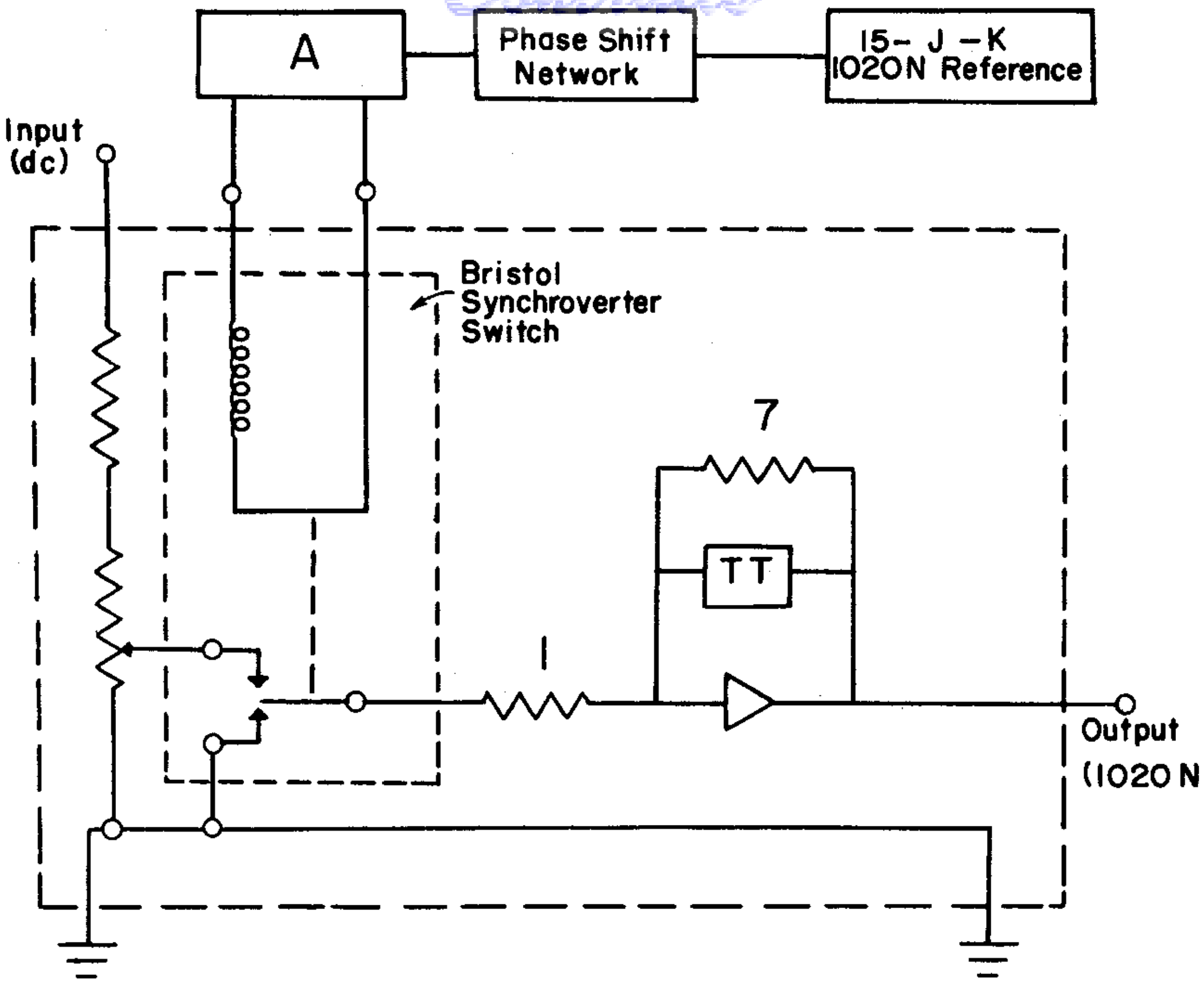

Fig. 19. Circuit diagram of modulator unit to adapt electronic target generator to device 15-J-1c.

one electronic target generator of the OSU-ATC simulator type, the 15-J-1c simulator could be converted by a simple plug-in operation.

The design of a single electronic target generator of the type used in the OSU-ATC simulator was presented in section 2.3. The design of an adapting modulator unit is presented in Fig. 19. These combined units can be used with the 15-J-1c simulator to present a single target on a PPI-type of radar display. Six of these units could be packaged so as to replace the existing 15-J-1c Six Target Generator Unit. This design was used in constructing an adapting modulator unit at OSU. This unit and one of the electronic target generator consoles were taken to Wright-Patterson Air Force Base to test the feasibility of this (3.4.3) design. The Engineering Development Section of the Test Engineering Branch, Engineering Division of the Directorate of Flight and All Weather Testing, worked with the OSU Laboratory of Aviation Psychology personnel in testing the design. The test situation included the driving of an AN/CPN-4 search indicator with simulated external antenna and trigger information and coupling this with the electronic signal generator components of the device 15-J-1c. Then the adapting modulator unit was plugged into the 15-J-1c components

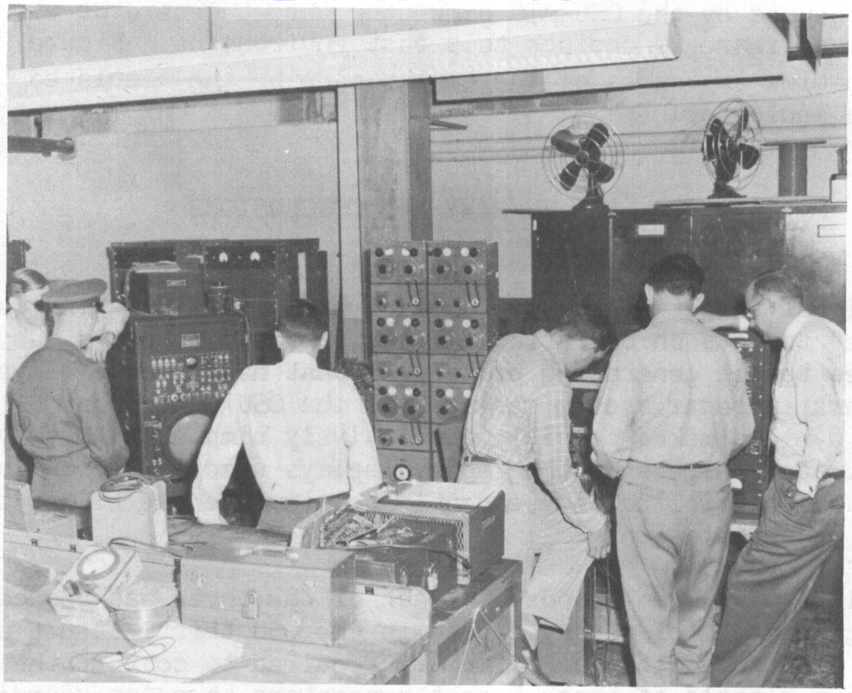

Fig. 20. Air Force and Laboratory of Aviation Psychology personnel testing the adaptations of the OSU-ATC simulator moving radar target generators for use with Air Force terminal area radars at Wright-Patterson Air Force Base.

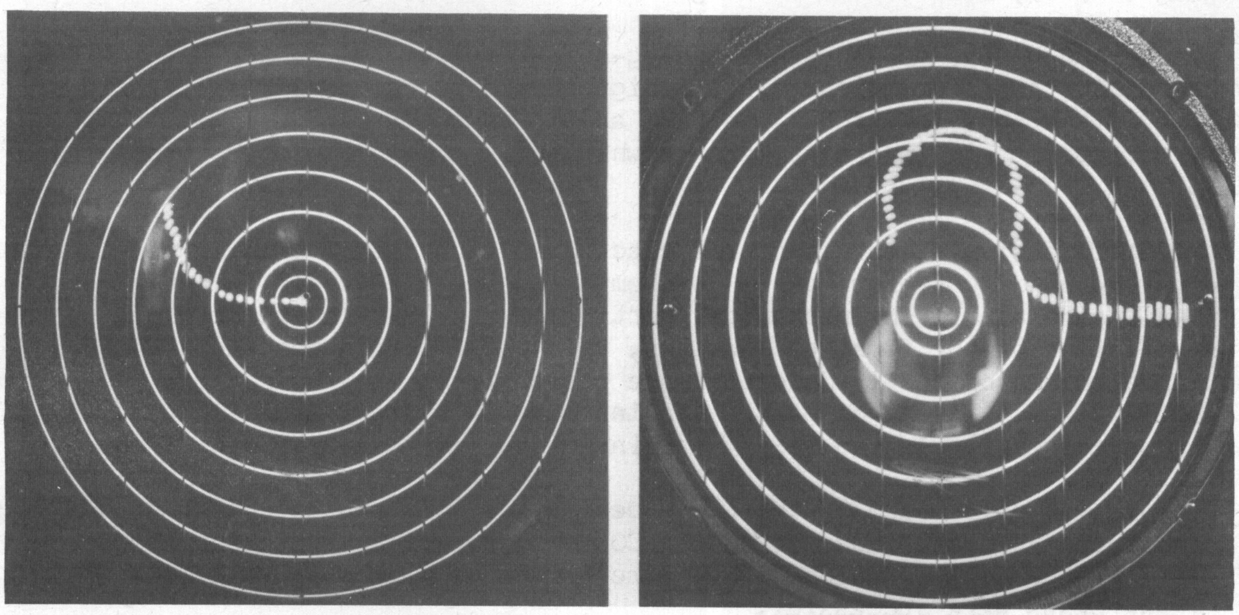

Fig. 21. Photographic records of the tracks of a simulated target generated by the OSU-ATC simulator as adapted to a 20-mi. display on an AN/CPN-4 search indicator. On the left is shown a 1-1/2 deg./sec. turn to a final heading of 270 deg.; on the right, a 3 deg./sec. turn from 270 deg. to 360 deg. and then a 180 deg. 1-1/2 deg./sec. turn to the left. Records are time exposures of an operational 10-in. display on a 12DP-7 CRT.

and a target produced by the OSU-ATC simulator target generator was displayed on the radar indicator. Figure 20 depicts this test environment. Figure 21 is composed of prints from two time exposures of the tracks made by the simulated target on the CRT of the AN/CPN-4 indicator.

4. SUMMARY AND CONCLUSIONS

An Operational Target Simulation (OTS) system for simulating targets and mixing them with "live" targets on operational PPI-type radar displays has been described. This system uses target generating procedures that have been employed successfully for several years in radar system research at the OSU Laboratory of Aviation Psychology (4, 5, 6), and makes possible a relatively simple and highly reliable method of placing simulated targets on the radar displays used in various operational units. Each target can be controlled independently to simulate the flight of aircraft under control from a ground station.

Three designs have been proposed. Each of the three was composed of an electronic target generator (of the type used in the OSU thirty-target electronic radar ATC simulator) and the additional circuitry required to convert the rectangular-coordinate output signals of these target generators to polar-coordinate signals compatible with the video-type intelligence required for operational radar displays. The three designs differed only in the method used for the transformation of this information from rectangular to polar form.

The first design makes use of a carrier system to facilitate an all-electronic coordinate transformation. It has the advantage of providing the possibility of packaging a small, self-contained target simulator unit.

The second design makes use of analog-computer elements to achieve the necessary coordinate transformation. This design should be especially applicable to laboratory situations in which a standard analog computer is available, in which extreme versatility is important, and in which only a few simulated targets need be displayed.

The third design makes use of the electronic elements of the signal generator of the Device 15-J-1c to form an OTS system using the electronic target generator of the OSU-ATC simulator. The mechanical portion of the 15-J-1c is not used. Although not as efficient as the first two designs, this third design has the advantage of employing elements of the 15-J-1c that are presently at many operational and training installations. It can be used as an interim OTS system, and will provide adequate radar target simulation for ATC training and limited experimental purposes.

A prototype unit based on the third design was constructed and tried out using the operational AN/CPN-4 radar at the RAPCON Center, Wright-Patterson Air Force Base, through the collaboration of the Directorate of Flight and All Weather Testing. These tests were successful.

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