LOW LEVEL AIRCRAFT RADAR SIMULATION

by 4589

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DEFINITION OF TERMS

PPI	Plan position indicator
FSS	Flying spot scanner
PMT	Photomultiplier tube
h_t	Terrain height above sea level
h_{cp}	Desired aircraft clearance plane height
h_a	Aircraft height above sea level
h_c	Aircraft terrain clearance at range = 0
R	Aircraft radar range
R_{min}	Radar minimum range
R_{max}	Radar maximum range
V	Aircraft velocity
$\dot{x}, \dot{y}$	Resolved aircraft velocity
x, y	Resolved aircraft positions
$\dot{\psi}$	Aircraft heading rate
ψ	Aircraft heading
θ_p	Aircraft pitch with respect to the horizontal
θ_r	Aircraft roll with respect to the horizontal
β_u	Aircraft antenna up-look limit
β_d	Aircraft antenna down-look limit
$\dot{\alpha}$	Aircraft antenna angle rate
α	Aircraft antenna angle with respect to heading
α_0	Aircraft antenna angle offset
$(h_a - h_t)_s$	Change in instantaneous shadow mask clearance as a function of range
E_{smf}	Shadow mask function voltage

$(\Delta_{ht})_s$	Instantaneous clearance as a function of β_u, β_d, θ_p, and θ_r
PPIC	Minimum range cursor
CRT	Cathode-ray tube
ϕ	Shadow mask generator computing angle
h_x	Any altitude point
R_{x_1}, R_{y_1}	x and y terrain position with respect to the aircraft
Range gate	Period of terrain computations
SS	Single shot
Comp.	Analog comparator
t	Time

STATEMENT OF THE PROBLEM

This paper will investigate the problems and requirements needed to design a simulated airborne radar system that is capable of producing a Plan Position Indicator (PPI) type of display. The radar return information will be displayed as a function of the radar antenna position and the aircraft position with respect to the terrain. Aircraft instrument readings such as true heading and altimeter clearance, which are a function of the aircraft position, are also included. The described system will employ a combination of analog and digital methods to compute the desired results of pilot control and hardware display effectiveness that are vital to advanced aircraft design.

LOW LEVEL RADAR AIRCRAFT REQUIREMENTS

An important tool in the area of engineering research has been the use of analog and digital computer systems to simulate real situations and hardware. These systems, if properly designed, can provide savings in time, money, and possibly human life. The real value in simulated systems stems from the ability to investigate problems that in many cases would be virtually impossible by any other method, yet they provide reliable design information to produce a desired product.

A typical low level aircraft radar system must present the return radar signal information in a clear and informative manner to be useful. Aircraft using this type of system usually desire to fly the terrain at some minimum clearance offset which will be consistent with aircraft stress and control limitations. A typical plan view of the problem is shown in Fig. 1, which illustrates the radar energy painting the oncoming terrain at various antenna positions (3). The radar system has the ability to look about the aircraft by various antenna positioning and to display a return of resolution no greater than the antenna's beam width. The position of the aircraft with respect to the terrain will determine those portions of terrain that produce no radar returns; therefore the area is shadow masked. The illustration also shows the area of terrain below the aircraft being sampled by radar to give aircraft altitude.

The basic requirements of a typical real radar must include circuits to provide the following:

1. Radar sweeps and timing.
2. Deflection circuits and display formats.
3. Change in terrain height computation.
4. Radar altimeter readings and range information.
5. Antenna controls and modes of operation. (3)

The requirement needs of a simulated radar must be able to provide:

1. An area of realistic terrain stored in some manner that is readily accessible upon demand in real time.
2. A definition of terrain that will produce realistic data for the aircraft speeds and altitudes to be

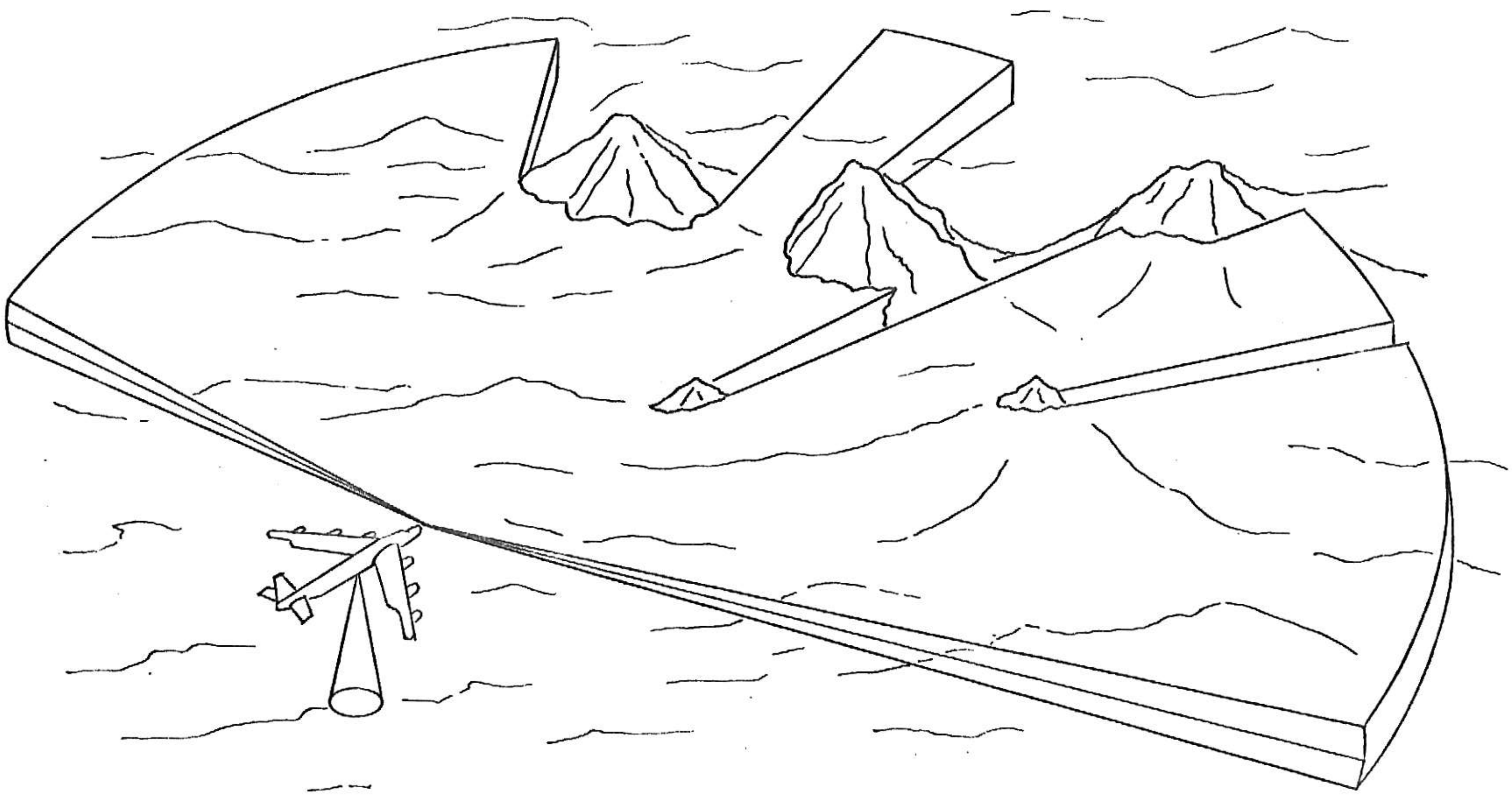

Fig. 1. Basic radar problem.

under test.

3. A terrain area large enough for complete test runs.
4. A method of translating the aircraft with respect to the terrain, i.e., north-south, east-west.
5. A method of changing aircraft altitude, pitch and roll motions with respect to the terrain.
6. Controls for sweeping the terrain at simulated radar rates such that changes in aircraft headings and antenna positions will maintain a realistic display of radar information.
7. A selection of radar ranges and modes of operation consistent with actual hardware and display formats.
8. Information for displays, including heading, velocity, aircraft altitude, and terrain clearance.
9. All computations that are a function of the pilot and aerodynamics must be computed in real time.
10. Realistic terrain masking caused by low level flight and certain terrain formations. (6)

BASIC AIRCRAFT SIMULATION REQUIREMENTS

To simulate an aircraft flying low level over terrain, the basic equations of motion of the aircraft, air turbulence, and the commands of the pilot must all be interrelated to produce the same characteristics dictated by the real world. The basic block flow diagram of a simulated aircraft with radar and displays is shown in Fig. 2. This configuration provides for pilot control of all primary flight functions

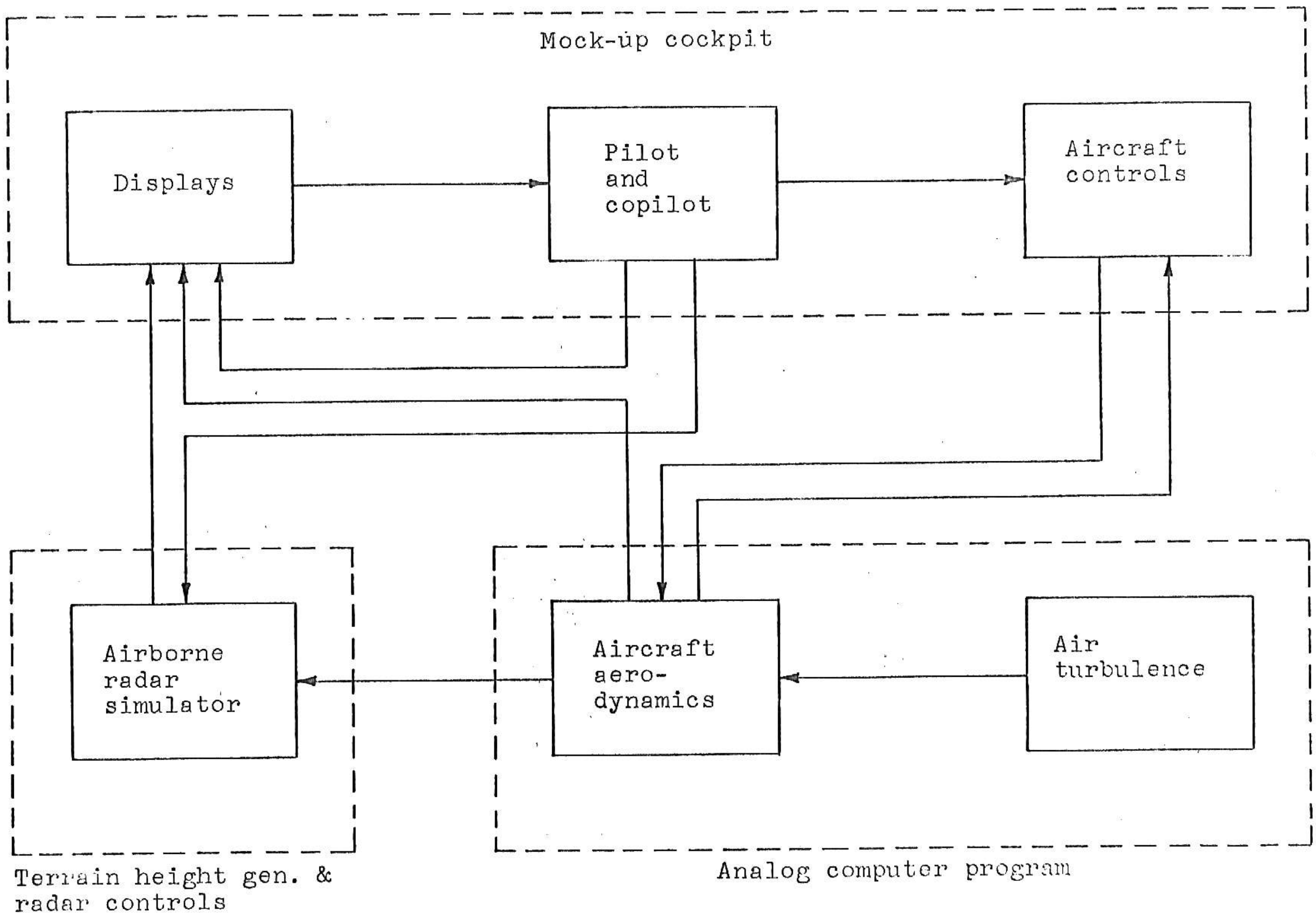

Fig. 2. Block diagram of basic aircraft simulation.

and displays (11). The mock-up cockpit consists of pilot and copilot seats, instruments, displays, and controls that are realistic to actual aircraft hardware. The pilot's input controls, such as stick position, throttle, and trim and rudder positions are used to control an analog computer program that contains the particular aircraft aerodynamics. The resulting computer outputs provide the inputs for the force-feel system on the pilot's control column, fuel flow, etc., as well as aircraft pitch, roll, height, velocity, and heading information to the simulated radar system. The radar simulator generates the necessary sweeps and terrain computation necessary to give the pilot a realistic display which in turn determines how he reacts on the control column. The pilot also has controls which allow him to adjust his displays for the most favorable viewing and to insert data into the terrain computations section of the radar simulator which adjust his display for desired offset information (9).

This report will investigate only two areas shown in Fig. 2--the airborne radar simulator and the displays that are controlled by that simulator.

THE AIRBORNE RADAR SIMULATOR

Figure 3 shows the basic radar simulator block diagram. The first requirement is to obtain a suitable terrain height (h_t) that can be used in the calculation of terrain clearance below the aircraft (h_c). The terrain computer also performs calculations for the terrain masking problem and allows for

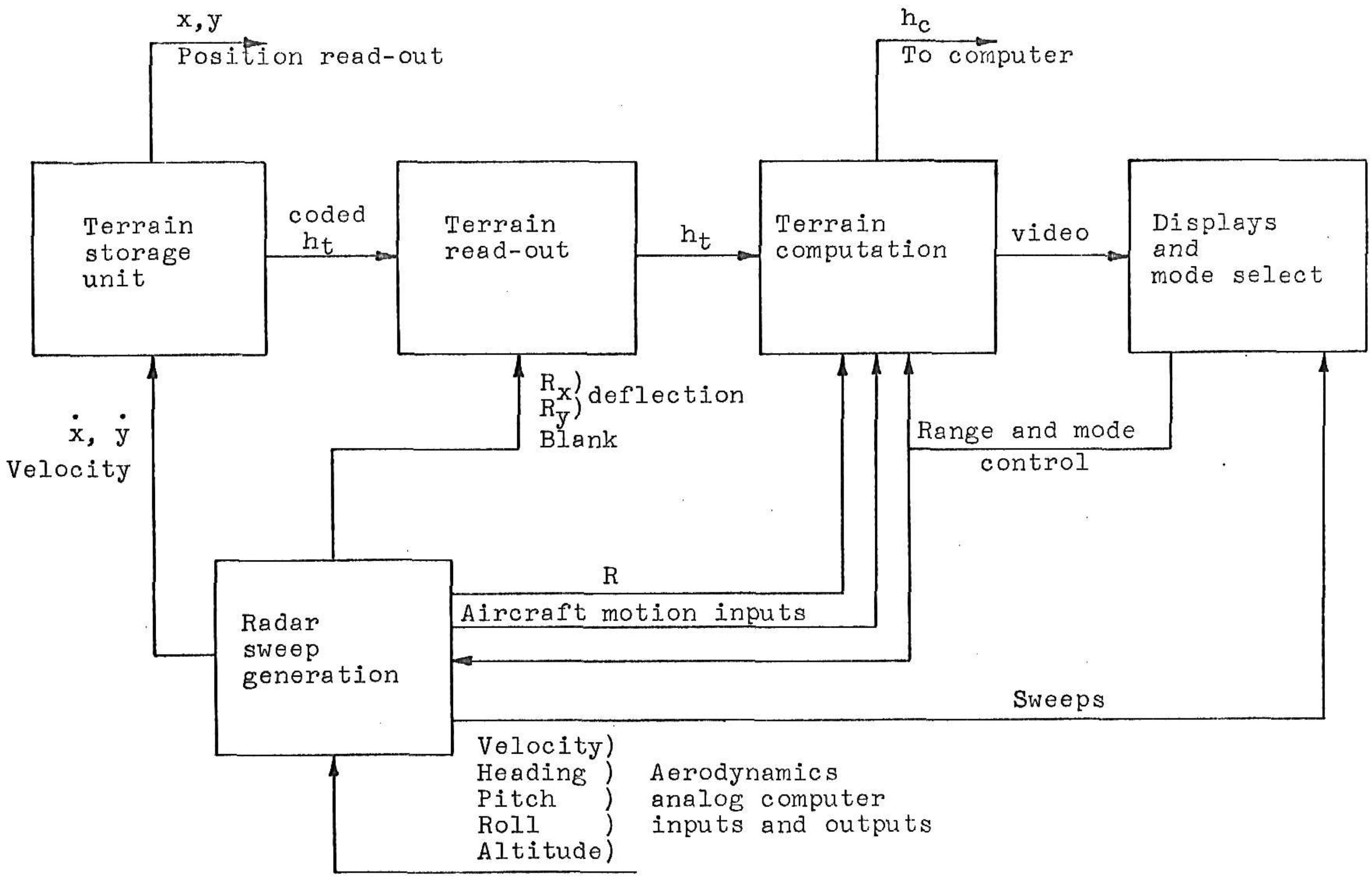

Fig. 3. Basic block diagram of radar simulator.

the aircraft's pitch, roll, and altitude functions to control the display for those sections of terrain that protrude above the radar's view as shown in Fig. 1 (5).

The pilot's control over his display allows for different modes of operation as well as various radar ranges and antenna positions. The radar sweep generation consists of that circuitry necessary to control the displays and antenna positions, to provide the basic timing for the entire simulator, and to generate simulated range, heading, and velocity signals as a function of the aerodynamic computer outputs (9). This radar system will employ a land mass storage unit consisting of an area of 1250 x 1250 nautical miles and containing terrain height information from sea level to approximately 15,000 feet. The storage unit is constructed as a large color transparency of 30 inches square with a scale factor of three million to one. Using scale factors of this magnitude, it is possible to maintain extended flight tests without repeating the same terrain as would be needed in navigation problems (7).

The basic land mass area is constructed in digital form by the use of colored dyes. These dyes consist of eight shades of red, seven shades of blue, and seven shades of green which have been constructed in a particular arrangement depending upon the terrain. The shades of red and blue are coded as terrain height; therefore any one of fifty-six steps of terrain height are available for read-out. The seven levels of green are used to code radar reflectivity such as buildings, water, and bridges. The resolution of the terrain is determined by the physical area of the particular shade of colors and may be as small as two mils. This land mass unit is capable of a resolution of 500 feet in the x-y plane and 100-, 200-, or 600-foot increments of resolution in terrain height where the increments are greater at increased terrain height (9).

Figure 4 shows a simplified arrangement of the terrain read-out system (7). This is accomplished by optically projecting a spot of white light from a flying-spot scanner (FSS) through the transparency and collecting the resultant colored light by special color sensitive photomultiplier tubes (PMT). An automatic brightness servo control is used to insure that the light output of the FSS remains a constant, which is mandatory if proper terrain signals are to be recovered. The light servo control gets its input from a reflected portion of the FSS light (12). The focused spot of light that is projected through the terrain map must be smaller in size than the terrain resolution if optimum performance is to be realized. This spot should be less than two mils in diameter when projected onto the transparency if the minimum area of resolution of 500 feet is to be met. The terrain height at any instant of time is computed by summing the PMT voltage outputs into a small digital to analog hybrid computer that operates on the digital terrain coding signals in a predetermined format. The output of the computer is an analog voltage proportional to the terrain height (14).

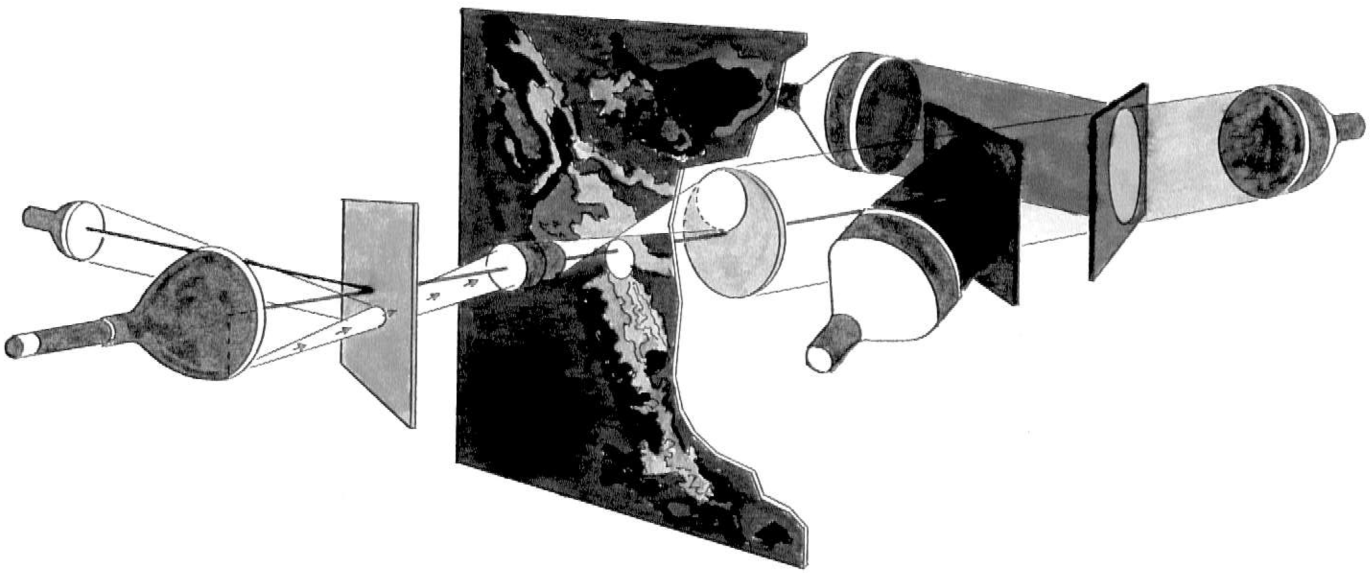

Fig. 4. Basic terrain read-out system.

The velocity of the aircraft is accomplished by transporting the storage unit about the FSS by mechanical servos geared to the x-y plane of the terrain map. A more complete figure of the system is shown in Fig. 5. This detailed block diagram shows the interrelationships of all the signals necessary to produce the radar displays (10). The range and antenna sweep generators are triangular wave oscillators that simulate radar range and antenna positions in time as a function of voltage. The simulator system is slaved to the repetition rate of the range generator to insure proper synchronizing of the terrain display signals (11). The simulated radar range signal (R) and the antenna angle (α), which is referenced to the aircraft heading, are the primary radar signals used to determine terrain position as a function of time. Basic heading rate ($\dot{\psi}$) and velocity (V) are fed into the heading resolver to produce the velocity components $\dot{x}$ and $\dot{y}$ that are needed to drive the storage unit servos so as to "fly" the aircraft. The range signal R is also resolved as a function of α, into R_x and R_y sweep voltages that provide simultaneous positioning of the FSS and display sweeps. Heading information (ψ) is produced by integrating $\dot{\psi}$ by a rate servo (9).

The timing logic is controlled at the repetition rate of R and includes the video and blanking controls for the display and the FSS. Figure 6 illustrates a typical radar sweep and terrain as a function of time (10). The geometry of this figure must be solved in the shadow mask generator and Δh_t

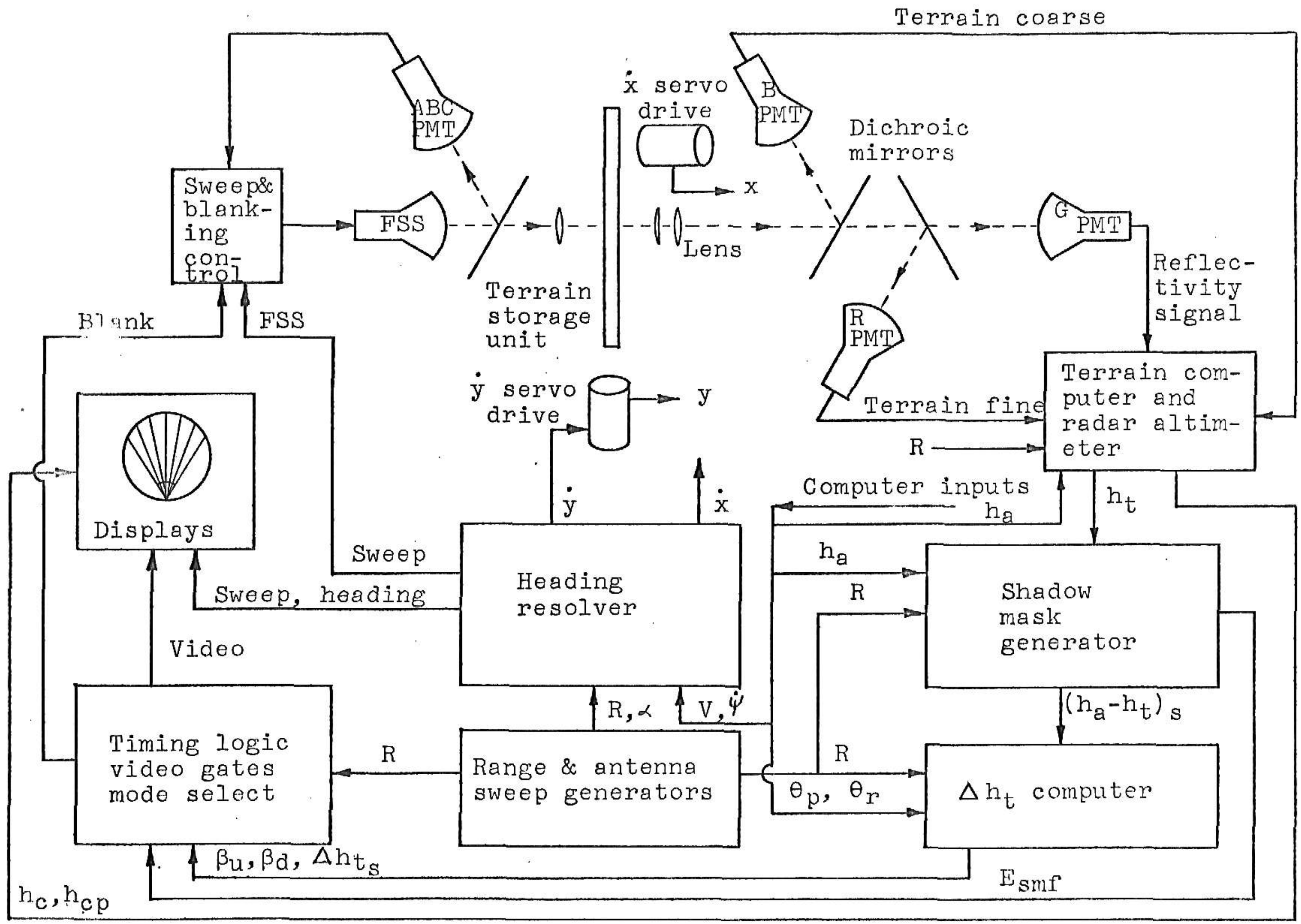

Fig. 5. Detailed block diagram of radar simulator.

computer of Fig. 5. The aircraft antenna has mechanical limitations of movement in the up-down position; thus the up-look limit (β_u) and the down-look limit (β_d) are the maximum angles the antenna may be positioned above and below the fuselage reference line. The aircraft pitch angle θ_p is the fuselage reference with respect to the horizontal. The aircraft altitude above sea level is an initial condition on the aircraft aerodynamic computer and is varied from the start of each test as a function of the aircraft position. The value of h_a at R = 0 is the basic data that is used to compute the terrain clearance (h_c) (1). The value of the clearance plane (h_{cp}) determines the minimum terrain clearance offset the pilot should fly if he interprets his display correctly. The value of h_{cp} is an electrical input that can be inserted into the Δh_t computer to insure this information is shown in the display, thus only terrain that protrudes through the clearance plane need be displayed as shown in Fig. 6a (9). Figure 6a shows how a side profile of the oncoming terrain might appear during a typical range sweep in time. The shaded area shown is that area painted by radar that is above the clearance plane; thus all other information that occurs is either within minimum range, or is shadow masked, or the antenna is up or down-look limited. The look limit angles β_u and β_d are computed as a function of instantaneous clearance $(h_a - h_t)_s$, pitch (θ_p), and roll (θ_r) in the Δh_t computer and are used along with Δh_t to insure proper video display signals. The shadow mask generator calculates the area of

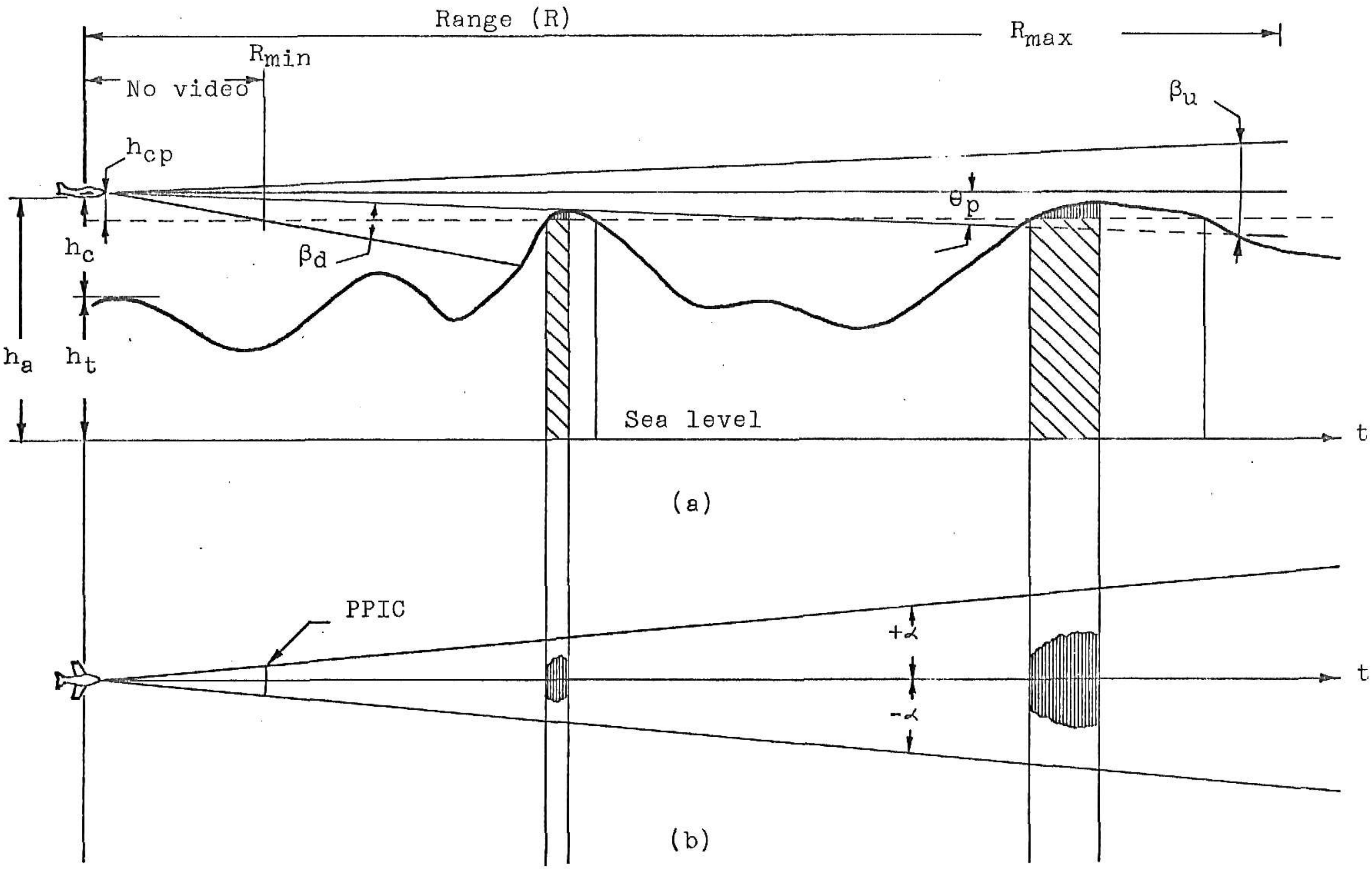

Fig. 6. Terrain wave forms.

terrain that should be displayed and produces a digital command shadow masked function (E_{smf}) that controls the logic and video information (10).

Figure 6b shows a small sector of Fig. 1, which shows the basic antenna and aircraft heading angles. The shaded terrain represents the single range sweep shown in Fig. 6a. The time axis in Fig. 6b represents the single range sweep shown in Fig. 6a. The PPIC is a cursor (E_{PPIC}) or video control voltage that determines minimum range for the display. These computations are accomplished in the video logic.

The display information consists of a PPI display that can provide a 360-degree plan view of the terrain or may produce an off-center sector scan, if that is desired. This information is displayed on a cathode-ray tube (CRT) which is situated directly in front of the pilot. The other display includes the radar altimeter which shows the aircraft clearance in real time and is read on a real aircraft radar altimeter. The heading of the aircraft is also displayed on a synchro-controlled servo unit giving degrees from true north (3).

DETAILED GEOMETRY AND DERIVATIONS OF COMPUTER EQUATIONS

The radar range sweep generator is the heart of the deflection and timing signals. The range (R) sweep generation is performed by the circuit shown in Fig. 7 which provides the desired scaled sweep trace and retrace timing complete with blanking pulses. The circuit can be analyzed by first assuming zero initial conditions on amplifier No. 1 and a period of 600 μs for a maximum range of 10 nautical miles. The wave forms to be designed are shown in Fig. 8.

Condition No. 1: $e_{03} > 0$. The output of amplifier No. 1 at $t = 0$ is $e_{01} = 0$. Assuming e_{03} was positive at $t = 0$ and $e_{03} = +50$ volts, then the output

$$E_{01} = - \frac{E_{03}}{CSR_1} , \qquad (1)$$

thus

$$e_{01} = - \frac{50t}{R_1 C} .$$

Letting $C = 10^{-8}$ fd and $R_1 = \dfrac{-50\ t}{10^{-8}(-30)}$ at $t = 250$ μs, then

$$R_1 = 41.6 \text{ K.}$$

$$e_{02} = -(e_{03} \frac{R_6}{R_5} + e_{01} \frac{R_6}{R_3})$$

$$= - \left[50(\frac{R_6}{R_5}) - \frac{50\ t}{416 \times 10^{-6}} (\frac{R_6}{R_3}) \right] . \qquad (2)$$

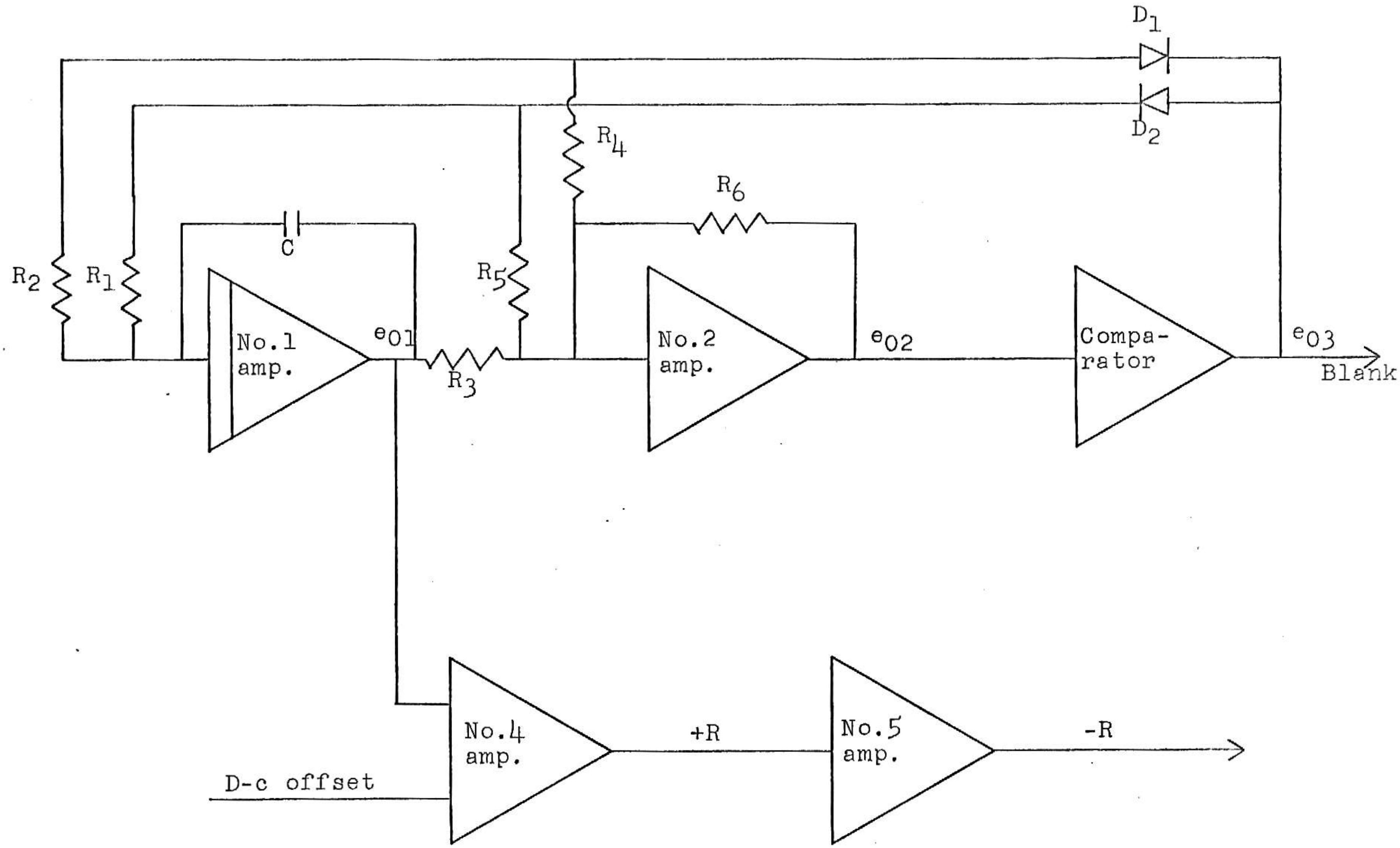

Fig. 7. Range sweep generator.

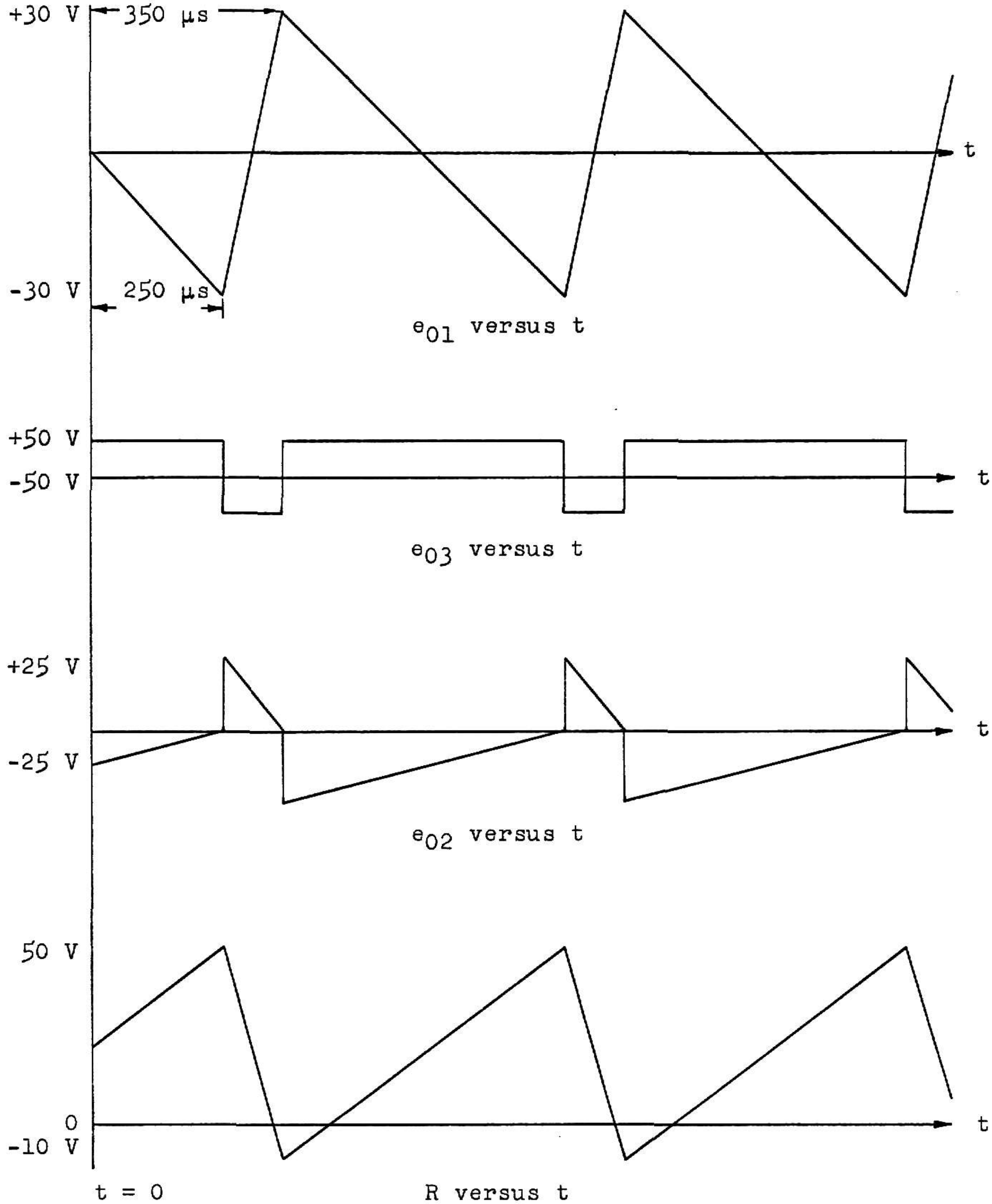

Fig. 8. Range sweep generator wave forms.

$$e_{02} = -25 \text{ V at } t = 0$$

$$e_{02} = 0 \text{ V at } t = 250 \ \mu s.$$

Using these two conditions, the following relationships are obtained:

$R_6 = .5 R_5$ Let $R_6 = 100$ K $R_5 = 200$ K

$R_3 = .6 R_5$ $R_3 = 120$ K

Condition No. 2: $e_{03} < 0$.

It can be seen that for $t > 250 \ \mu s$, $e_{02} > 0$. Thus $e_{03} < 0$.

$$e_{01} = -\left(\frac{-50\ t}{R_2 C}\right) - 30 \qquad (3)$$

and $e_{01} = 30$ V at $t' = 100 \ \mu s$.

Thus $R_2 = 8.33$ K.

$$e_{02} = -\left[-50\left(\frac{R_6}{R_4}\right) + \left(\frac{50t}{R_2 C} - 30\right)\left(\frac{R_6}{R_3}\right)\right]. \qquad (4)$$

$e_{02} = 0$ at $t' = 100 \ \mu s$ and $R_4 = 200$ K (4).

The signals actually used in timing and computations are $\pm$R and the blanking signal. R is a ramp of voltage proportional to sweep trace length (radar range) and is used to drive the FSS, display circuits, and control logic levels. The blanking signal controls blanking during retrace of sweeps and is the basic timing pulse of the system (12). The circuits these signals control will be shown later.

To drive the FSS correctly for changes in antenna and heading positions, a method of transforming heading rate ( )

and velocity (V), which is obtained from the basic aerodynamic equations, into sweep position and x, y translation is essential. Figure 9 shows a large view of the heading and antenna angle geometry required to produce the correct antenna scan patterns for any aircraft heading or antenna angle. These computations are performed in the heading and sweep resolver computer. The angle α may be any angle less than 180 degrees and must change at a rate consistent with actual antenna hardware. Assuming Ψ is reference to north and α with respect to Ψ, the following is true.

$$R_x = R \sin (\Psi + \alpha) \qquad (5)$$

$$R_y = R \cos (\Psi + \alpha) \; . \qquad (6)$$

Using the trigonometric identity for the sum of two angles,

$$R_x = R \sin (\Psi + \alpha) = R (\sin \Psi \cos \alpha + \cos \Psi \sin \alpha) \qquad (7)$$

$$R_y = R \cos (\Psi + \alpha) = R (\cos \Psi \cos \alpha - \sin \Psi \sin \alpha) . \qquad (8)$$

The relationship between heading and velocity are shown in Fig. 10. These voltages are used to drive the rate servos that translate the simulated aircraft with respect to the ground.

$$V_x = \dot{X} = V \sin \Psi , \qquad (9)$$

$$V_y = \dot{Y} = V \cos \Psi . \qquad (10)$$

The analog computer program which provides the FSS and display sweeping wave forms, is shown in Fig. 11. The velocity

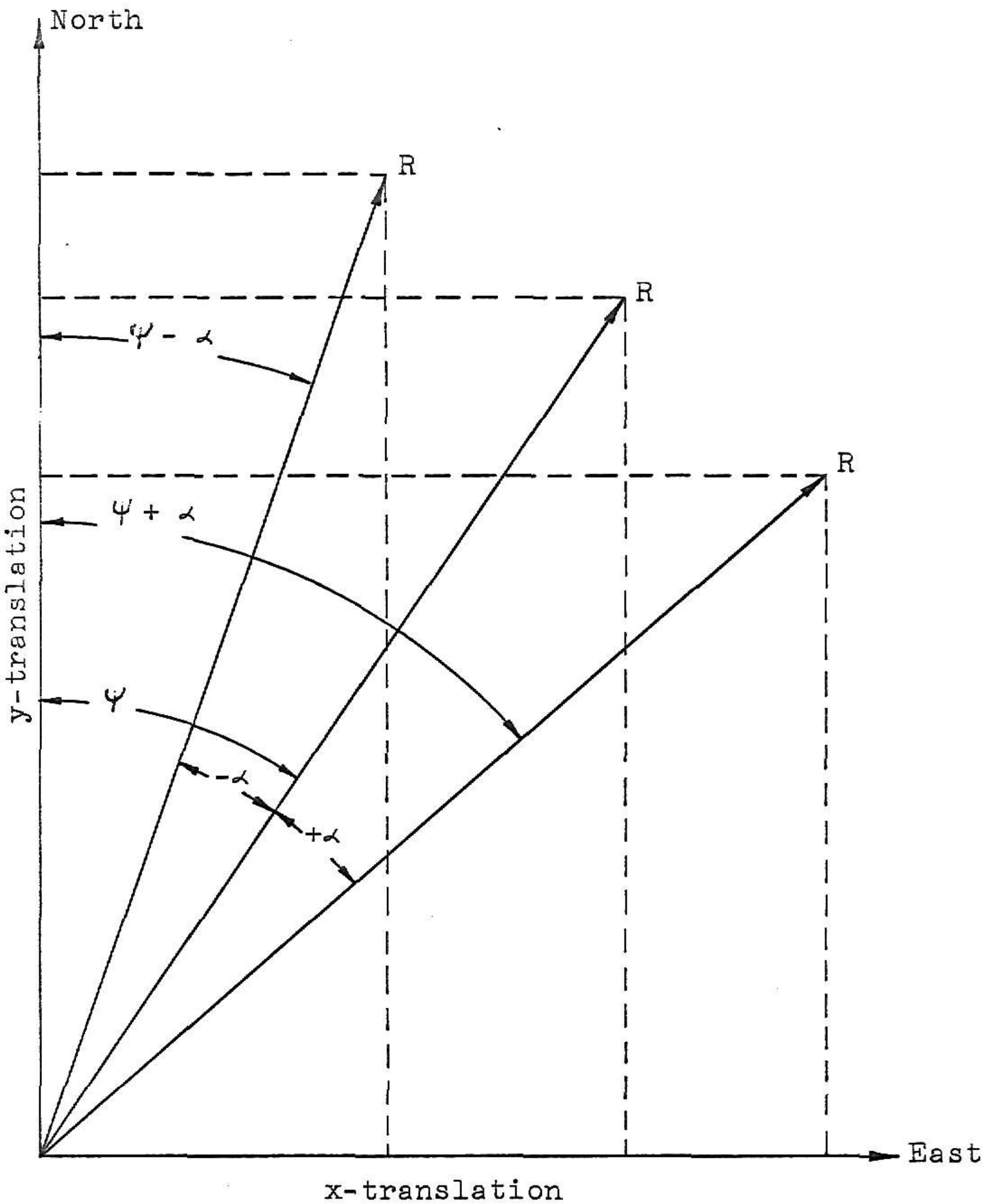

Fig. 9. Aircraft radar sweep pattern.

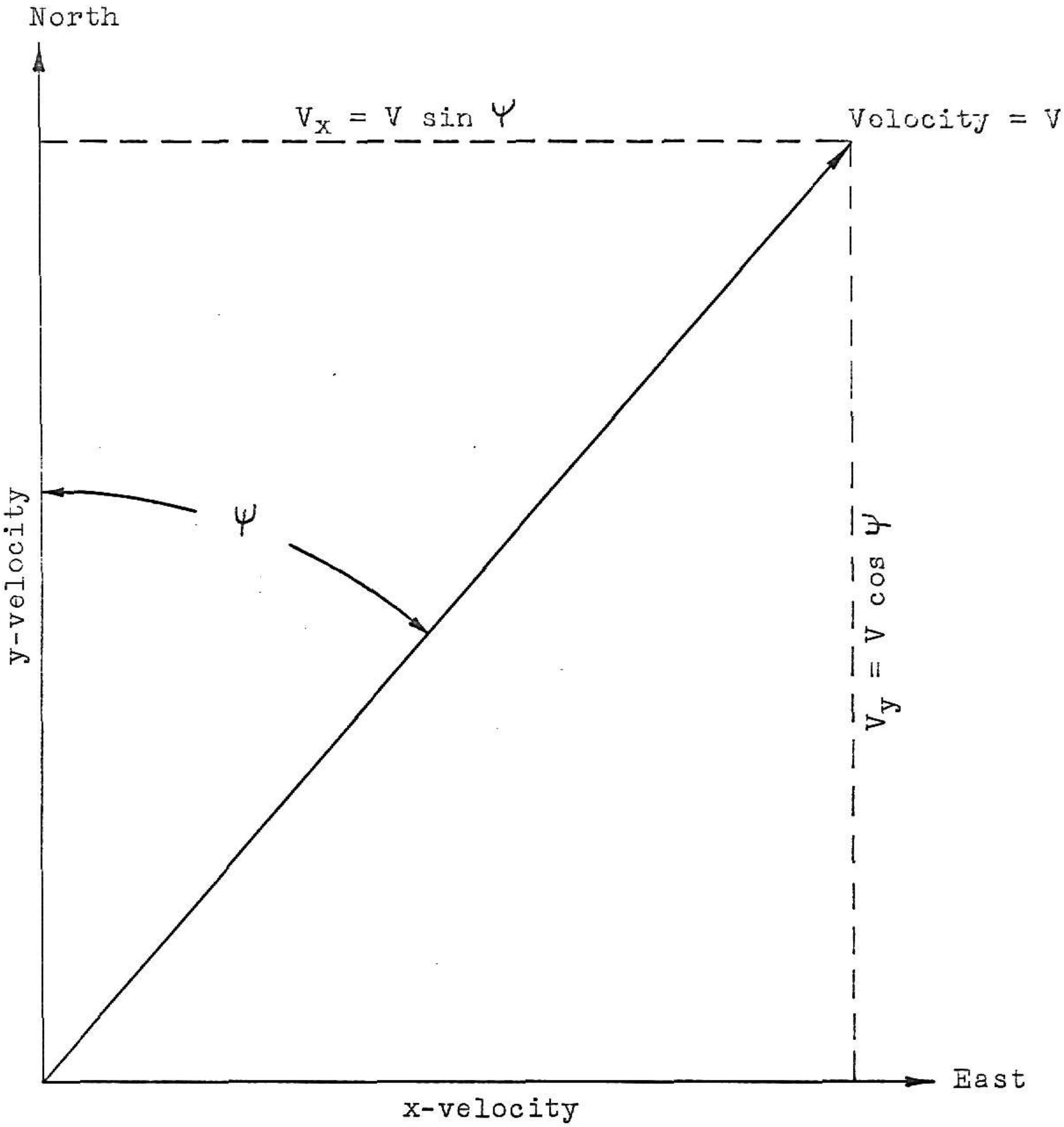

Fig. 10. Aircraft velocity pattern.

components for driving the storage unit are also derived (9).

The antenna angle (α) is generated in a circuit very similar to that of R except for sweep rates. The signal R may be in the order of 2 K H_z, while the rate for α may be as low as .3 H_z, which is typical for antenna rotation. The antenna position voltage is scaled such that α_{max} is less than the excitation voltage E. This condition must be met when α is used as a position function to prevent over scanning the potentiometer. When a complete PPI display is desired instead of a sector scan, the motor-generator servo system provides the position of α from 0 degree through 360 degrees. The antenna offset angle (α_o) is used to position the antenna off the fuselage reference, when sector scanning, if it is desired to do so.

Another rate servo integrates $\dot{\Psi}$ to produce the positioning of the heading angle which computes the x and y positions of range and velocity as a function of Ψ. A synchro is mechanically geared to the potentiometer shaft allowing the heading position to be easily distributed to a synchro receiver, with dial, in the pilot cockpit for visual heading information. The resolved $\dot{x}$ and $\dot{y}$ velocity signals are integrated by rate servos which translate the land mass storage unit about the FSS, thus allowing the aircraft to fly in the desired heading of the velocity of V.

The remainder of Fig. 11, except R sin α, R cos α is the summation of the resolved voltage to fulfill equations (7) and (8). The pilot's display, when in a sector scan-mode,

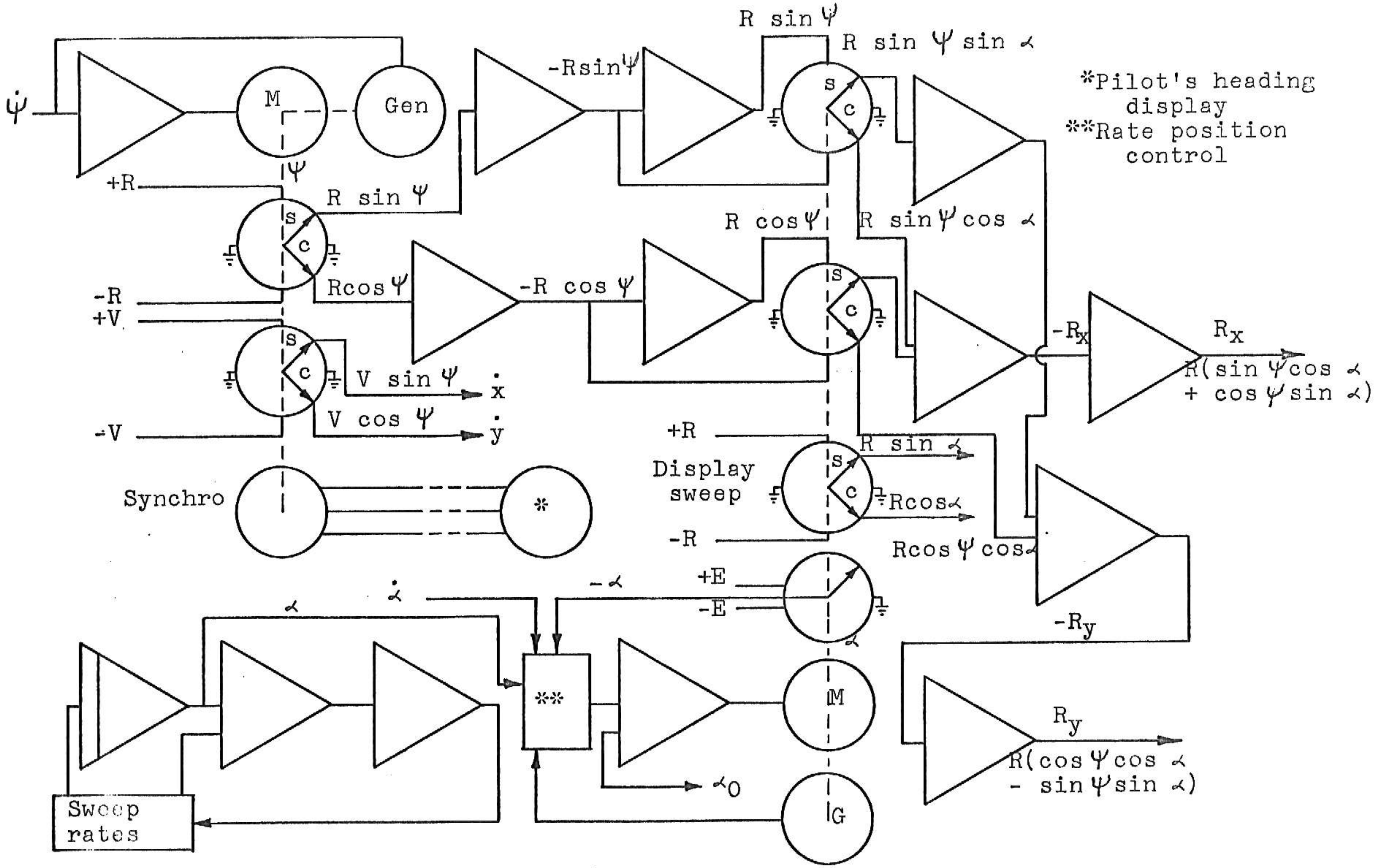

Fig. 11. Heading and sweep resolver computer.

will show the radar video information being displayed as a function of α only; thus the returns displayed on the right and left are actually on his right and left looking out of the cockpit. The resolved range voltages (R_x) and (R_y) are used to position the spot of light from the FFS in a similar manner on the terrain storage unit (13).

As previously stated, one of the requirements of a simulated radar is the ability to provide proper shadow masking of the terrain. In the real world, low level flights and steep terrain formations prevent the pilot from seeing behind the hills and mountains to see what is "coming up"; thus the ground returns cannot occur from nonexposed areas. The simulated radar must have the same capability if realistic radar information is to be displayed (8). In the simulator, the FSS sweeps the terrain as though it were always directly above it; thus for any instant of time from R = 0 to $R = R_{max}$, the height of each discrete colored area is reproduced to give a typical sweep as shown in Fig. 12. This figure demonstrates the need for computing this shadow masking function (smf) for each terrain sweep R at each antenna and heading position as a function of aircraft altitude. The only terrain that can be allowed for display is that shaded portion shown; the remaining is either limited by minimum range, the up or down look limits, the smf or R_{max}. The correct information at the display would appear similar to that shown in Fig. 6b.

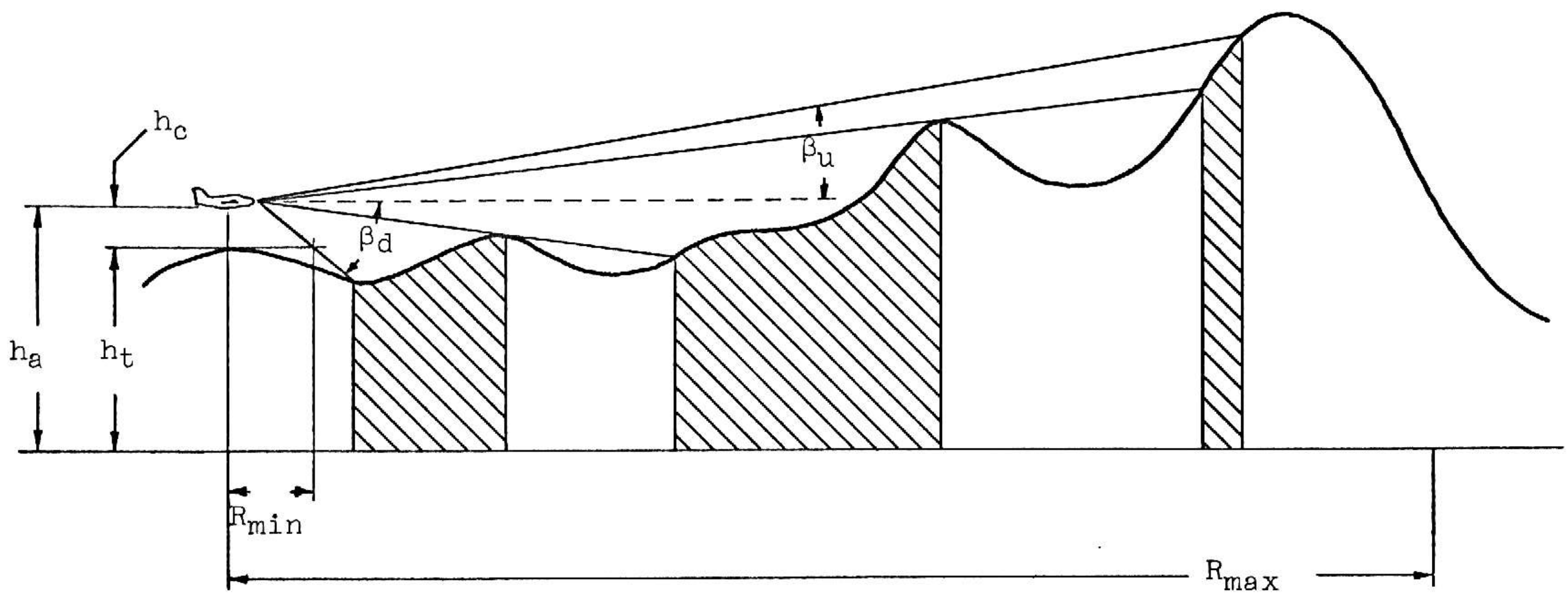

Fig. 12. The basic shadow mask problem.

An expanded view of this situation is shown in Fig. 13 and will be used to derive the conditions and equations necessary for the analog computer program for proper terrain shadow masking.

For any instant of time of the sweep R, it is obvious that

$$\frac{h_a - h_t}{R} = \tan \phi \ . \qquad (11)$$

From Fig. 13, it is obvious that the terrain should be seen for continually decreasing tan ϕ and should be masked or gated off for a continually increasing tan ϕ. Therefore, for any sweep, if the angle ϕ starts to increase above the prior instantaneous minimum value, the masking of terrain should occur. The complete analog computations with gating are shown in Fig. 14.

Assume scale factors of h_a = 10 mv/ft, h_t = 5 mv/ft, and R = .75 mv/ft, an altitude of h_a = 5000 feet and a terrain height of one sweep as shown in Fig. 15. The amplifier outputs for this one sweep have been computed and are shown in Fig. 15. The divider number 9 is used to compute the tan ϕ as shown in equation (11), which is then minimum peak detected in a sample-hold circuit. This sample-hold and associated reset gate includes amplifier No. 5, 6, 7. The reset is provided for the peak detector prior to R_{min} and cannot compute until R_{min}, thus allowing the divider to recover from saturation at R = 0 before computations are made.

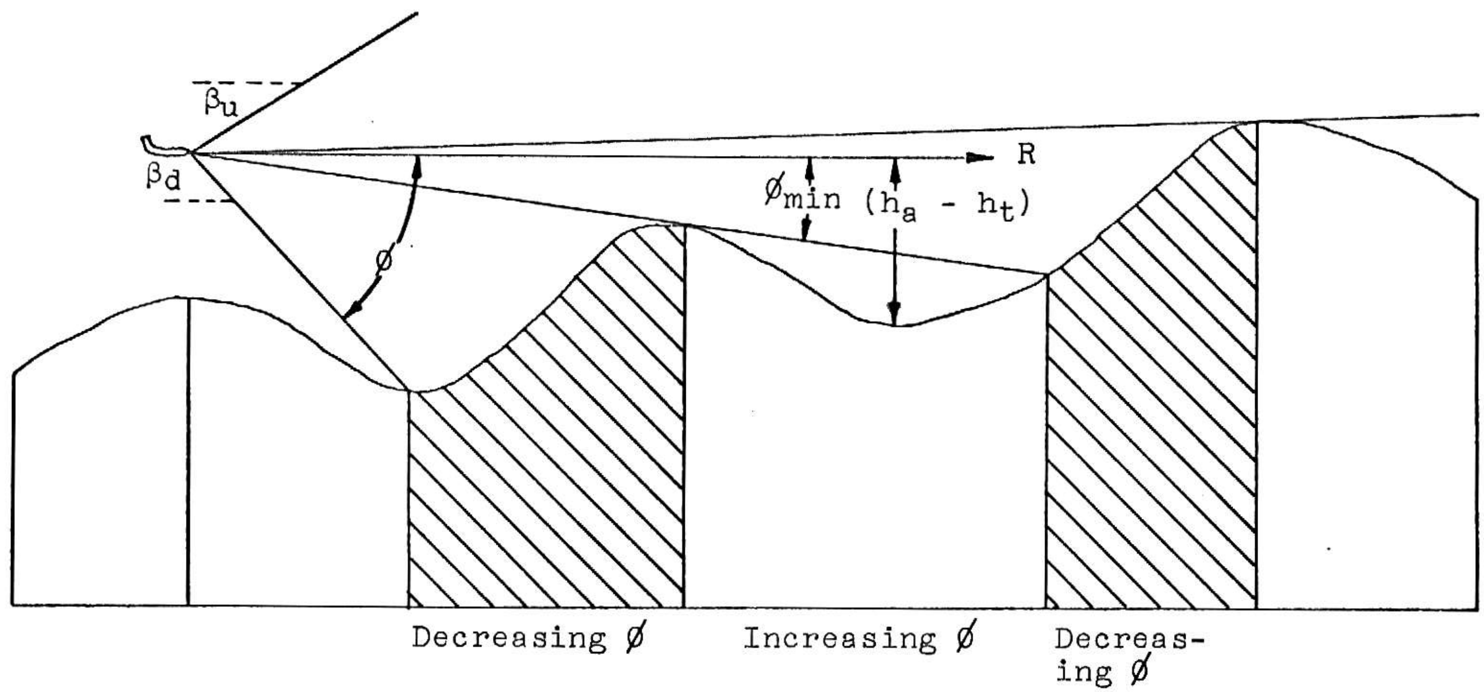

Fig. 13. The detailed shadow mask problem.

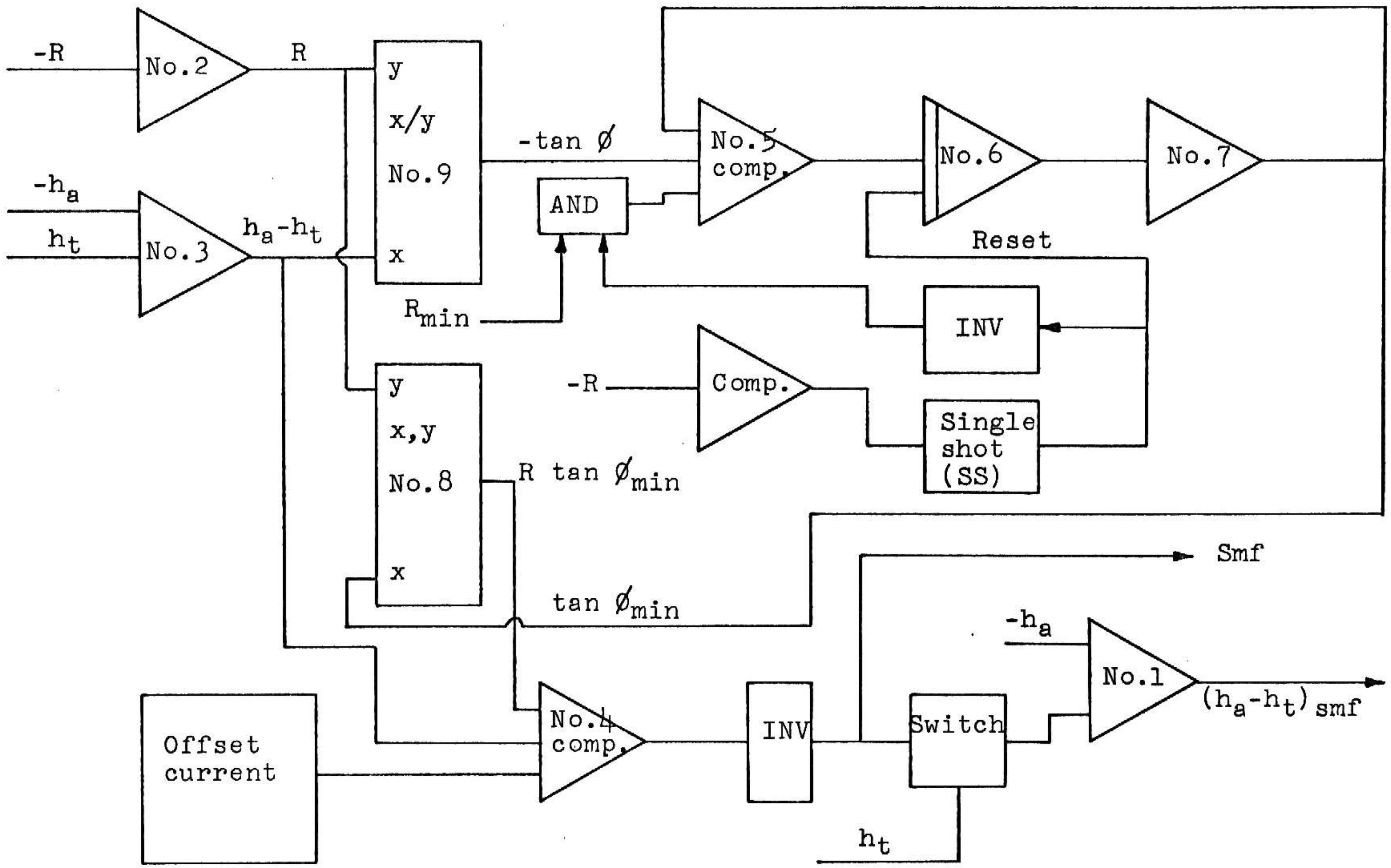

Fig. 14. Shadow angle computer.

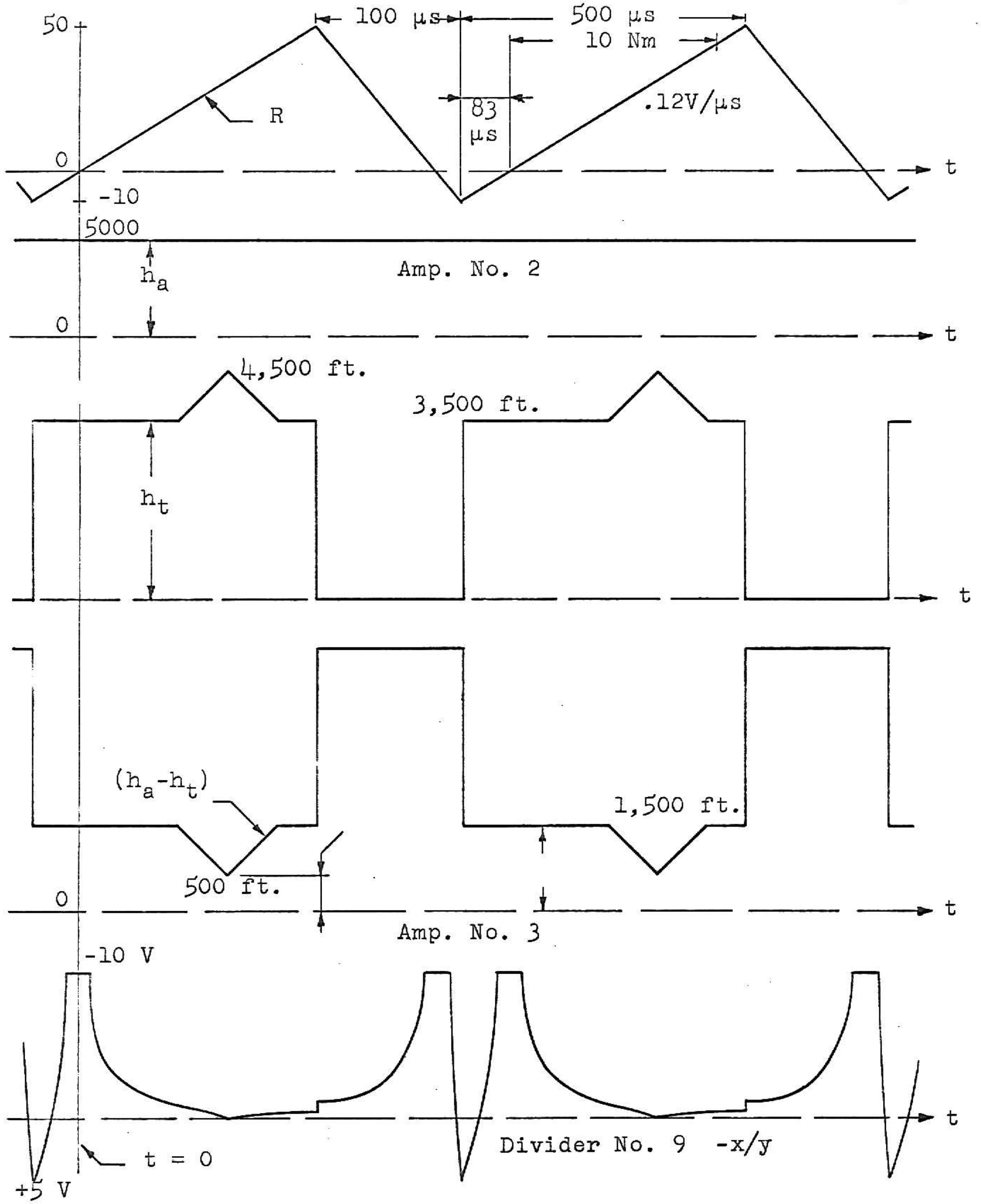

Fig. 15. Shadow angle computer wave forms.

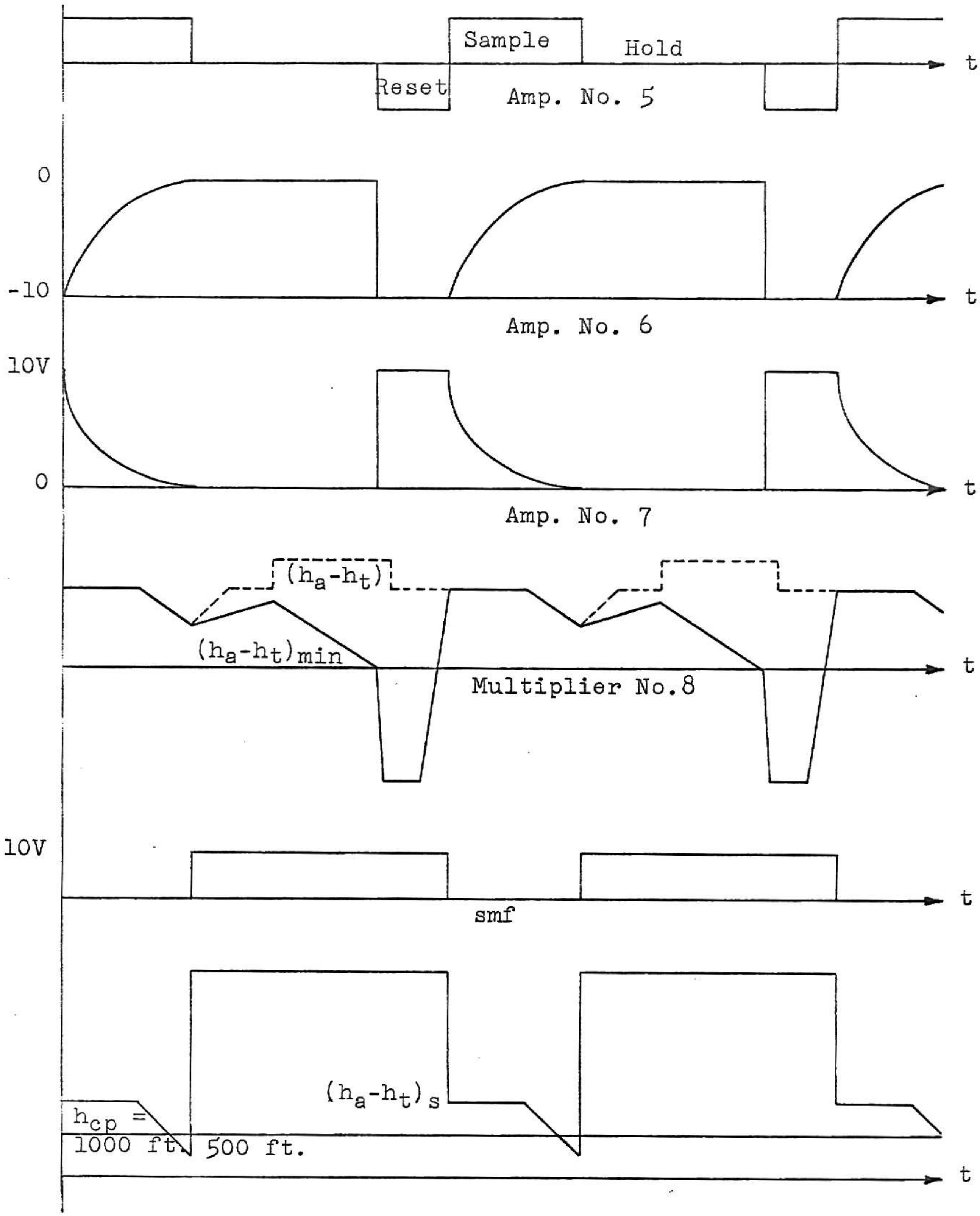

Fig. 15. Shadow angle computer wave forms (cont.).

This insures reliable data for display purposes. When the output of amplifier No. 7 is multiplied again by R, the resulting output is the minimum detected clearance during that sweep which when compared to the instantaneous clearance, produces the shadow gate (smf), as shown in Fig. 15. The gate is then used to control the conditions $h_t = h_t$ or $h_t = 0$ at the input of amplifier No. 1. The output of amplifier No. 1 now becomes the basic instantaneous sweep equation for pitch, roll, and display clearance (4).

It will be recalled that x and y translations were obtained by positioning the storage unit by servos with respect to the FSS. Y_{aw} was obtained via the heading resolver to position the spot of light on the FSS at the aircraft heading plus or minus the antenna angle, z was obtained in the shadow mask generator to make the instantaneous terrain clearance a function of altitude. The previously computed clearance signal $(h_a - h_t)_{smf}$ must now be operated upon as a function of range to provide the remaining two degrees of freedom, pitch, and roll. These functions are performed in the Δh_t computer.

Figure 16 is a plan view of the aircraft and its basic antenna sweep pattern for any heading Ψ (9). Let R_{x_1} be the distance in front of the aircraft and R_{y_1} be the distance to the side of the aircraft, P is any point at the instantaneous range R and angle α from the origin. Thus

$$P_1 = R \cos \alpha + R \sin \alpha = R_{x_1} + R_{y_1} \ . \qquad (12)$$

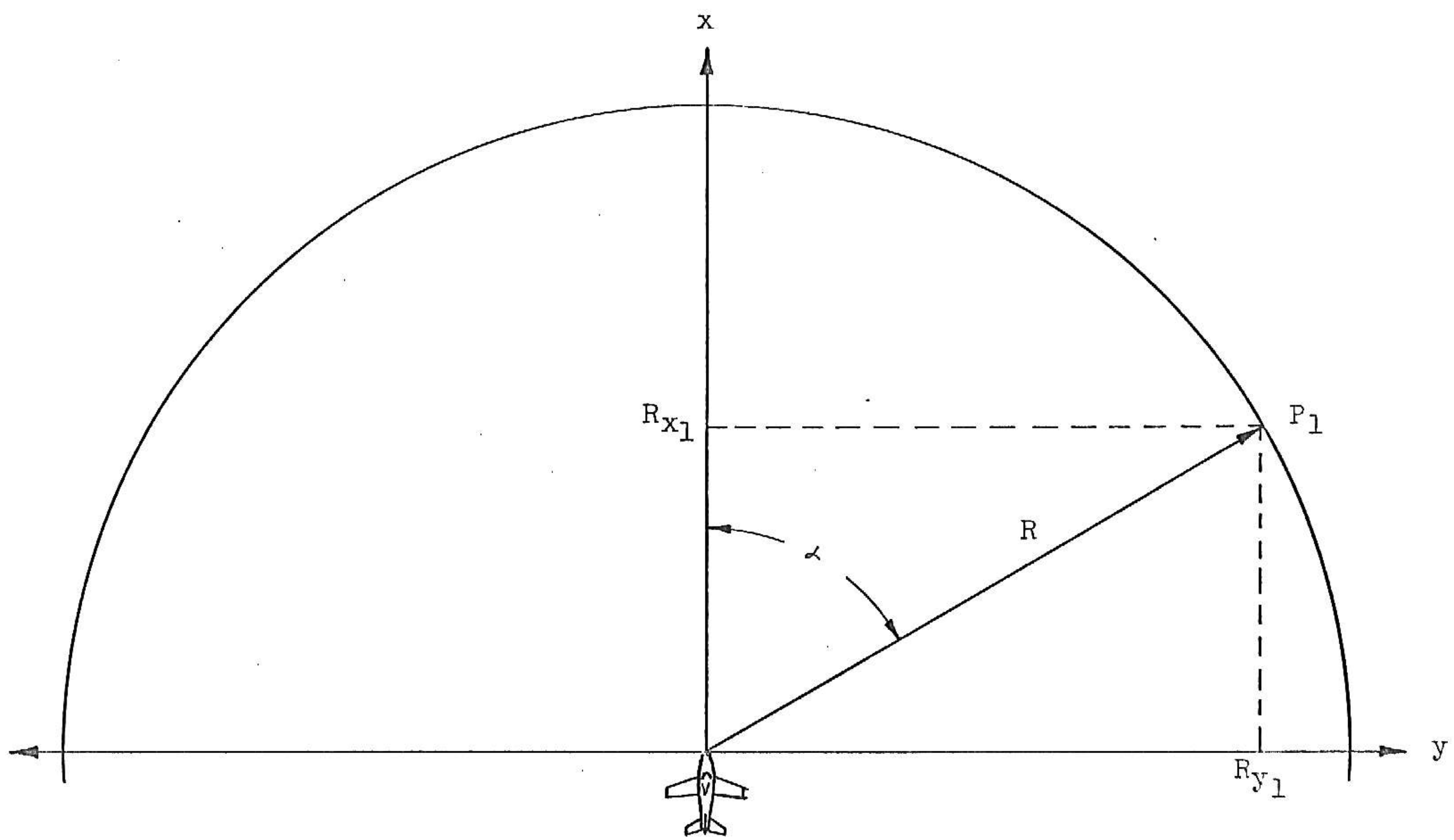

Fig. 16. Range versus antenna pattern.

P_1 is in the horizontal plane of the aircraft because the FSS can only sweep perpendicularly to the terrain height. When the aircraft pitches, it rotates about the y-axis and rotates about the x-axis during roll maneuvers; thus R cos α is used in the computation of pitch and R sin α is used in the computation of roll as shown in Fig. 17.

The instantaneous computations needed in the x-plane are:

$$\frac{(h_a - h_{\theta_p})}{R \cos \alpha} = \tan \theta_p \approx \theta_p, \text{ assuming } \theta_p \lesssim 15^\circ < 3\% \text{ error} \tag{13}$$

and

$$\frac{(h_{\theta_p} - h_x}{R \sin \alpha} = \tan \theta_r \approx \theta_r \text{ in the y-plane.} \tag{14}$$

The instantaneous clearance from the horizontal of the aircraft to the point it has pitched and rolled toward is $(h_a - h_x)$; thus

$$\begin{aligned}(h_a - h_x) &= (h_a - h_{\theta_p}) + (h_{\theta_p} - h_x) \\ &\approx \theta_p R \cos \alpha + \theta_r R \sin \alpha = R (\theta_p \cos \alpha + \theta_r \sin \alpha)\end{aligned} \tag{15}$$

If $h_a - h_t < h_a - h_x$, the terrain should always be displayed indicating that if the present pitch and roll attitudes are not changed, a collision with the terrain will occur.

Figure 18 shows the analog program to compute the pitch, roll, up and down look limits of the radar, and the clearance offset (h_{cp}) effects operating on $(h_a - h_t)_s$. Neglecting the β_u and β_d inputs for the moment, it is seen

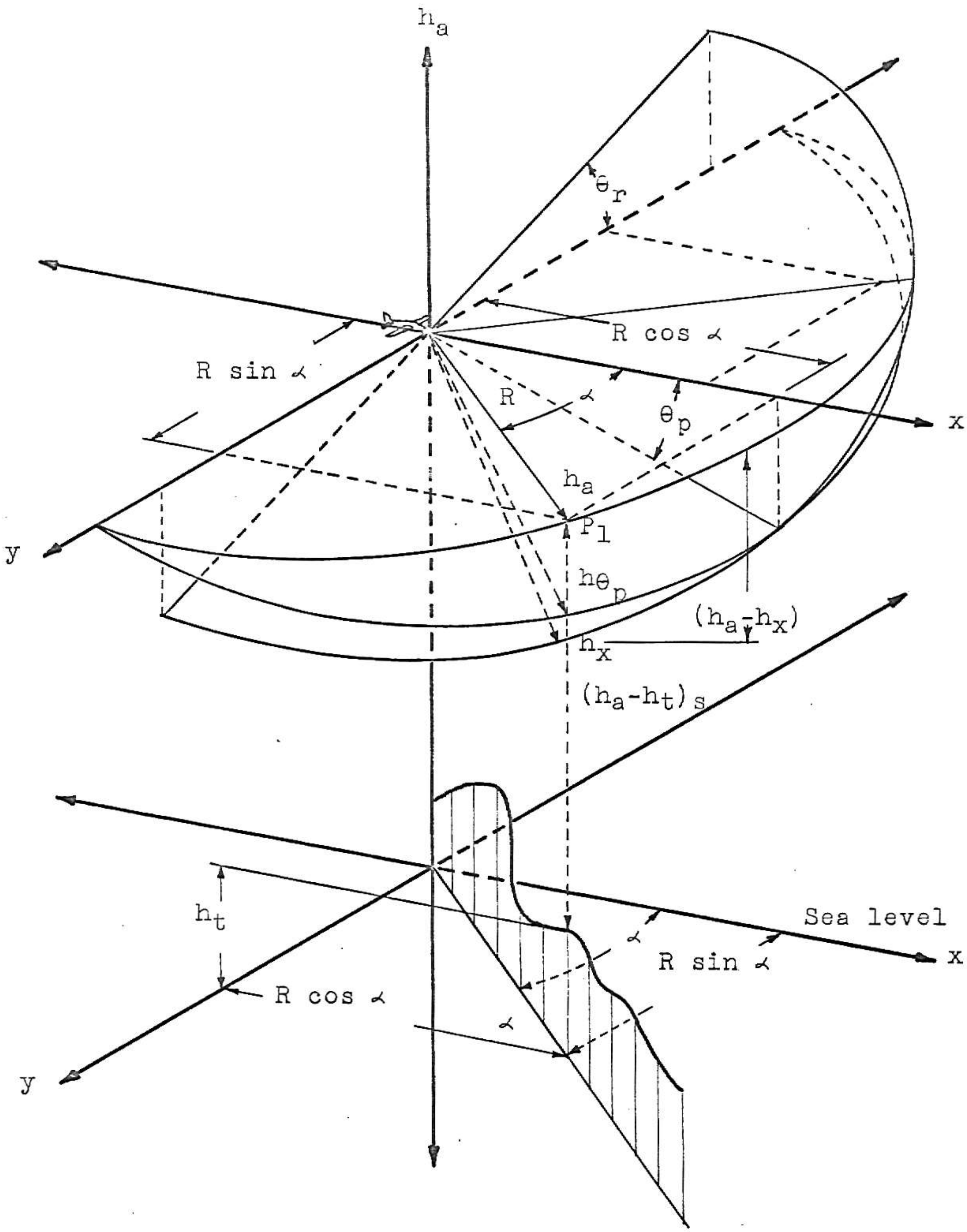

Fig. 17. Basic Δh_t computer computations.

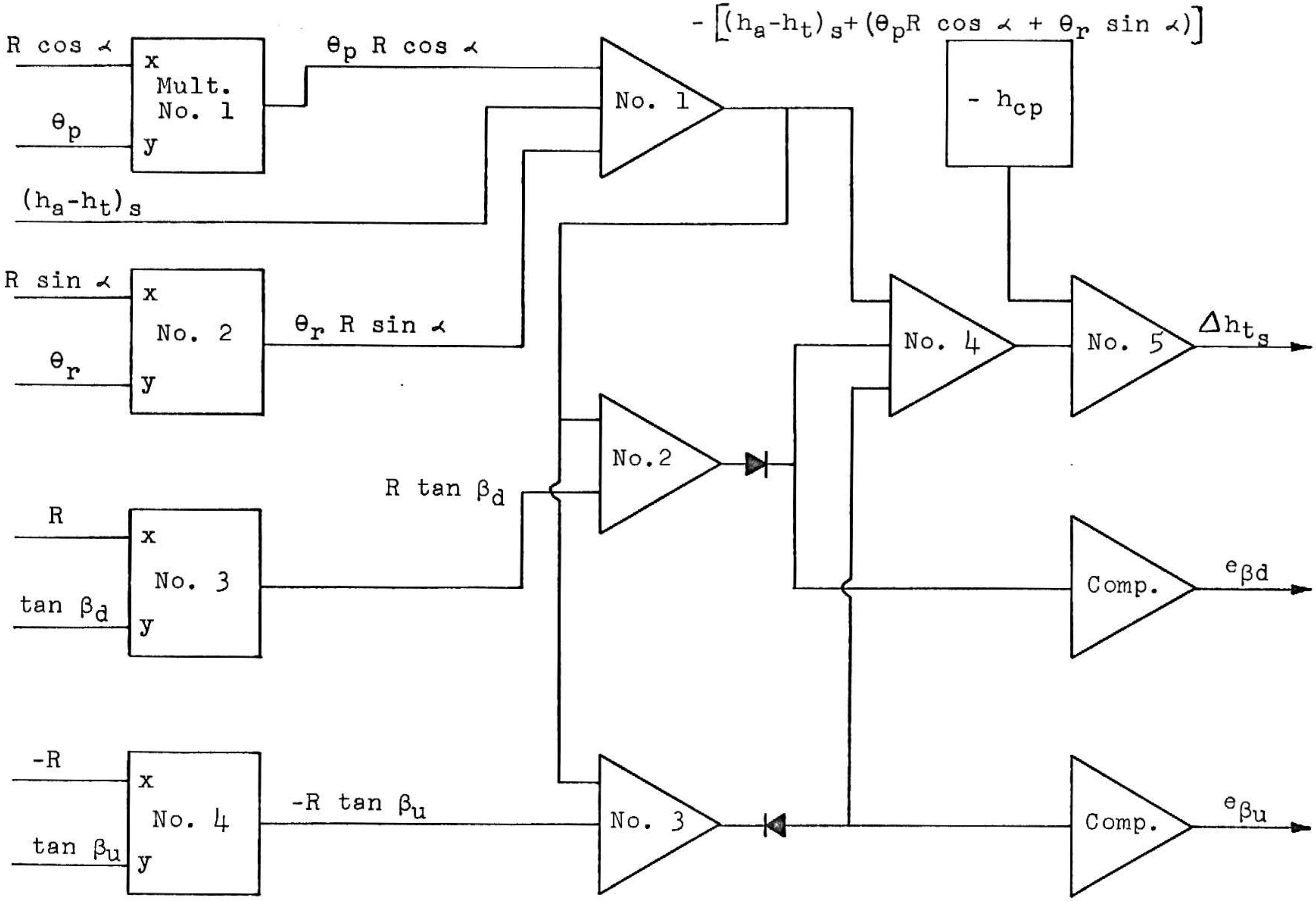

Fig. 18. The Δh_{t_s} computer.

that Δh_t is positive for $h_{cp} - \left[(h_a - h_t)_s + \theta_p R \cos \alpha + \theta_r \sin \alpha\right] > 0$. Thus the aircraft will clear all terrain; if the bracketed term is zero, the aircraft will clear the terrain by the desired clearance h_{cp} (4).

The effects of the up and down look limits are shown in Fig. 6a and Fig. 12. It can be seen that if $h_a - h_x > h_a - h_{\beta_d}$, no radar information can paint the terrain because of the physical characteristics of the antenna; thus $h_a - h_{\beta_d} = R \tan \beta_d$. Similarly, $h_{\beta_u} - h_a = R \tan \beta_u$. The total Δh_{t_s} function including the up and down look limits is as follows:

$$\begin{aligned}\Delta h_t &= h_{cp} - (h_a - h_t + \theta_p R \cos \alpha + \theta_r R \sin \alpha) \\ &+ \left[(h_a - h_t + \theta_p R \cos \alpha + \theta_r R \sin \alpha) - R \tan \beta_d)\right] \\ &+ \left[(h_a - h_t + \theta_p R \cos \alpha + \theta_r R \sin \alpha) + R \tan \beta_u)\right]. \end{aligned} \tag{16}$$

The terms in the bracket correspond to the effects of β_u and β_d which must obey the following three conditions for controlling amplifier No. 2 and No. 3.

If β_d gate is on, β_u gate is off.

If β_u gate is on, β_d gate is off.

If β_u gate and β_d gate are both off, neither amplifier No. 2 nor No. 3 conducts.

Thus if $R \tan \beta_d < h_a - h_t + \theta_p R \cos \alpha + \theta_r R \sin \alpha$, amplifier No. 2 conducts, and if $R \tan \beta_u > h_a - h_t + \theta_p R \cos \alpha + \theta_r R \sin \alpha$, amplifier No. 3 conducts. Only when the above inequality signs are reversed can there be intelligent video information displayed as shown in Fig. 19. Digital output

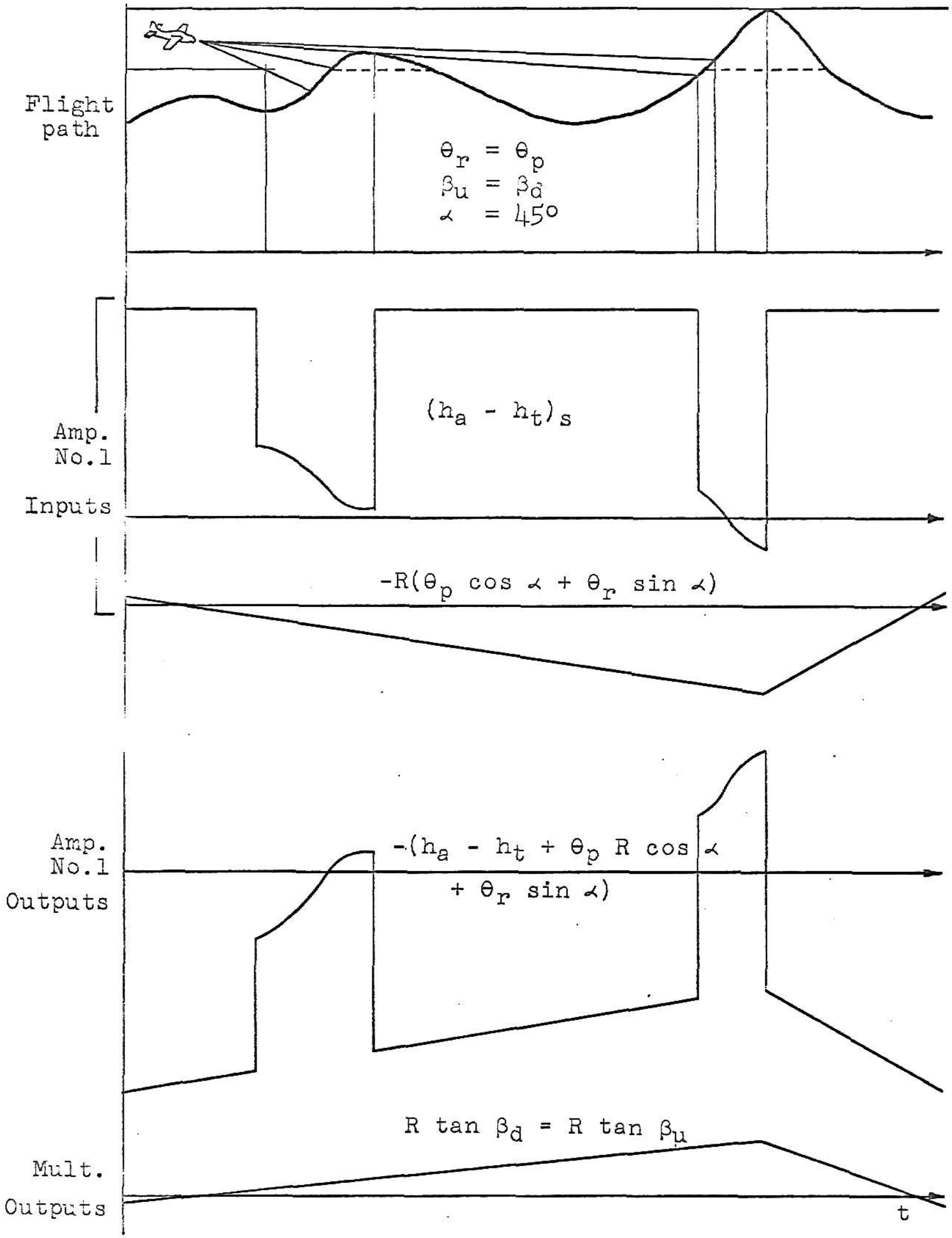

Fig. 19. The Δh_t computer wave forms.

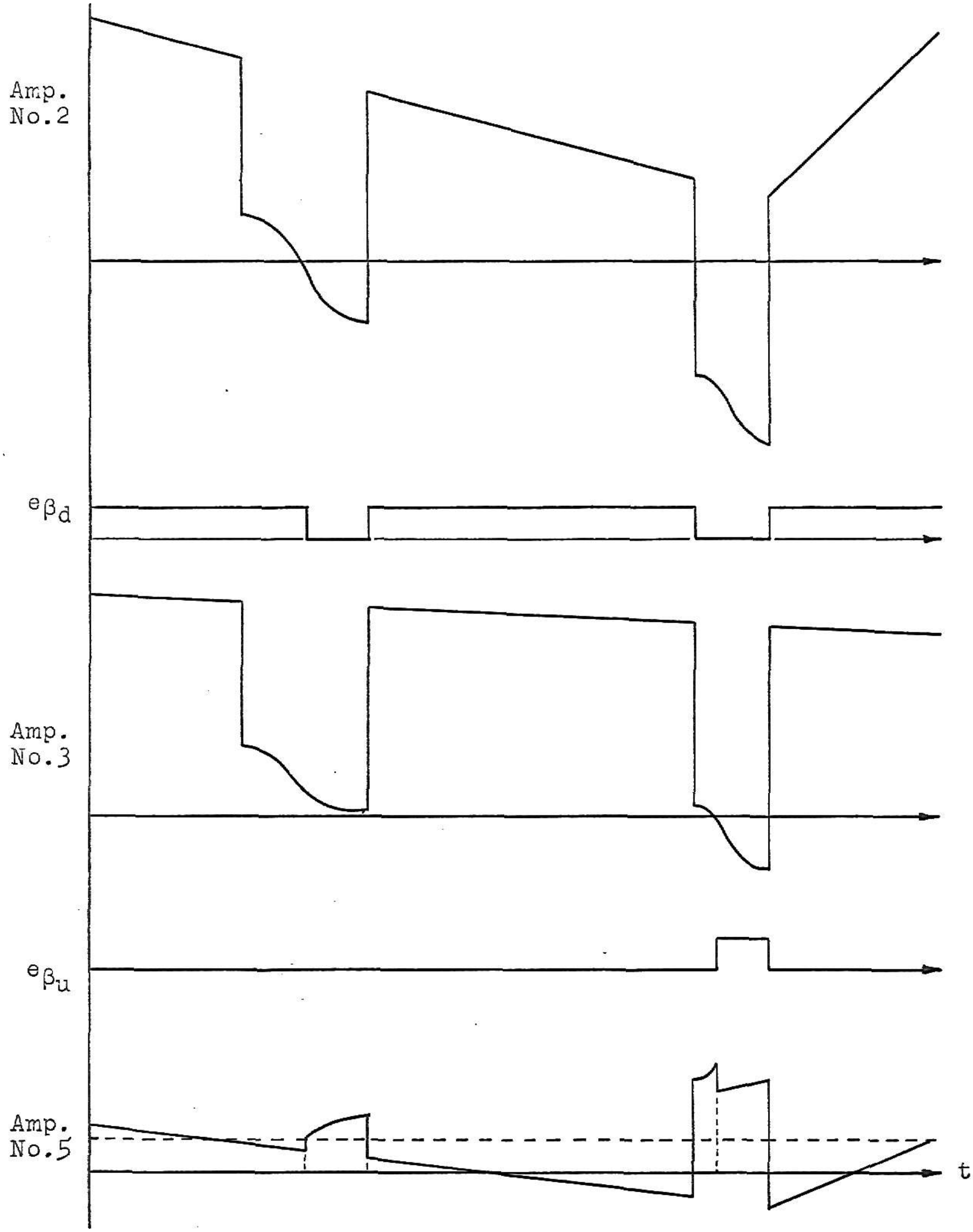

Fig. 19. The Δh_t computer wave forms (cont.).

gates that correspond to the up and down look limited conditions are derived from comparators which sense the change in aircraft instantaneous projected height minus instantaneous terrain height positions. These voltages are used in video logic to insure reliable video gating for the conditions when $\Delta h_{t_s} = h_{cp} + R \tan \beta_u$, when display video is displayed with no terrain definition; and when $\Delta h_{t_s} = h_{cp} - R \tan \beta_d$ when no video information is displayed for $R \tan \beta_d > h_{cp}$. It should be noted that the h_{cp} setting is mainly determined by aircraft type and low flying capabilities.

DISPLAYS

Nearly all aircraft large enough to have navigation and special purpose radars will have a PPI type display (1). This particular display is produced by gating the video on at selected intervals during the active trace across the terrain storage unit.

For this particular low level type of radar the only information of importance is that terrain which protrudes through the clearance plane. The conditions for the PPI display of terrain are:

1. $R_{min} = f(\beta_d) \;\; g \;(h_{cp})$. (17)
2. $R_{min} \leq R \leq R_{max}$.
3. $\Delta h_{t_s} > 0$.
4. $e_{\beta_d} = 0$.
5. $e_{\beta_u} = 0$.

6. $e_{smf} = 0$.

7. PPI Scan Mode = 1.

Therefore, if the aircraft is not up or down look limited and is not shadow masked, the video will be turned on at the display tube as long as the range gate is on and Δh_{t_s} is > 0. Grey shades of intensity are not important for this display. The only information that is important is that the terrain protrudes above the clearance plane; thus pulsed saturated video is satisfactory to produce a crisp looking display. The digital circuit that meets the following conditions is shown in Fig. 20a (2).

$$\left(\overline{e_{\beta u} + e_{\beta d} + e_{smf} + \overline{\Delta h_{t_s}} + \overline{\text{range gate}}} + \text{PPIC}\right) \text{PPI mode} = e_{video}$$

$$\left((\overline{e_{\beta u}}\ \overline{e_{\beta d}}\ \overline{e_{smf}}\ \Delta h_{t_s}\ \text{range gate}) + \text{PPIC}\right) \text{PPI mode} = e_{video} \ . \qquad (18)$$

It can be seen from Figs. 9 and 11 that the x and y displacement of terrain with respect to the aircraft (thus dead ahead) is:

$$X = R \sin \alpha \qquad (19)$$

$$Y = R \cos \alpha \ . \qquad (20)$$

These voltage displacements are used to drive the radial sweep on the display CRT, as shown in Fig. 20b. Off-center sector scan can be implemented by biasing the pivot point off center, using the desired ratios of V and V'.

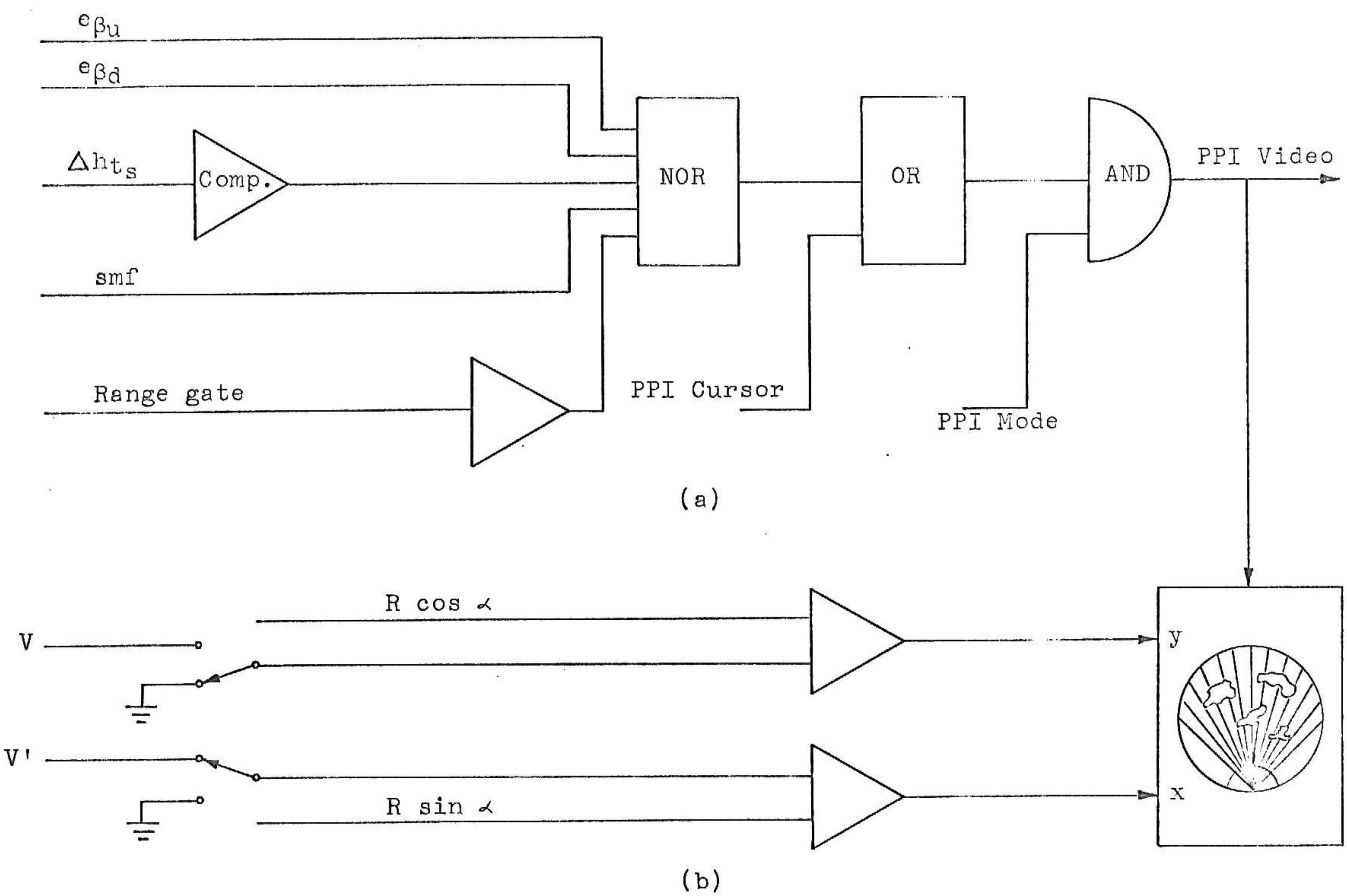

Fig. 20. Displays.

Given the simulated range R as shown in Fig. 8, a logic condition must be made which will select the positive slope for trace and the negative slope for retrace. These conditions, plus the R_{min} and the R_{max} gates must be computed to fulfill the previous requirement given for the display (12). Figures 21 and 22 show the computations and resultant wave forms satisfying the display requirements (2). The FSS should scan with light during the trace portion and be blanked during retrace; thus the display must be compatible to these conditions which insures that the PPI video gate e_v will display the information during the trace portion and allow no information during retrace. By comparing R to some preset R_{max}, an on-off condition exists as one input to the AND gate in Fig. 21. The comparison of R tan β_d and the clearance plane (Fig. 6a) is the requirement for R_{min} which says that no information can be displayed if the antenna is down look limited and no terrain protrudes above the clearance plane. (9) This simulation has the assumption that this intersection is greater than or equal to the actual R_{min} of a real aircraft which is a function of rf pulse width, h_{cp} and β_d. If this were not true, another condition would be required to limit R_{min} to the required value.

Using AND logic for the previously defined inputs, R_{min}, R_{max}, and the blanking signal, it is insured that the range gate will have the correct timing and relationship with respect to the sweep voltages from the heading resolver computer.

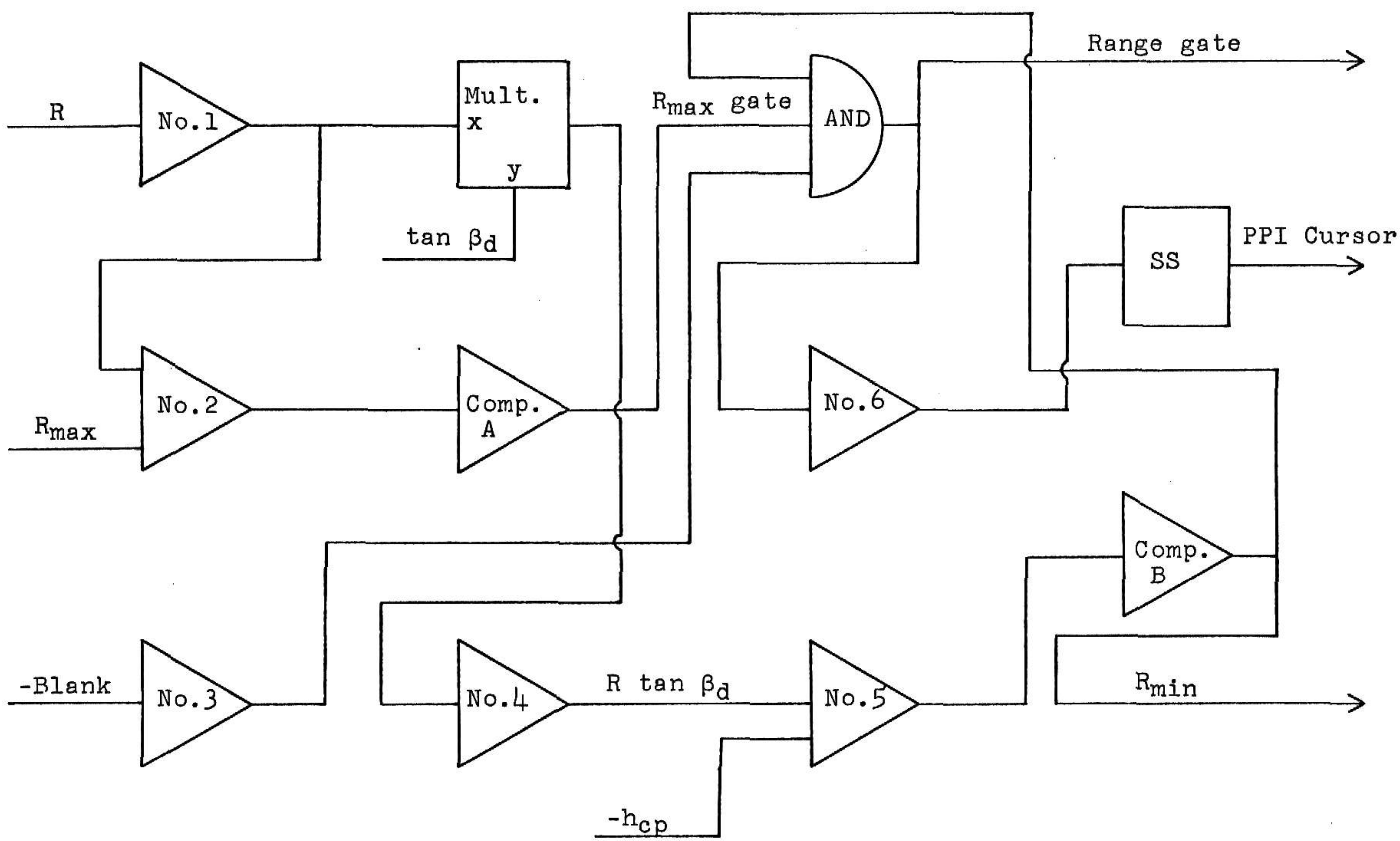

Fig. 21. Basic timing logic.

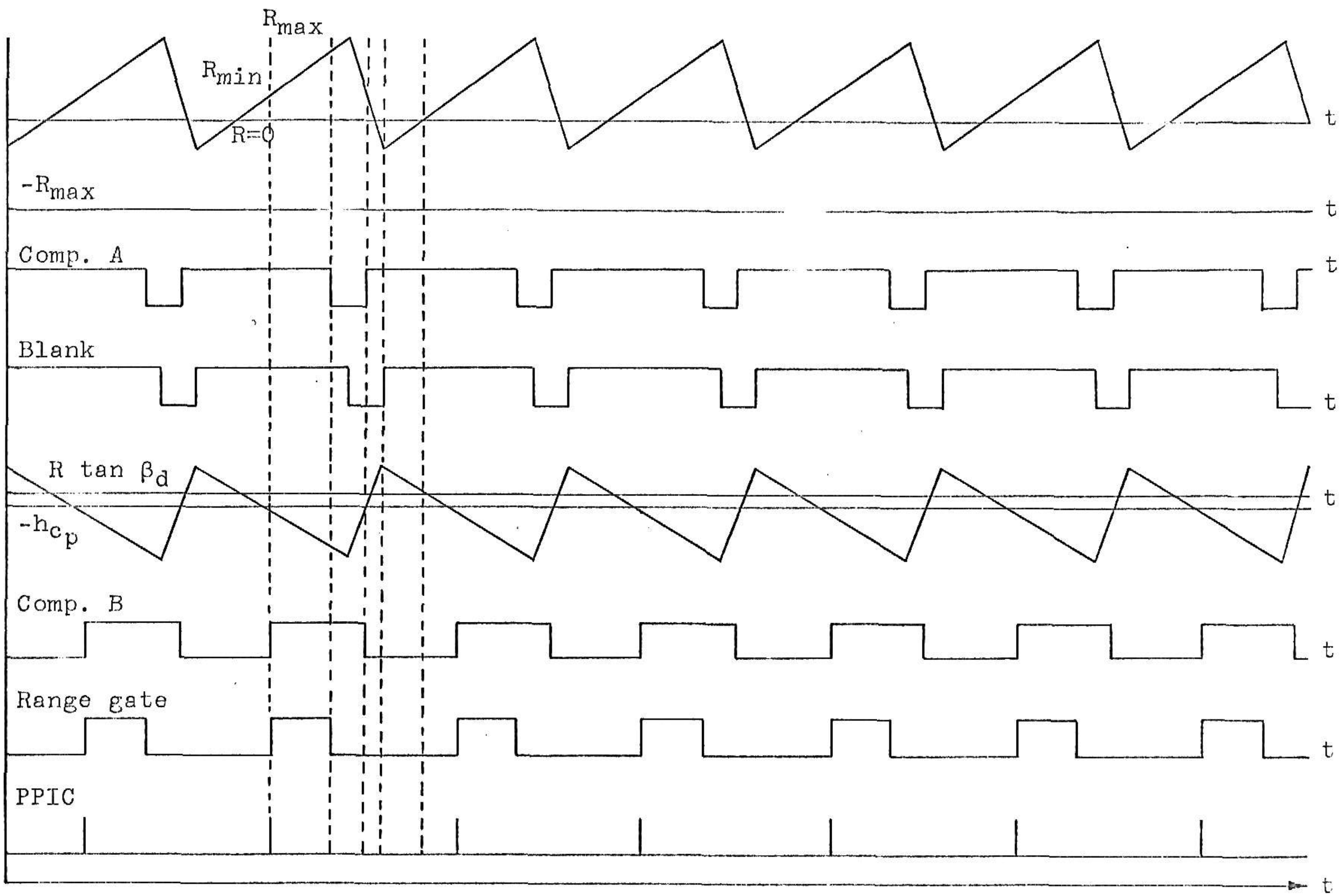

Fig. 22. Control logic wave forms.

The PPIC cursor is a video pip that occurs on the display at the intersection of h_{cp} and R_{min}; see Fig. 6b. This pip tells the display observer that any information seen prior to that gate is unreliable. Under normal conditions, no video will appear inside this cursor.

One of the primary flying instruments for any, and especially low flying aircraft, is the altimeter. In the real world, the altimeter may be either of the radar or barometric types, or both (1). The radar simulator accomplishes this by obtaining the aircraft clearance at R = 0, thus at the aircraft position. Since h_t is a function of R for any distance during the trace time and h_a is a known value, the true aircraft clearance h_c for each range sweep can be obtained by $h_a - h_t\big|_{R=0}$. The analog and digital control diagram of the radar altimeter circuit is shown in Fig. 23. The resulting wave forms, including the desired h_c, are shown in Fig. 24. The terrain height signal h_t is a typical voltage versus time of the output of the terrain storage unit with blanking. The aircraft is considered to be at time $t_n = 0$. The wave forms are shown for a terrain pattern moving toward the aircraft; thus indicating the storage unit is being driven. The repetition rate is 600 μs, which for all practical purposes would make the clearance voltage h_c appear as a continuous voltage since the terrain movement rate would normally not appear as rapid per sweep as shown here for clarity of analysis.

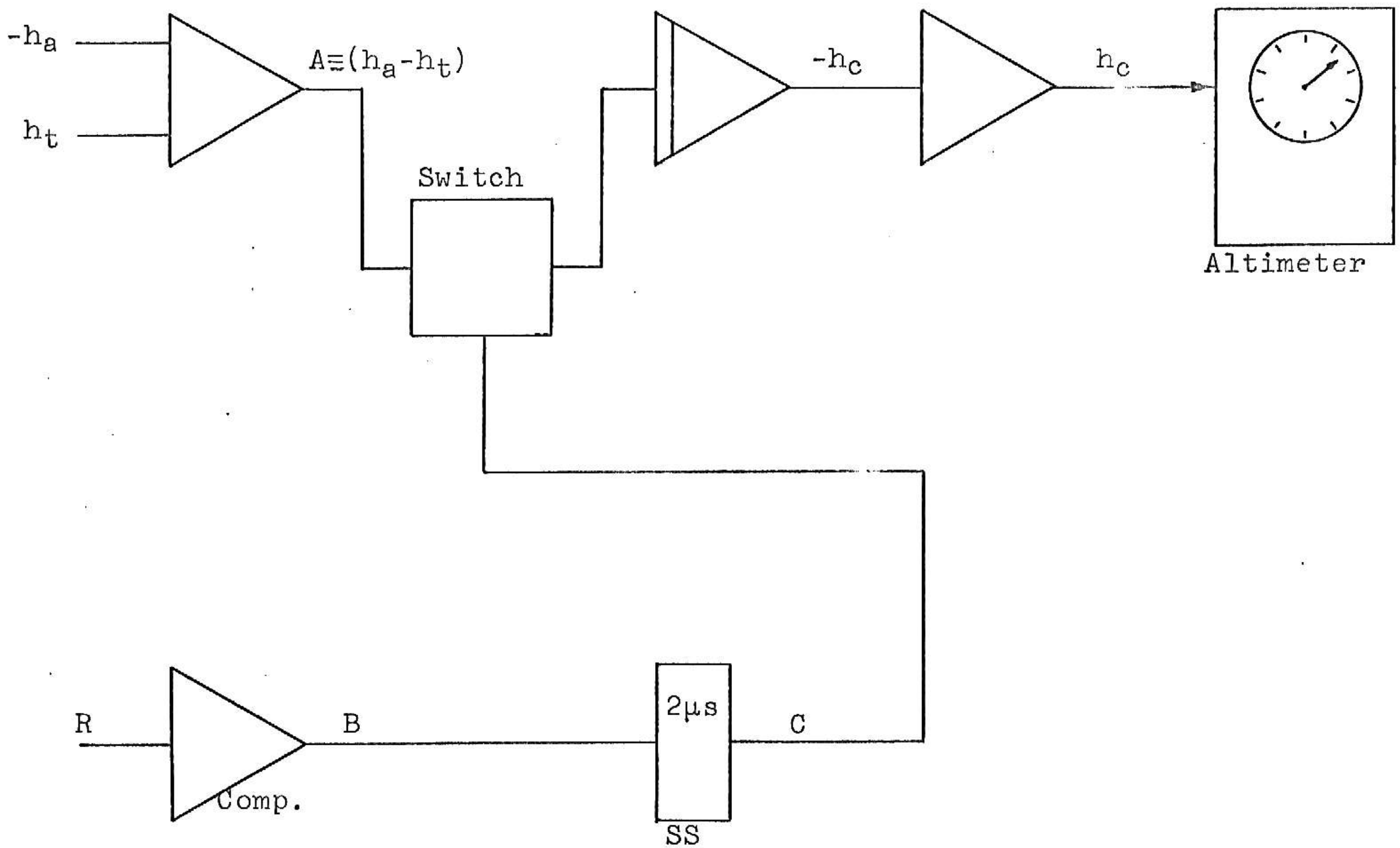

Fig. 23. The radar altimeter computer.

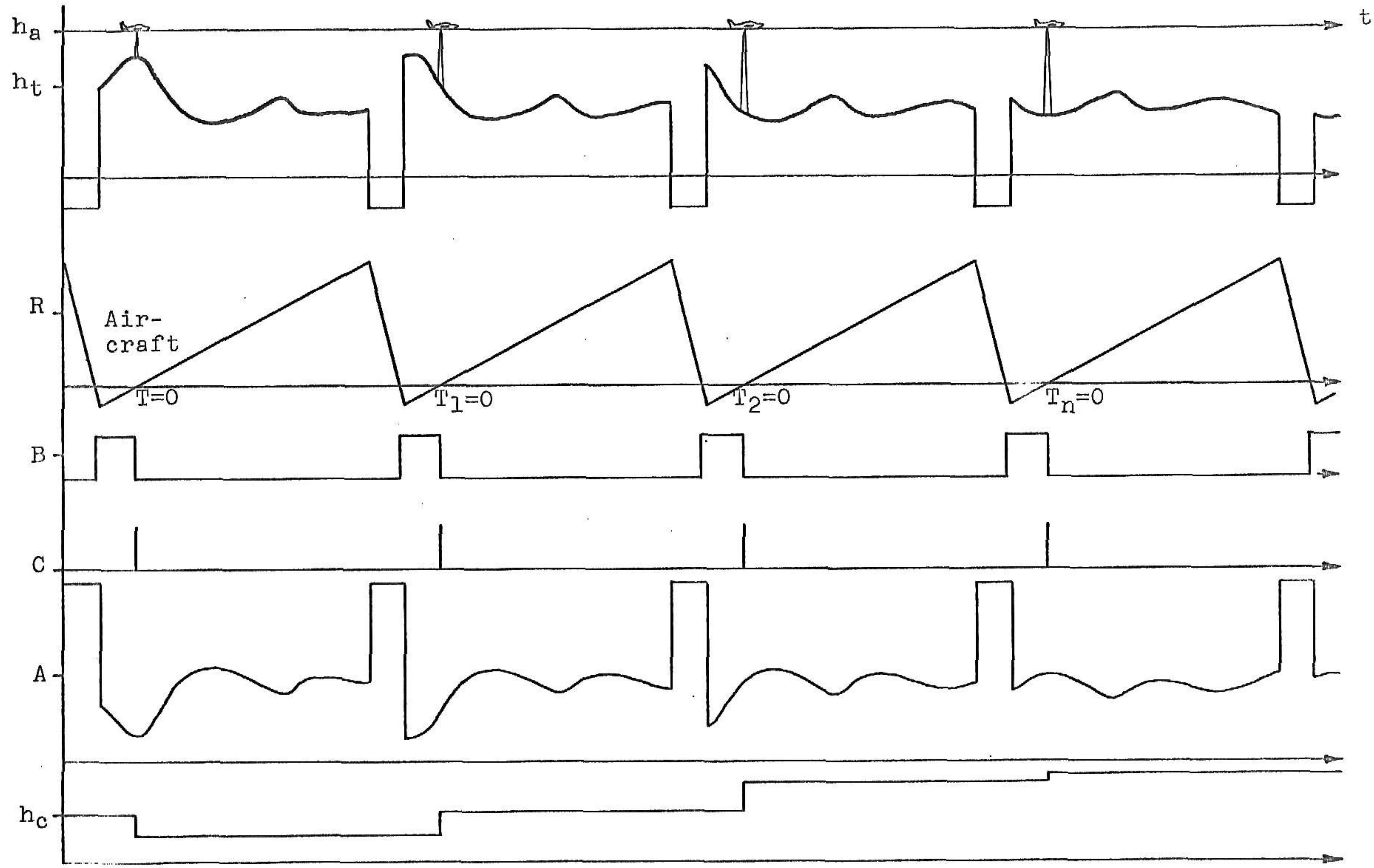

Fig. 24. Radar altimeter wave forms.

The value $h_a - h_t$ is sampled at the repetition rate of R for approximately 2 μs. This produces a terrain sample of 400 feet in width below the aircraft using equation (1) and 45 V = 10 nautical miles. The comparator and single shot multivibrator provide the 2 μs gate to the sample hold at R = 0. This sampled value is stored in a sample hold circuit until the next sweep when it is updated again. The resultant output voltage will produce a varying d-c voltage proportional to the terrain clearance. This value must always be a positive quantity or else a collision with the terrain will occur. When this signal is applied to a direct current to servo input, it can be made to drive real aircraft instruments, thus showing true clearance above the terrain for the simulated radar (9).

SUMMARY

The problems of simulating low level aircraft radar and various related displays have been investigated and a detailed analysis of the problem has been presented. Systems of this type may be used to provide design information for future products that would be very costly and sometimes virtually impossible to obtain by any other method. Simulated systems of this type have been used to obtain data in automatic terrain following and navigational investigations; they are also very valuable when used in training pilots and other aircraft crew members in methods of controlling and navigating the aircraft using visual displays.

The present system as described in the text has many possibilities for future expansion to provide a more realistic situation. The following are possibilities:

1. The reflectivity information of the green channel of the terrain read-out unit could be utilized to produce video information which would make the display vary as a function of coded objects and the terrain surface angle with respect to the aircraft.
2. An antenna beam width pattern could be inserted into the FSS sweep circuitry, thus producing a desired radiating pattern.
3. An automatic low level controller could be inserted in the pilot loop of Fig. 2, thus allowing automatic terrain following at a desired clearance.

In conclusion, it can be said that simulated systems of this type have been successfully utilized and will continue to be called upon to solve some of the complex problems of engineering.

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LOW LEVEL AIRCRAFT RADAR SIMULATION

by

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B. S., Kansas State University, 1965

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1970

The purpose of this report is to investigate the problems and requirements needed to design a simulated low level type airborne radar system that is capable of producing a Plan Position Indicator (PPI) type of display. The radar return information is displayed as a function of the six degrees of freedom of the aircraft; other displays include radar altimeter and heading information. The described system utilizes a combination of specialized analog and digital computers to achieve the desired results.

A comparison is made of the basic requirements of a real radar system and a simulated radar system, with emphasis being placed on the additional requirements of the simulated system. The generation of radar sweeps and timing logic, the generation of terrain and terrain positioning with respect to the aircraft are also discussed.

The derivation of the basic computer equations from the detailed aircraft-terrain geometry is also provided. These equations are used to generate circuits for sweep generators and basic timing logic, to compute the basic requirements of the shadow mask problem, to compute the variation of displayed terrain as a function of aircraft-terrain relationships, and to compute the aircraft's geometry with respect to the terrain. Radar altimeter clearance information is also computed as a function of aircraft-terrain geometry. This information is then used for cockpit displays. Methods of applying the simulator to various practical problems are briefly discussed and suggestions for updating the systems capability are also