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SIMULATION OF GEMINI
RE-ENTRY GUIDANCE

14 February 1964

MARTIN RUSH
WALTER VOGDES

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INTERNATIONAL BUSINESS MACHINE CORPORATION
SPACE SYSTEMS DEPARTMENT
BETHESDA, MARYLAND

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ABSTRACT

TITLE: Simulation of Gemini Re-Entry Guidance

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AUTHORS: Martin Rush, Walter Vogdes

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This report presents the results of an investigation on the feasibility of simulating Gemini computer controlled re-entries with a three degree of freedom program. The report includes a general description of the re-entry guidance system including the guidance computer math flow and the vehicle's response to guidance commands. A subroutine PHCAL, developed during the study to simulate the guidance system, is discussed in detail with a Fortran program listing and flow chart provided in an appendix. The results of a number of computer controlled re-entry simulations are also presented in detail.

Author

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1. INTRODUCTION

This report presents the results of an investigation on the feasibility of providing a three degree of freedom simulation of the Gemini vehicle's performance during computer-controlled re-entries. This investigation has led to the development of a subroutine, PHCAL, for the GEMINI Re-Entry Integration Program (GRIP). PHCAL provides a simulation of the onboard computer math flow during the maneuver phase of re-entry. It also simulates the response of the vehicle's attitude control system to commands generated by the onboard computer.

The Gemini vehicle will be the first United States manned spacecraft capable of controlled re-entries through the atmosphere. This capability is obtained by a center of gravity which is offset from the body center line of the vehicle. The unsymmetric attitude which results gives rise to an aerodynamic lift force, which can be used to alter the re-entry trajectory. By controlling the roll attitude of the capsule, the lift vector can be driven to a location anywhere in a plane normal to the wind vector. The time history of the orientation of the lift vector is then a controlling factor in descent trajectory characteristics and determines the impact point of the vehicle within its range capability profile.

or footprint. The control of the orientation of the lift vector or roll angle is obtained by the utilization of an inertial platform and a digital computer carried aboard the vehicle. The vehicle's orientation with respect to the platform provides a means of determining the attitude of the vehicle, while accelerometers mounted on the platform provide a means of sensing the aerodynamic and thrust forces on the vehicle. The computer monitors the acceleration outputs and computes the position and velocity of the vehicle in the navigation section of its mathflow. In the guidance phase of the computer math flow the computer generates attitude commands to control the roll orientation of the vehicle. These commands are transmitted to the attitude control system which controls the action of jets mounted on the vehicle. The jets torque the spacecraft to obtain the desired attitude.

Chapter 2 of this report provides an overall description of the re-entry phase of the Gemini mission. The portion of the computer math flow incorporated in PHCAL together with the model of the vehicle's response to roll commands simulated in the subroutine is discussed in Chapter 3. Chapter 4 presents typical results obtained using GRIP with subroutine PHCAL. A complete description of the subroutine PHCAL together with a detailed flow chart is given in the Appendix.

2. GEMINI COMPUTER-CONTROLLED RE-ENTRY

2.1. Introduction

This section is intended to provide an overall description of the re-entry phase of the Gemini mission. In particular, the discussion is limited to nominal re-entries in which the Gemini Computer is utilized as the source of navigation data and guidance commands. The re-entry phase itself may be broken down into 5 phases of flight: (Fig. 2.1)

- A. Pre-retrofire phase
- B. Retrofire Phase
- C. Descent Phase
- D. Maneuver Phase
- E. Parachute or Paraglider Phase

Phase A is that phase in which the vehicle and systems are prepared for retrofire. Phase B confines itself with the period during retrofire. Phase C deals with the vehicle after completion of retrofire and prior to the time the Gemini Computer initiates atmospheric maneuver of the vehicle to the target. During Phase D, the computer provides roll commands to the attitude control system (ACME) which will cause the vehicle to maneuver such as to impact at the target. It is in this phase of flight that PHCAL may be utilized for simulation of the computer's computations of bank angle commands and the vehicle's response to these commands. Phase E, the final

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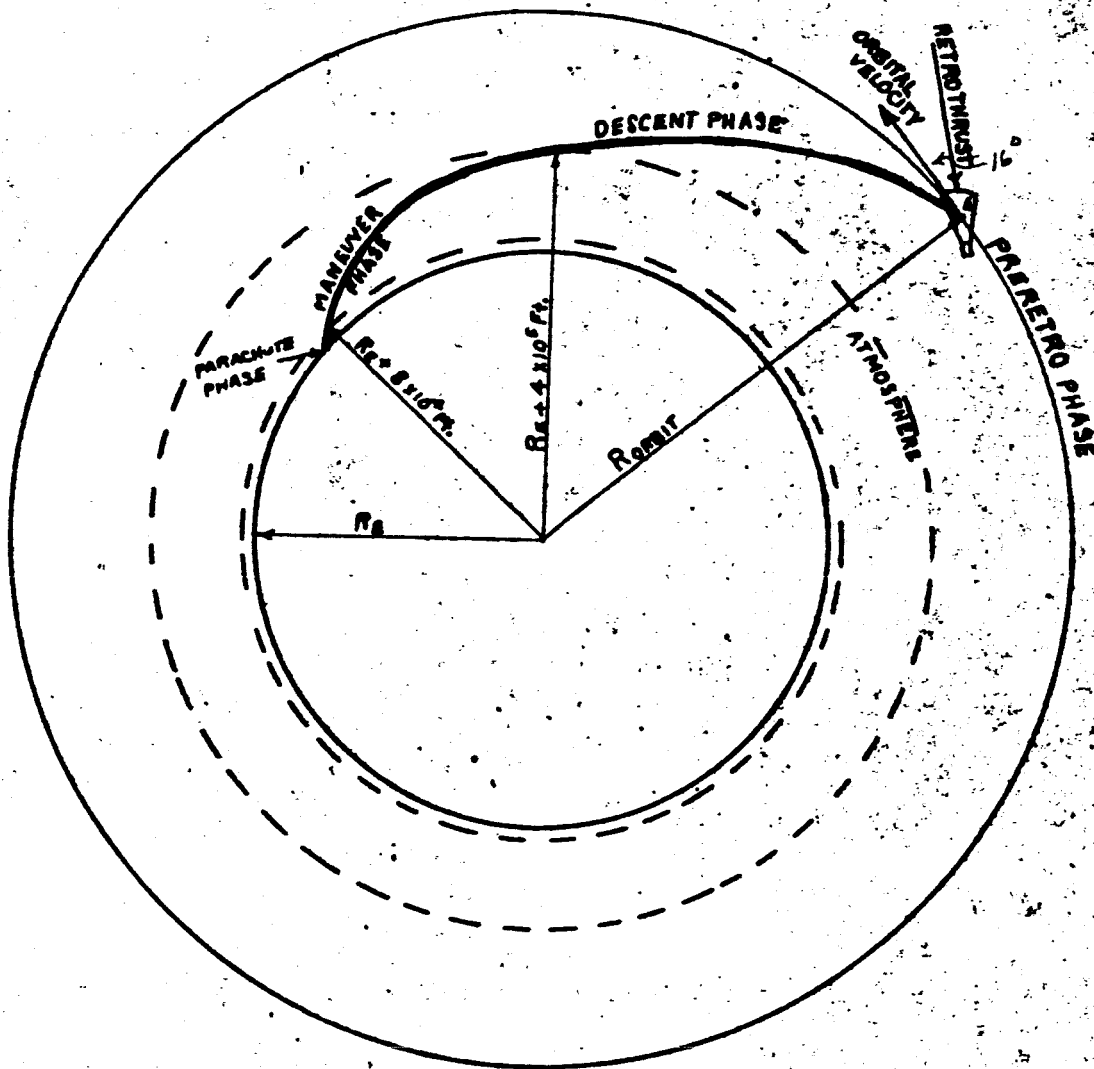


FIG. 2.1 TYPICAL GEMINI RE-ENTRY TRAJECTORY PHASES

phase is initiated with the release of the parachute or paraglider and terminates upon impact with earth's surface.

2.2. Pre-retrofire Phase

At the initiation of the pre-retrofire phase the computer accepts the following parameters transmitted to the vehicle from the ground via the DCS or manually inserted in the computer by the astronaut via the MDIU.

X_{ER}, Y_{ER}, Z_{ER} -

Predicted position of the vehicle at T_R in a geocentric inertial coordinate system.

$\dot{X}_{ER}, \dot{Y}_{ER}, \dot{Z}_{ER}$ -

Predicted inertial velocity of the vehicle at T_R in a geocentric inertial coordinate system.

$\Delta\theta_R$ -

Initial earth longitude at X_E axis at T_R .

T_R -

Time to retro fire.*

ϕ_T -

Target latitude

θ_T -

Earth referenced target longitude.

The astronaut controls the attitude of the vehicle such

* entered in the Time Reference System

that he is able to view the earth's horizon and to allow for proper retrothrust which will be initially applied 16 degrees below the horizontal and opposite to its orbital velocity. The inertial platform is torqued to provide one platform axis oriented toward the center of the earth (opposite the geocentric radius vector), one axis in the orbital plane and normal to the radius vector, and one axis normal to the orbital plane forming an orthogonal triad. The computer is in a standby mode during the pre-retrofire phase. The accelerometer outputs are not accumulated in the velocity registers and the computer running light is off. At 300 seconds to retrofire the computer deactivates its coupling with the DCS, preventing the transmission of new data from the DCS to the computer.

2.3. Retrofire Phase

The retrofire phase is initiated at T_R (time to retrofire) equal to zero. At $T_R = 0$ the computer running light goes on providing the astronaut with an indication that the computer is ready for retrofire. The computer will now begin to monitor the accelerometer outputs. The accelerometers output the specific force (non-field forces) along their input axes, which are non-rotating with respect to inertial space as the inertial platform is cut loose at $T_R = 0$. The nominal vehicle position

and velocity (X_{ER} , Y_{ER} , Z_{ER} , $\dot{X}_{ER}$, $\dot{Y}_{ER}$, $\dot{Z}_{ER}$) are used as initial conditions for the integration routine during this phase of flight. The accelerometer outputs are accumulated to provide inertial velocity changes along the three platform axes. The velocity changes are transmitted to the astronaut display for retrofire monitoring. The specific forces are transformed to geocentric inertial coordinates and combined with the gravitational force generated within the computer to provide the total force on the vehicle. The geocentric components of these forces are integrated asynchronously to provide inertial velocity and position of the vehicle during retrofire. This operation continues for 60 seconds after retrofire initiation.

2. 4. Descent Phase

This phase of the flight is initiated 60 seconds after nominal retrofire begins and terminates at an altitude of 400,000 ft. During this phase of flight the forces on the vehicle used to compute velocity and position of the vehicle are generated within the computer. The computer generates the gravitational and drag forces on the vehicle and applies them to a set of equations of motion. The equations of motion are integrated with a fixed (dt) of 16 seconds to provide the vehicles position and velocity in a geocentric inertial coordinate system. A transformation is utilized to provide computed latitude, longitude, velocity, flight

path angle, and heading angle in a rotating earth coordinate system. At altitudes above 500,000 ft, a parabolic fit to the 1959 ARDC atmospheric density model is used in the computation of drag, while between 500,000 ft, and 400,000 ft, a single scale height exponential model is used.

2.5. Maneuver Phase

Below an altitude of 400,000 ft, the vehicle enters the maneuver phase of flight. During this phase of flight the vehicle's roll attitude is controlled by commands from the computer. By means of controlling the roll angle of the vehicle the computer maneuvers the vehicle to the target. When the computed altitude reaches 400,000 ft, the computer commands an attitude of zero degrees bank angle. This angle is maintained until the sensed specific force, smoothed over four computer computation cycles, exceeds 0.4 ft/sec^2 . At this level of acceleration the re-entering capsule encounters sufficient dynamic pressure to allow for trajectory control.

The computer now generates bank angle commands to alter the trajectory such that the vehicle will impact at the target. Fig. 2.2 illustrates the information flow of the guidance system during the maneuver phase. The inertial platform provides the Gemini computer with the specific forces sensed by the accelerometers mounted on its inner gimbal; and the roll, pitch

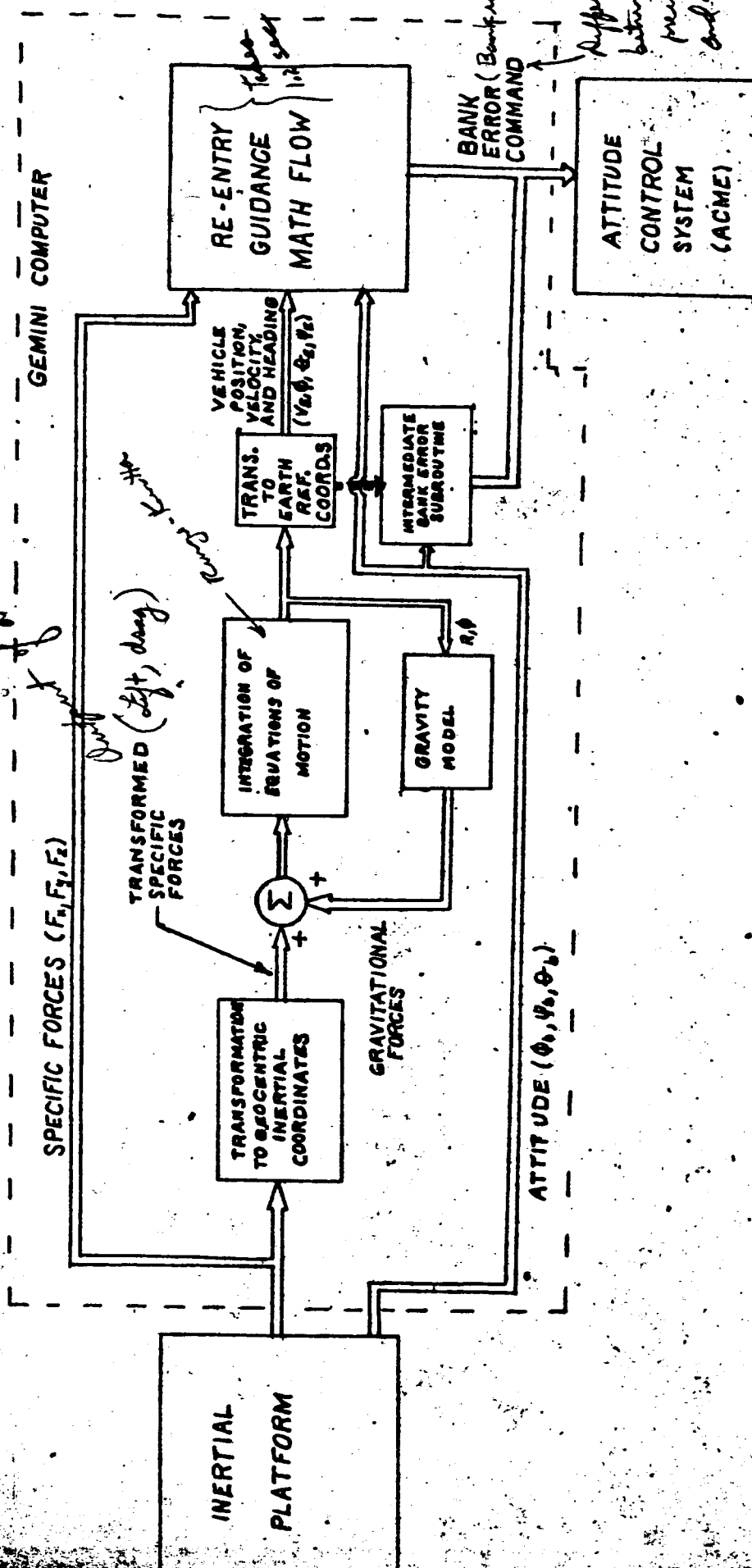


FIG. 2.2 INFORMATION FLOW OF THE ONBOARD GUIDANCE SYSTEM DURING THE MANEUVER PHASE OF RE-ENTRY

and yaw of the vehicle by means of transducers mounted on the corresponding gimbals. As shown in the figure the computer reads the specific forces which are in platform coordinates and transforms them to a geocentric inertial coordinate system. A gravity model, operating on the computed vehicle geocentric distance and geocentric latitude, computes the gravitational forces on the vehicle in geocentric inertial coordinates. The computer then sums the forces on the vehicle and applies them to a set of equations of motion. By integration, the vehicle's inertial position and velocity are then obtained. The next operation within the computer (approximately halfway through the cycle time of the math flow) is an intermediate bank error subroutine which computes a bank error command. The purpose of this command is to provide an intermediate update to the attitude control system and is discussed in more detail later in this report. The computer now transforms the vehicle's velocity and position to earth-referenced coordinates which are utilized by the re-entry guidance section of the math flow. The re-entry guidance math flow is utilized to provide bank error commands to the attitude control system (ACME). It computes these commands as a function of the vehicle's position relative to that of the target. This portion of the computer math flow is simulated in subroutine PHCAL. The output of the computer

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is then a bank error command which is converted to an analog signal and transmitted to the ACME. The operation of the computer is asynchronous with the intermediate Bank Angle Subroutine reached approximately 0.5 seconds after the start of a computation cycle. The total computation cycle time is approximately 1.2 seconds.

3. RE-ENTRY GUIDANCE IN THE MANEUVER PHASE

3.1. Introduction

This section is intended to provide a detailed description of the re-entry guidance math flow during the maneuver phase of flight. The response of the vehicle to bank error commands is outlined and a model developed which is incorporated in subroutine PHCAL.

3.2. Re-Entry Guidance System

The capability of guiding the vehicle to the target is obtained by controlling the roll angle of the vehicle. The function of the re-entry guidance math flow is to provide bank angle commands such as to assure that the vehicle will arrive at the target's location on the earth. Operating on the vehicle's position, which is continuously updated by the navigation section of the computer math flow; and the target's position, which is inserted during the pre-retrofire phase, the great circle distance to the target is computed. This is then resolved into down-range and crossrange distance to go. Referring to Fig. 3.1 the calculations are derived below:

In the upper figure the vehicle's position (V) is shown at a relative longitude and latitude of Θ_E and Φ respectively. The target's relative longitude (Θ_T) and latitude (Φ_T) are shown

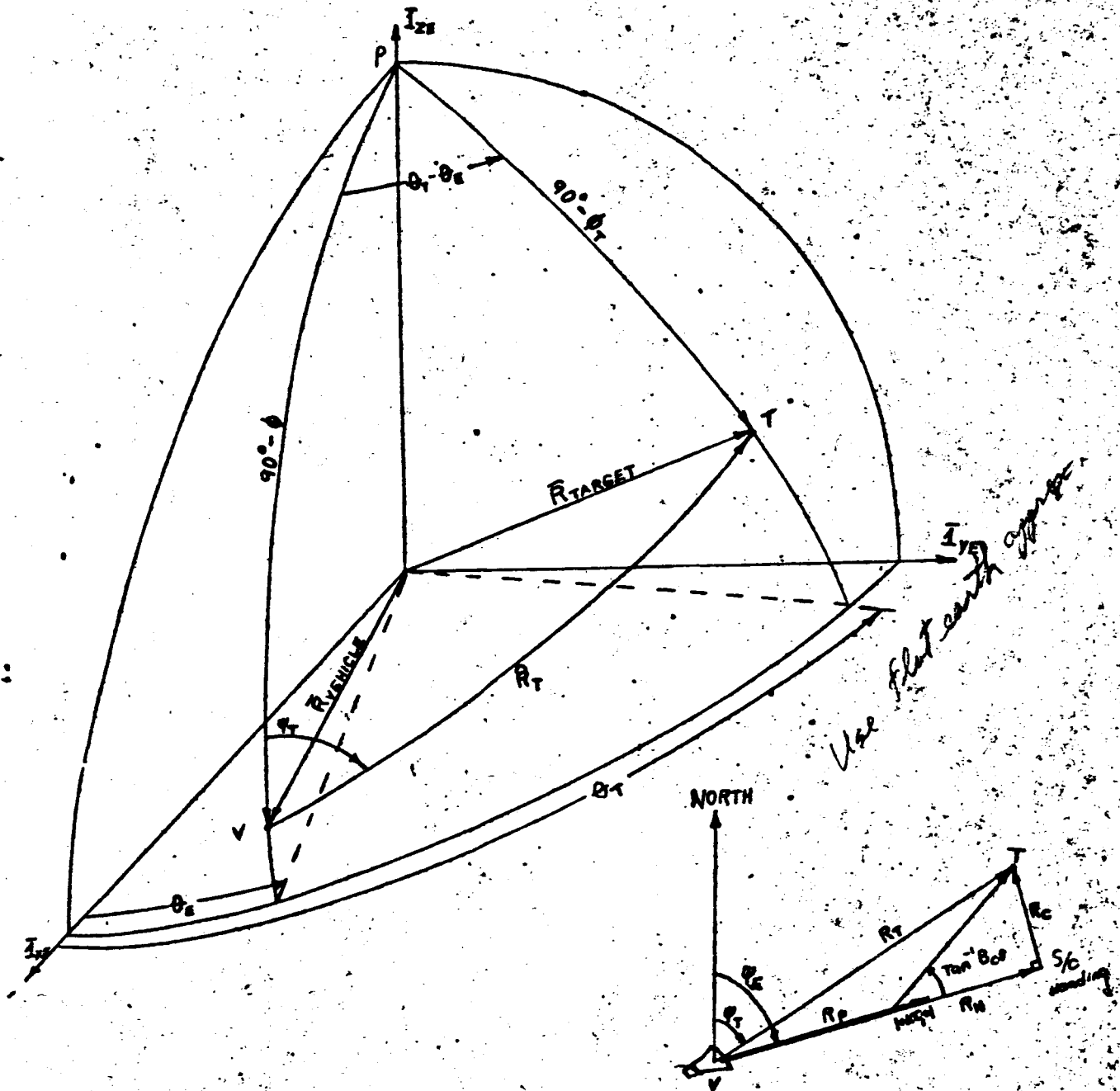


FIG. 3.1 GEOMETRY USED IN THE COMPUTATION OF DOWN RANGE AND CROSS RANGE DISTANCES TO THE TARGET

defining the target's position (T) on the earth. By means of the spherical triangle VPT we can write the Gauss group of relationships:

$$B \approx \sin \hat{R}_T \sin \psi_T = \cos \phi_T \sin (\theta_T - \theta_E) \quad (3.1)$$

$$E \approx \sin \hat{R}_T \cos \psi_T = \sin \phi_T \cos \phi - \cos \phi_T \sin \phi \cos (\theta_T - \theta_E) \quad (3.2)$$

where $\hat{R}_T$ is the great circle arc from the vehicle to the target and ψ_T the heading to the target.

Thus from the expressions above we can obtain:

$$R_T = 60 \sin^{-1} \{B^2 + E^2\}^{1/2} \quad (\text{n. m.}) \quad (3.3)$$

$$\psi_T = \tan^{-1} \left\{ \frac{B}{E} \right\} \quad (3.4)$$

where R_T is the distance on a circular earth in nautical miles corresponding to the arc $\hat{R}_T$.

Down Range (R_n) is defined by the relative heading of the vehicle and the center of the earth. Cross range (R_c) is now defined as the projection of the arc R_T onto a plane normal to the downrange plane. While these range components are, in reality, great circle arcs forming a spherical triangle, a flat earth approximation is instrumented in the guidance computer. It is to be noted that as the vehicle is guided to the target, this approximation becomes more valid. Referring to the lower figure (Fig. 3.1) we have the downrange

distance to go and the cross range distance to go as:

$$R_n = R_T \cos(\psi_E - \psi_T) \quad (\text{n.m.}) \quad (3.5)$$

$$R_c = R_T \sin(\psi_E - \psi_T) \quad (\text{n.m.}) \quad (3.6)$$

where: R_T = total range to target in n.m.

ψ_E = relative heading of the vehicle

ψ_T = heading to the target

The computer then generates a zero-lift down range vehicle capability, R_p , as a function of velocity and flight path angle, and smoothed sensed specific force. The prediction equation utilized for the determination of spinning capability is:

$$R_p = F_0(D) + F_1(D)\gamma + F_2(D) V_E \quad (\text{nm}) \quad (3.7)$$

$$D = \log_{10} \left\{ \frac{V_E^2}{a} \right\}$$

where: γ = relative flight path angle

V_E = relative velocity

a = smoothed sensed acceleration

$F_0(D)$, $F_1(D)$, $F_2(D)$ = functions of D

The guidance technique used is based upon a comparison of the downrange distance to go, (R_n), and the predicted ballistic range, (R_p). A controlled bank angle mode is used if R_p is less than R_n and a spin mode applied if R_p is equal to or greater than R_n . In the controlled mode the computer commands a bank angle

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such as to reduce the crossrange error. The calculation

of commanded bank is based upon the planer triangles on Fig. 3.1.

The angle $\tan^{-1} B_{cf}$ is computed as:

$$B_{cf} = \frac{R_c}{R_n - R_p + KC_1} \quad (3.9)$$

where KC_1 is a constant used to remove any bias placed in R_p for protection against overshooting the target.

If B_{cf} is greater than 1; that is, the angle between $R_n - R_p + KC_1$ and R_c is greater than forty-five degrees, the commanded bank angle is set equal to plus or minus ninety degrees depending on the sign of R_c . If B_{cf} is less than one, the commanded bank angle is a function of B_{cf} .

Specifically:

$$B_c = B_{cf}^3 K_{R1} + B_{cf}^2 K_{R2} + B_{cf} K_{R3} \quad (3.10)$$

where K_{R1} , K_{R2} , K_{R3} , are constants stored in the computer.

As long as the down range distance to the target exceeds the predicted zero lift (spinning) range capability the computer generates a bank angle such as to reduce crossrange error. When the vehicle's trajectory parameter's are such that the down-range distance to go is equal to or greater than the ballistic capability the computer generates a spin command which causes the vehicle to spin at a constant angular velocity about it's roll axis. During

the spin mode a continuous check is made upon crossrange.

Should the crossrange exceed 1 nm, spin will cease and the vehicle will be banked 90° in a direction such as to reduce the crossrange distance to the target. When crossrange has been reduced to a value less than a magnitude of one nautical mile the vehicle will once again be commanded to spin.

3.3 Vehicle Response to Bank Angle Commands

Fig. 3.2 represents the computer and attitude control system as it pertains to the vehicle's response to bank angle commands. The left hand portion of the figure represents a simplification of the math flow within the computer. The vehicle's actual bank angle (B_A) is read into the program at 0.5 seconds after the beginning of a computation cycle by means of the intermediate bank error subroutine. It is also sampled at 1.0 seconds after the beginning of a computation cycle by means of the gimbal angle subroutine in the re-entry guidance section of the math flow. This function is shown by the sampler. In the commanded bank angle mode a bank angle error B_E , obtained as the difference between the commanded bank angle and the actual bank angle, is computed at 0.6 and 1.2 seconds after the initiation of a computation cycle. The 0.6 second update of bank angle error is obtained in the intermediate bank error subroutine which utilizes the bank command calculated during the previous pass thru the math flow. The 1.2 second (end of computation cycle) update of bank angle error is based

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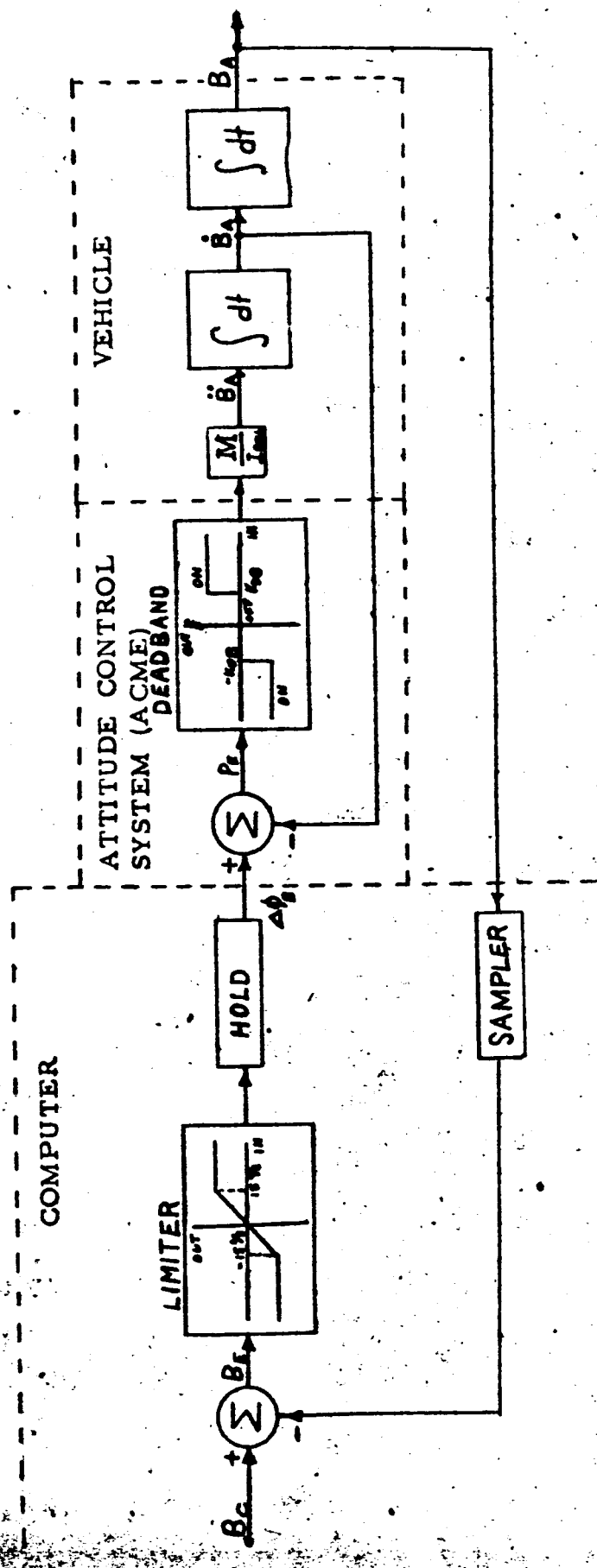


FIG. 3.2 BLOCK DIAGRAM OF INFORMATION FLOW IN CONVERSION OF COMMANDED TO ACTUAL BANK ANGLE.

upon the present computed bank angle command and found as the output of the re-entry guidance portion of the math flow. During the spin mode the bank error is set equal to the nominal spin rate of 15° /sec. The bank error is then limited to 15° /sec and outputted as a constant value. It is then converted to an analog signal and transmitted to the attitude control system (ACME). The output of the computer is $\Delta\phi_b$, the bank error command, which is treated by the ACME as a roll rate command. The ACME then compares the commanded roll rate with the actual roll rate measured by a rate gyro. A roll rate error, P_E , is then generated, and jets applied in a direction such as to reduce the roll rate error. As shown in the figure, the jet actuators have a dead band K_{DB} . The function of the dead band is to prevent limit cycles and therefore unnecessary fuel consumption in the roll jets. K_{DB} has a value of 2 degrees/second. The effect of the deadband then is to cause the roll attitude jets to remain off unless the roll rate error is greater in magnitude than K_{DB} . When the magnitude of the roll rate error is greater than K_{DB} the jets will be turned on to rotate the vehicle in a direction such as to reduce the roll rate error. The action of the jets is such as to produce, to a first order approximation, a constant roll acceleration B_A . With the above assumption, the magnitude of the roll

acceleration is the ratio of the torque generated by the jets to the roll moment of inertia of the vehicle. The astronaut has the capability of selecting the number of jets used in torquing. For the GEMINI vehicle missions of interest the resulting angular acceleration obtained with one ring of jets on is $5^{\circ}/\text{sec}^2$, and $10^{\circ}/\text{sec}^2$ with two rings of jets. The actual roll rate and bank angle is then shown as two integrations.

To understand the vehicle's response to a spin command let us assume that the previous commanded bank angle, actual bank angle and roll rate were zero. The roll rate command ($\Delta\phi_b$) will be a constant value of $15^{\circ}/\text{sec}$, as (B_E) the bank error, will be maintained at that value for as long as a spin is commanded. The roll rate error will be initially $15^{\circ}/\text{sec}$ since the initial roll rate was zero. Since this value is larger than K_{DB} the jets will go on. Assuming a single ring of jets is being used we will have a roll acceleration of $5^{\circ}/\text{sec}^2$. The vehicle will continue to accelerate about the roll axis until the vehicle has obtained a roll rate of $13^{\circ}/\text{sec}$. This will occur 2.6 seconds after the jets are turned on. At this time the roll rate error (P_E) has dropped to $2^{\circ}/\text{sec}$ and due to the jet deadband the jets will go off. Hence the steady state roll rate will be $13^{\circ}/\text{sec}$ rather than the command rate of $15^{\circ}/\text{sec}$. Any variation of the actual roll rate between $17^{\circ}/\text{sec}$ and $13^{\circ}/\text{sec}$ will not actuate the jets due to the dead

bands.

In the case of a commanded bank angle the performance is more complex. Fig. 3.3 illustrates the response of the system to a commanded bank angle of +35 degrees with the vehicle initially at zero degree bank angle and zero roll rate. The lower figure shows the commanded roll rate ($\Delta\dot{\phi}_b$) which is generated by the computer and transmitted to the ACME. As described previously this is equal to the bank angle error limited to a magnitude of $15^\circ/\text{sec}$. It is observed that a roll rate command is not generated until 1.2 seconds or a full computation cycle after the initiation of control. In this example, the intermediate bank error subroutine will output zero on the first pass as the previous bank angle command and the actual bank angle at 0.6 seconds are zero. The value at the midpoint (0.6 seconds) of the computer cycle is provided by the intermediate bank error subroutine and the value at the end of a computation cycle (1.2) seconds obtained by the guidance section of the math flow. The center figure presents the time history of the jets resulting from the comparison of commanded roll rate and actual roll rate. When the jets are " + on" a positive roll angular acceleration of $50^\circ/\text{sec}^2$ is obtained and when the jets are "-on" a negative roll angular acceleration of

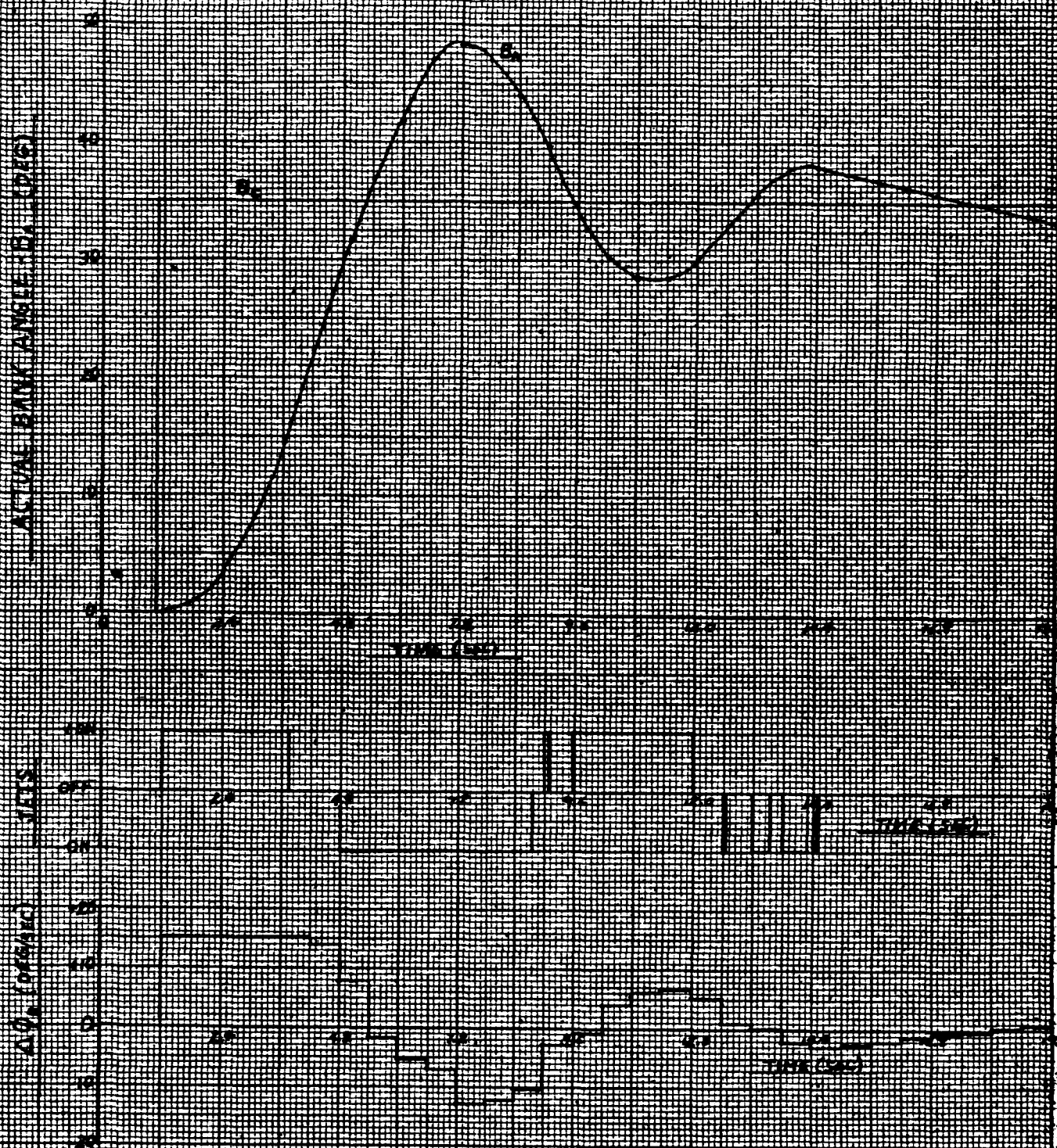


FIG. 3.3 PERFORMANCE OF THE ATTITUDE CONTROL SYSTEM (ACME) TO A COMMANDED BANK ANGLE OF 10 DEGREES.

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$5^{\circ}/\text{sec}^2$ is produced. The jets are off for those time intervals in which the commanded and actual roll rates are within the deadband, taken here as $2^{\circ}/\text{sec}$. The upper figure shows the actual bank angle as a function time. For those periods of time in which the jets are on, the bank angle time history are arcs of parabolas. When the jets are off the actual bank angle rate is a constant and thus we have straight line segments for the actual bank angle. The figure shows that for a step command of +35 degrees the actual bank angle will overshoot the desired value reaching a maximum angle of approximately 48 degrees and take over 20 seconds to damp to the commanded value. This characteristic loose damping is further illustrated in the typical closed loop results discussed later in this report.

3.4. Re-Entry Guidance Math Flow.

Fig. 3.4 illustrates the math flow instrumented in subroutine PHCAL. The figure is taken from reference 1 which contains a complete description of both the navigation and guidance math flow during all the re-entry phases. The small insert on the figure shows the intermediate bank error subroutine. As described previously this subroutine has been placed in the navigation portion of the math flow such that it reads the actual roll angle (ϕ) 0.5 seconds after the start of a pass thru the computer logic and outputs an intermediate

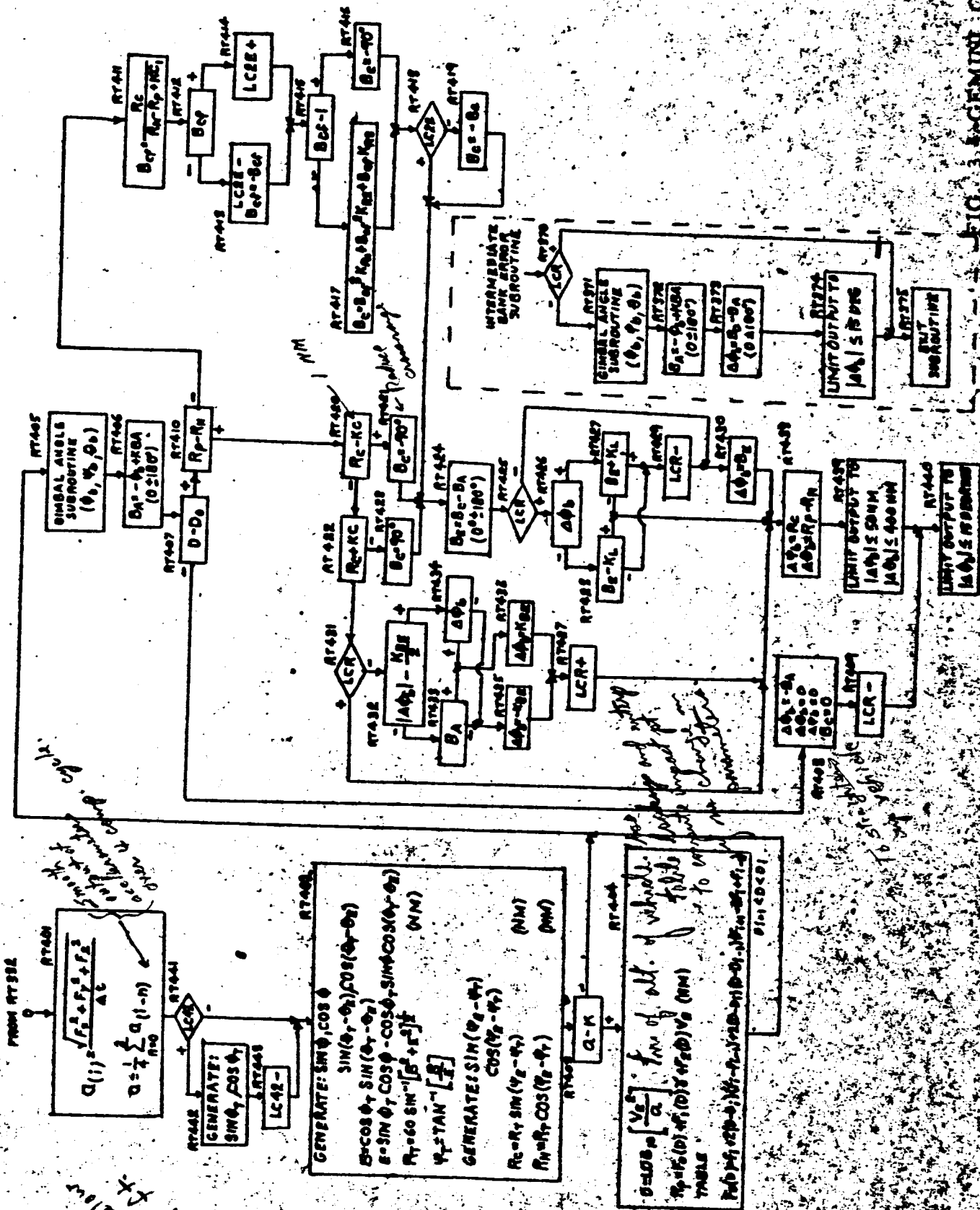


FIG. 3. GEMINI COMPUTER MATH FLOW SUBROUTINE IN SUBROUTINE PHGAL

roll rate command 0.1 seconds later. The main flow diagram, will now be discussed in detail. Logic block RT 401 will be activated on reaching an altitude of 400,000 ft. The logic flow on the first pass thru the guidance section will be:

- RT 401 - Calculate smoothed sensed acceleration from the output of accelerometers at start of this sequence. The value of acceleration used is the average of the latest four values of sensed acceleration.
- RT 441,
RT 442, - Generates the sine and cosine of the target latitude ϕ_T once to save computation time. The logical choice 42 is initially set to + in the navigation math flow. Since RT 443 sets LC - this computation will be bypassed in succeeding passes thru RT 441.
- RT 443
- RT 402 - Calculate great circle distance to target, heading to target, downrange and cross-range distances to target using equations described previously in this report.
- RT 403 - Compare value of averaged sensed acceleration, a , and K . ($K = .4$). This test is used to determine when dynamic pressure on the vehicle is such that impact can be controlled by controlling bank angle (" a " will be greater than K starting at some point below 350,000 feet) Take - exit.
- RT 405 - Read gimbal angle
- RT 406 - Calculate the bank angle (KBA is the gimbal angle bias and set equal to 0)
- RT 407 - Take - exit (D set equal to zero in the navigation section and not updated since RT 404 was bypassed, $D_0 = 4.675$)

- RT 408 - Set $\Delta\phi = -B_A$ (this causes the ACME to bring bank angle to 0). Setting $\Delta\theta$, $\Delta\psi$ to 0, sets the capsule attitude display needles to 0. Set $B_C = 0$ for intermediate bank error subroutine.
- RT 409 - Set LCR -
- RT 440 - Limit magnitude of $\Delta\phi$ to 15 degrees.
- EXEC - Returns flow to computer to excuter to repeat.

The sequence for the succeeding passes below 400,000 ft until "a" is greater than K are:

RT 401, RT 441, RT 402, RT 403, RT 405, RT 406, RT 407, RT 408, RT 409, RT 440, EXEC.

Now assume "a" has finally increased to K. Then as above:

RT 401 → RT 402

RT 403 - Take + exit. (a stays greater than K until touchdown).

RT 404 - Calculate D (discussed previously - D starts at approximately 9.5 and ends at approximately 4.5) Calculate R_p , a quantity related to the zero-lift downrange distance left based on present value of acceleration, velocity and flight path angle. Using a linear interpolation for F_1 and F_2 and the indicated expression for F_0 .

RT 405, RT 406 Read gimbal angles and calculate present bank angle.

RT 407 - Take + exit. Continue taking +, exit until about 80,000 ft when $D = D_0 = 4.675$

RT 410 - $R_n - R_p$ is the down range distance to go to the target beyond the capsule's zero lift range. This will normally be + during these early passes. Take $(R_p - R_n)$.

RT 411 - B_{cf} is used to calculate bank command need to hit the target.

RT 412 - If $R_c > 0$ then $B_{cf} > 0$ and B_c should be -. If $R_c < 0$ then $B_{cf} < 0$ and B_c should be +. B_c is calculated assuming B_{cf} is +. If B_{cf} is - the sign of B_c will be changed after it is calculated. Take B_{cf} .

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- RT 413 - Set LC2E -. Set $B_{cf} = -B_{cf}$
- RT 415 - If $|B_{cf}| \geq 1$ make $|B_c| = 90^\circ$. Take $|B_{cf}| < 1$ branch.
- RT 417 - B_c is computed as described previously. B_c will lie between 0 and -90° . The constants are $K_{R1} = -184.9553 \text{ DEG}$, $K_{RL} = 393.9718 \text{ DEG}$, $K_{R3} = -299.0165 \text{ DEG}$.
- RT 418 - Sample LC2E (set - in RT 413)
- RT 419 - Change sign of B_c
- RT 424 - Calculate bank error. (Add or subtract 360° if necessary, to place B_E between -180° and $+180^\circ$)
- RT 425 - Sample LCR (set - in RT 409)
- RT 430 - Set $\Delta\phi_b = B_E$. This allows present value of $\Delta\phi_b$ to be tested in next pass, after a new B_E is calculated. $\Delta\phi_b$ is sent to the ACME and attitude display.
- RT 438 - $\Delta\psi_b, \Delta\theta_b$ are sent to the attitude display (in EXEC)
- RT 439 - Limit $\Delta\psi_b, \Delta\theta_b$
- RT 440 - Limit $\Delta\phi_b$

EXEC

The above sequence is repeated until $R_N \leq R_p$:

RT 401 $\rightarrow$ RT 407

- RT 410 - Take $R_N \leq R_p$ (No longer need any downrange component of lift, but still must reduce any cross-range error)
- RT 420 - Assume $R_c = -2nm$ ($KC=1$) take - exit
- RT 422 - Take - exit
- RT 423 - Set $B_c = 90^\circ$

RT 424 - Calculate bank error

RT 425 - Sample LCR (set - in RT 409)

RT 430, RT 438, RT 439, RT 440

EXEC

Assume now that R_n is still less than R_p and that the previous crossrange error has been reduced to less than 1 n.m.

RT 401 → RT 410

RT 420 - Assume $R_c = .5$ Take - exit

RT 422 - Take + exit

RT 431 - The first pass thru RT 431, LCR will be - (set - in RT 409).

RT 432 - Take $\Delta\phi$ equal to the vehicle's present roll rate. Assume this is less than 7.5 deg/sec, ($K_{BE} = 15$). If capsule is rolling at greater than 7.5 deg/sec check direction in RT 434 and step up the rate to 15 deg/sec in the same direction.

RT 433 - Check on which side of maximum lift ($B_A = 0^\circ$) the lift vector is now oriented. Assume $B_A = 90^\circ$. Start constant roll in direction away from maximum lift. Take + exit.

RT 436 - Set $\Delta\phi_b = K_{BE} = 15$ (capsule will now roll clockwise at 15 deg/sec)

RT 437 - Set LCR -

RT 438 → RT 440

EXEC

RT 401 → RT 422 (Assuming $R_n < R_p$ and $|R_c| < KC$).

RT 431 - Sample LCR (set + in RT 437). Value of $\Delta\phi_b$ will not be changed, therefore capsule will keep rolling at $\Delta\phi_b = K_{BE}$.

RT 438 → RT 440

EXEC

Now assume that $|R_c|$ grows greater than K_C or the R_n becomes greater than R_p , (LCR is +, $\Delta\phi_b = K_{BE}$).

RT 401 → RT 410

Bc will now be calculated by RT 411 → RT 418 (419) or

RT 420 → RT 421 (423)

RT 424 - Calculate present bank error

RT 425 - Sample LCR (set + in RT 437).

RT 426 - Take + exit

RT 427 - ($K_L = 130^\circ$) If lift vector is within 130° of where it should go and if capsule is rolling away from the desired bank angle, (Bc), command roll in opposite direction; in all other cases continue rolling in original direction. Assume $B_E = -100^\circ$. Take + exit.

RT 429 - Set LCR -.

RT 430 - $\Delta\phi_b = B_E$, therefore capsule will roll counter clockwise. (Capsule was rolling clockwise but B_A was within 130° of B in counter clockwise direction)

RT 438 → RT 440

Note that if B_E was -140° , then take - exit of RT 427, and a new value of $\Delta\phi_b$ would not be calculated so that the vehicle would continue rolling in same direction.

EXEC

When D finally decreases to D_0 (at about 80,000ft) maximum lift is commanded in order to properly orient the capsule for chute/gliders deployment.

RT 401 → RT 406

RT 407 - Take - exit

RT 408 - $\Delta\phi_b = -B_A$ This is equivalent to setting $B_c = 0$,
and results in maximum lift attitude.

RT 409 - Set LCR -

EXEC

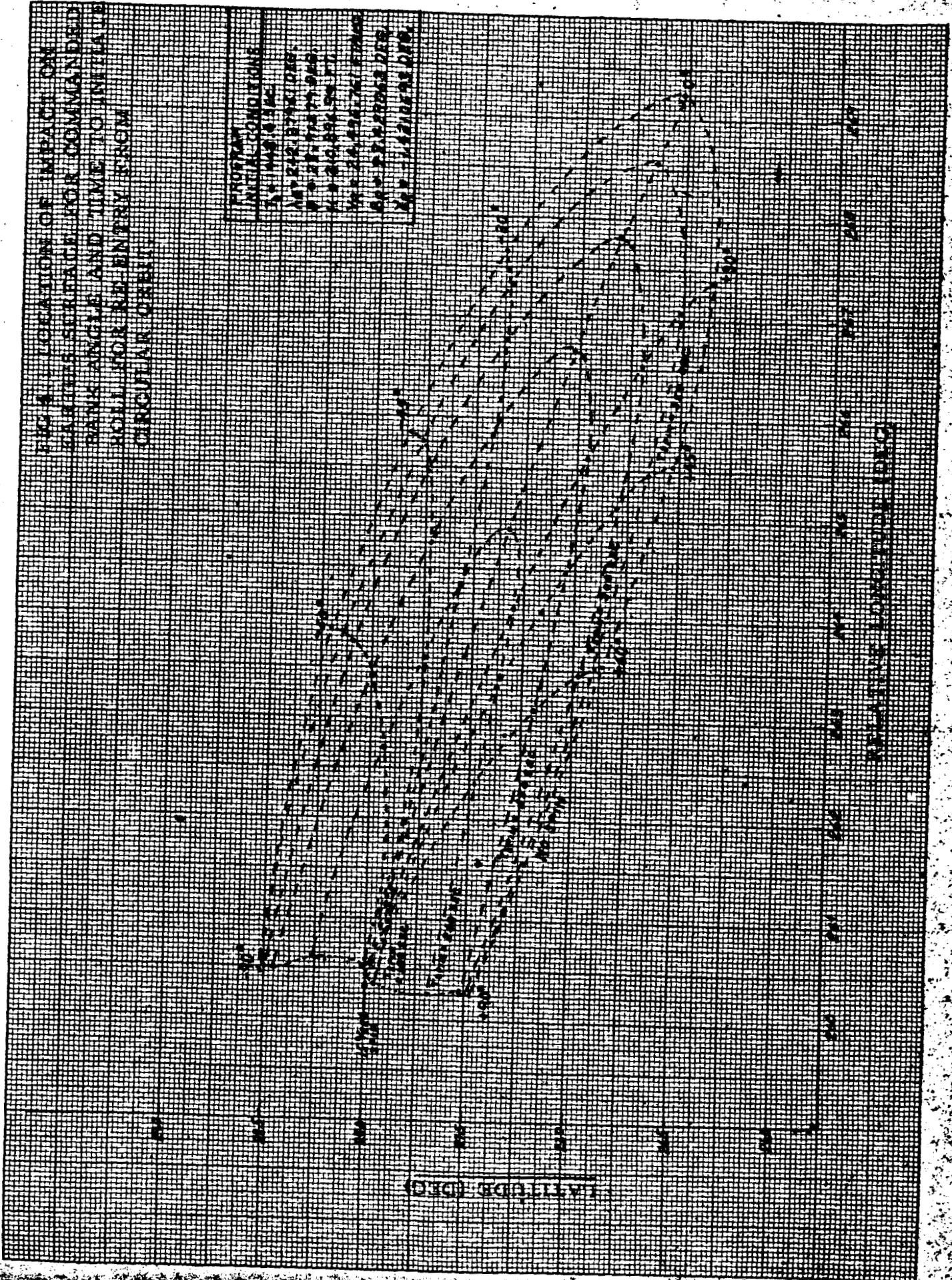
4. TYPICAL RESULTS

4.1 INTRODUCTION

This section presents the results of a simulation study of the characteristics of computer controlled re-entry. The Guided Re-Entry Integration Program (GRIP) was used with Subroutine PHCAL providing the source of the vehicle's bank angle. Retrofire from a constant altitude orbit of 161 n.m. was used to obtain the trajectory parameters during the descent phase. Targets were obtained from Figure 4.1 which show the location of impact points obtained by maintaining a constant bank angle for a specified time and then spinning until impact. The figure provides the maneuver capability of the vehicle as the locus of "no spin" impact points. This is the locus of impact points obtained by holding the indicated bank angle until impact. For the simulation study of PHCAL three targets were selected from the figure. The first target selected was the minimum lift point; which is the location of the impact point if the vehicle maintains a constant roll rate of 15 deg/sec. The second target was the maximum lift impact point. This is the "zero degree, no spin" point on the figure; obtained by holding zero degrees bank angle until impact on the earth's surface. The

FIG. 4. LOCATION OF IMPACT ON
EARTH'S SURFACE FOR COMMANDED
BANK ANGLE AND TIME TO INITIATE
ROLL FOR RE-ENTRY FROM
CIRCULAR ORBIT

PROGRAM	INITIAL CONDITIONS
1	1000000000
2	1000000000
3	1000000000
4	1000000000
5	1000000000
6	1000000000
7	1000000000
8	1000000000
9	1000000000
10	1000000000
11	1000000000
12	1000000000
13	1000000000
14	1000000000
15	1000000000
16	1000000000
17	1000000000
18	1000000000
19	1000000000
20	1000000000
21	1000000000
22	1000000000
23	1000000000
24	1000000000
25	1000000000
26	1000000000
27	1000000000
28	1000000000
29	1000000000
30	1000000000
31	1000000000
32	1000000000
33	1000000000
34	1000000000
35	1000000000
36	1000000000
37	1000000000
38	1000000000
39	1000000000
40	1000000000
41	1000000000
42	1000000000
43	1000000000
44	1000000000
45	1000000000
46	1000000000
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62	1000000000
63	1000000000
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65	1000000000
66	1000000000
67	1000000000
68	1000000000
69	1000000000
70	1000000000
71	1000000000
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73	1000000000
74	1000000000
75	1000000000
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82	1000000000
83	1000000000
84	1000000000
85	1000000000
86	1000000000
87	1000000000
88	1000000000
89	1000000000
90	1000000000
91	1000000000
92	1000000000
93	1000000000
94	1000000000
95	1000000000
96	1000000000
97	1000000000
98	1000000000
99	1000000000
100	1000000000



third target used was the 250 second/-45 degree impact point.

This point is obtained by holding a bank angle of -45 degrees for 250 seconds and then spinning to the ground. The time to spin is referenced to the initial conditions shown on Figure 4.1.

These are the trajectory parameters 1448.4 seconds after retro burnout and represent a point on the descent trajectory before a value of smoothed sensed acceleration "a" equal to 0.4 ft/sec^2 is reached.

Utilizing subroutine PHCAL computer-controlled trajectories were generated for the above targets. The resultant impact points are shown in the table below.

	TARGET		ACTUAL IMPACT		MISS DISTANCE
	RELATIVE LONGITUDE	LATITUDE	RELATIVE LONGITUDE	LATITUDE	
	(Degrees)	(Degrees)	(Degrees)	(Degrees)	(naut. miles)
MINIMUM LIFT	260.43499	27.992944	260.53958	27.974550	5.6
MAXIMUM LIFT	269.26439	26.526207	269.19660	26.534415	3.9
250 Sec / -45 Deg	264.77326	27.712554	264.84989	27.696255	4.2

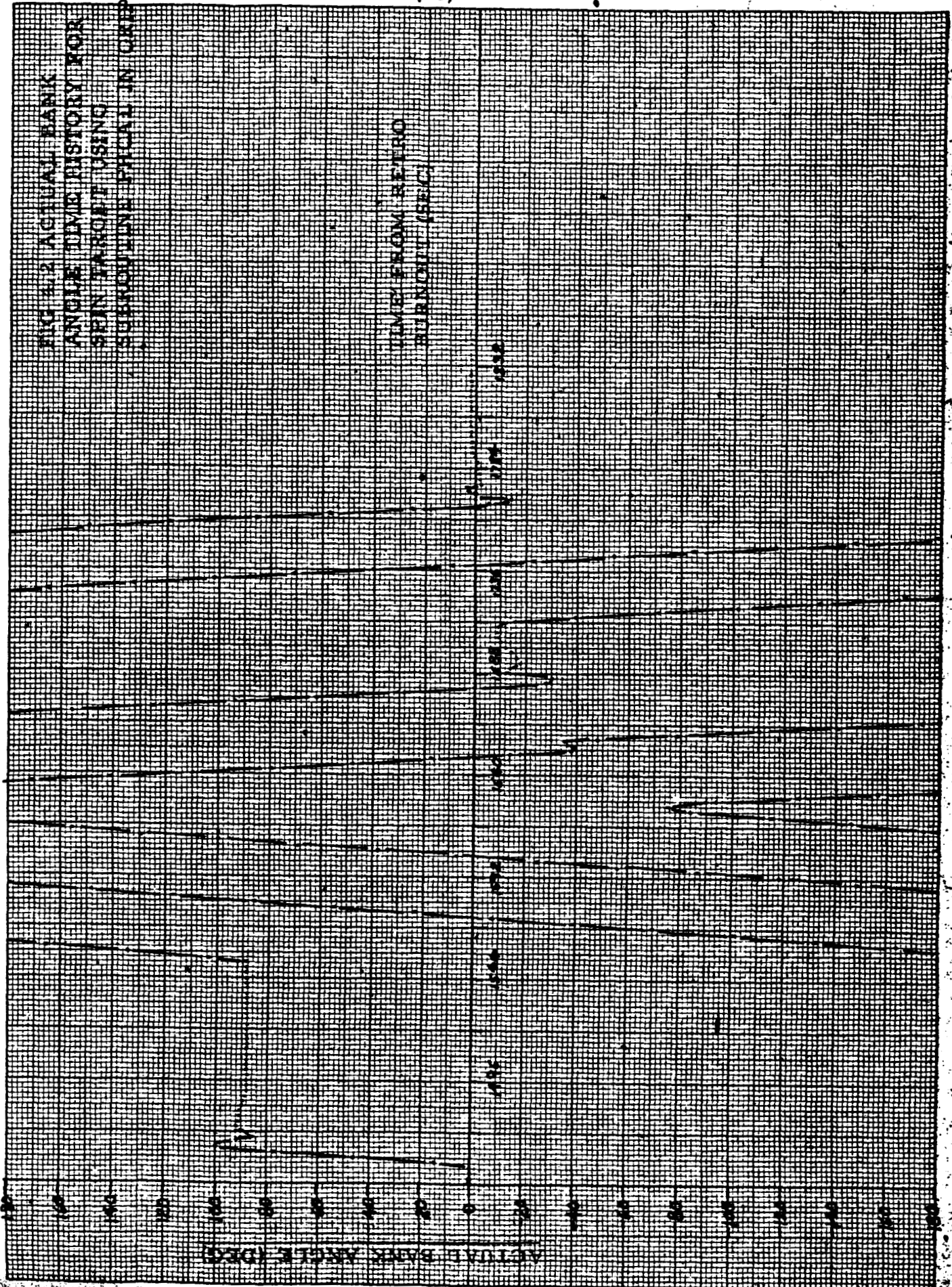
Detailed results of the simulation runs are discussed below.

4.2 SPIN TARGET

Figures 4.2 thru 4.5 show the bank angle and resulting

trajectory time histories of the vehicle during the maneuver phase of flight. Since the target selected is the minimum lift point a "perfect" guidance system would be expected to cause the vehicle to spin all the way to the ground. Due to inaccuracies in the ballistic range predictor and the flat earth approximations instrumented in the computer, the bank angle time history obtained has a somewhat different response. Referring to Figure 4.2 we observe that the computer initially commands a bank angle of +90 degrees. Here the computer is in the spin mode and has generated a crossrange greater than 1 n.m. The response of the vehicle to this command has the typical overshoot discussed in chapter 3.1. It is observed that the computer continues in the spin mode until approximately 1688 seconds after retro burnout. The reversal of spin prior to this time is due to intermittent commanded bank angles of 90 degrees to which the vehicle attempts to roll. For a short period between 1688 and 1712 seconds after retro burnout the predicted ballistic range becomes less than the down range distance to go and the vehicle stops its spin. For the remainder of the maneuver phase the computer is in the spin mode. At 1766 seconds the vehicle has reached an altitude of

FIG 3.2 ACTUAL BANK
ANGLE DIVE HISTORY FOR
SPIN TARGET USING
SUBROUTINE FACAL IN ORP



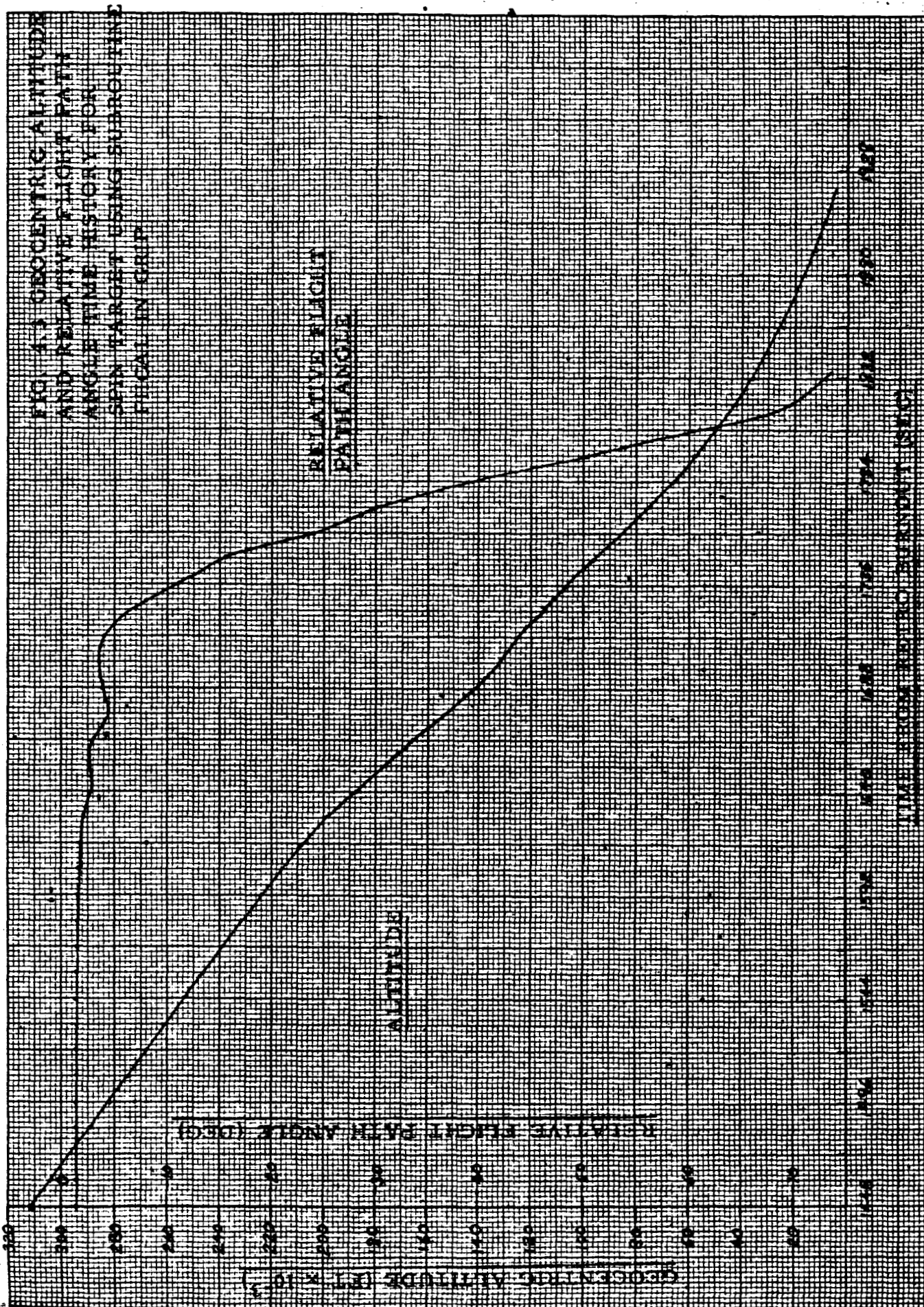
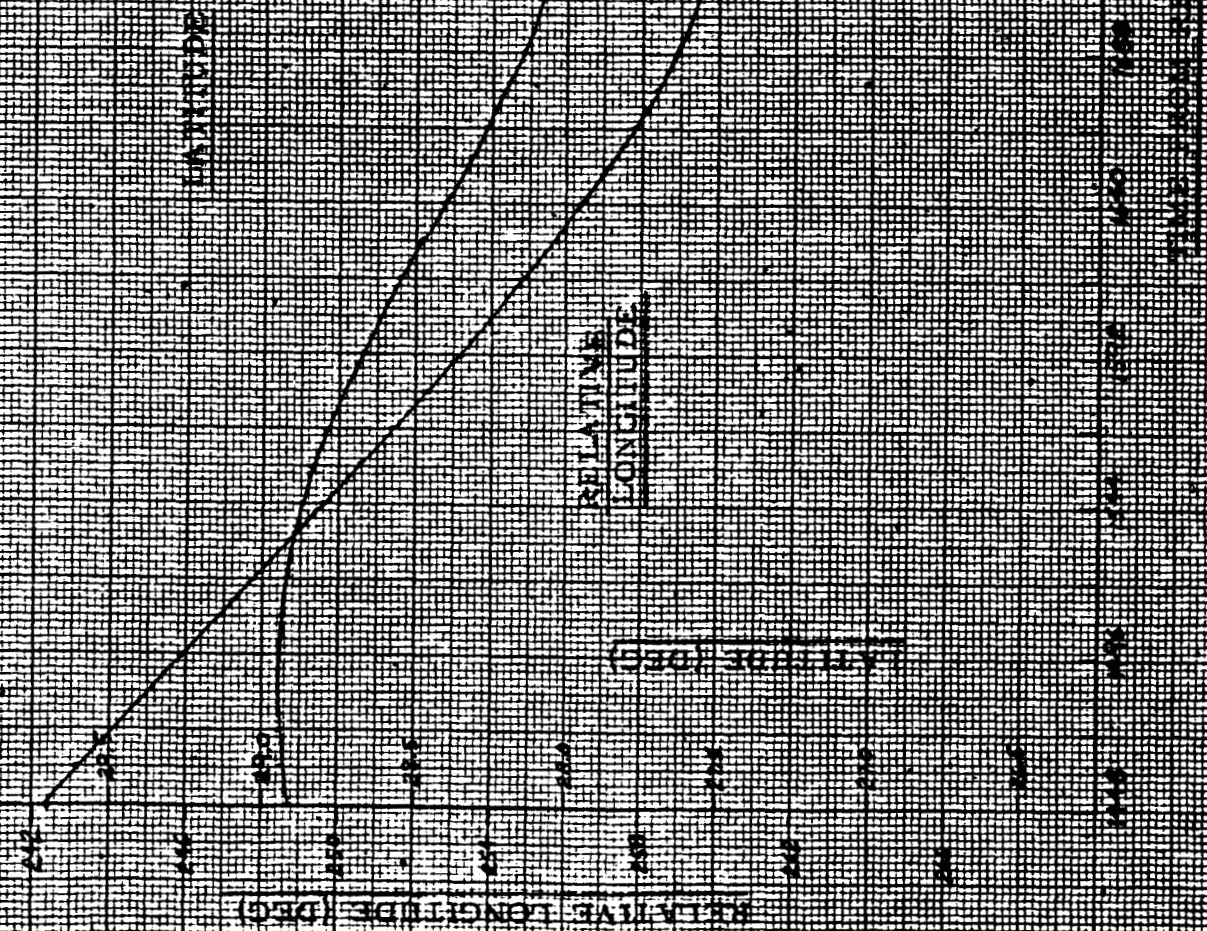


FIG. 5. RELATIVE LONGITUDE
AND LATITUDE TIME HISTORY
FOR SPIN TARGET USING
SUBROUTINE PHCAL IN CRIP



Of 80,000 ft and the computer commands the vehicle to zero degrees bank angle in anticipation of parachute deployment. Figures 4.3 through 4.5 provide the geocentric altitude, relative flight path angle, relative heading angle, relative longitude, and latitude of the vehicle during the maneuver phase of re-entry flight.

4.3 MAXIMUM LIFT TARGET.

The bank angle time history for the maximum lift target is shown on Figure 4.6. It is observed that the vehicle does develop bank angles other than zero which may be explained as being due to computed crossranges which are not zero. A maximum positive bank angle of 19 degrees is obtained immediately after entering the maneuver phase. The actual bank angle slowly decreases, crossing zero at approximately 1712 seconds, and reaches a maximum negative angle of -14 degrees at 1834.8 seconds. At approximately 1935.6 seconds after retro burnout the vehicle reaches an altitude of 80,000 ft and rolls to zero degrees commanded bank angle. Figures 4.7 thru 4.9 provide the trajectory parameters during the maneuver phase.

4.4 250 SEC. / -45 DEG. TARGET

This simulation run provides a typical controlled re-entry for a target within the footprint. Figure 4.10 presents the

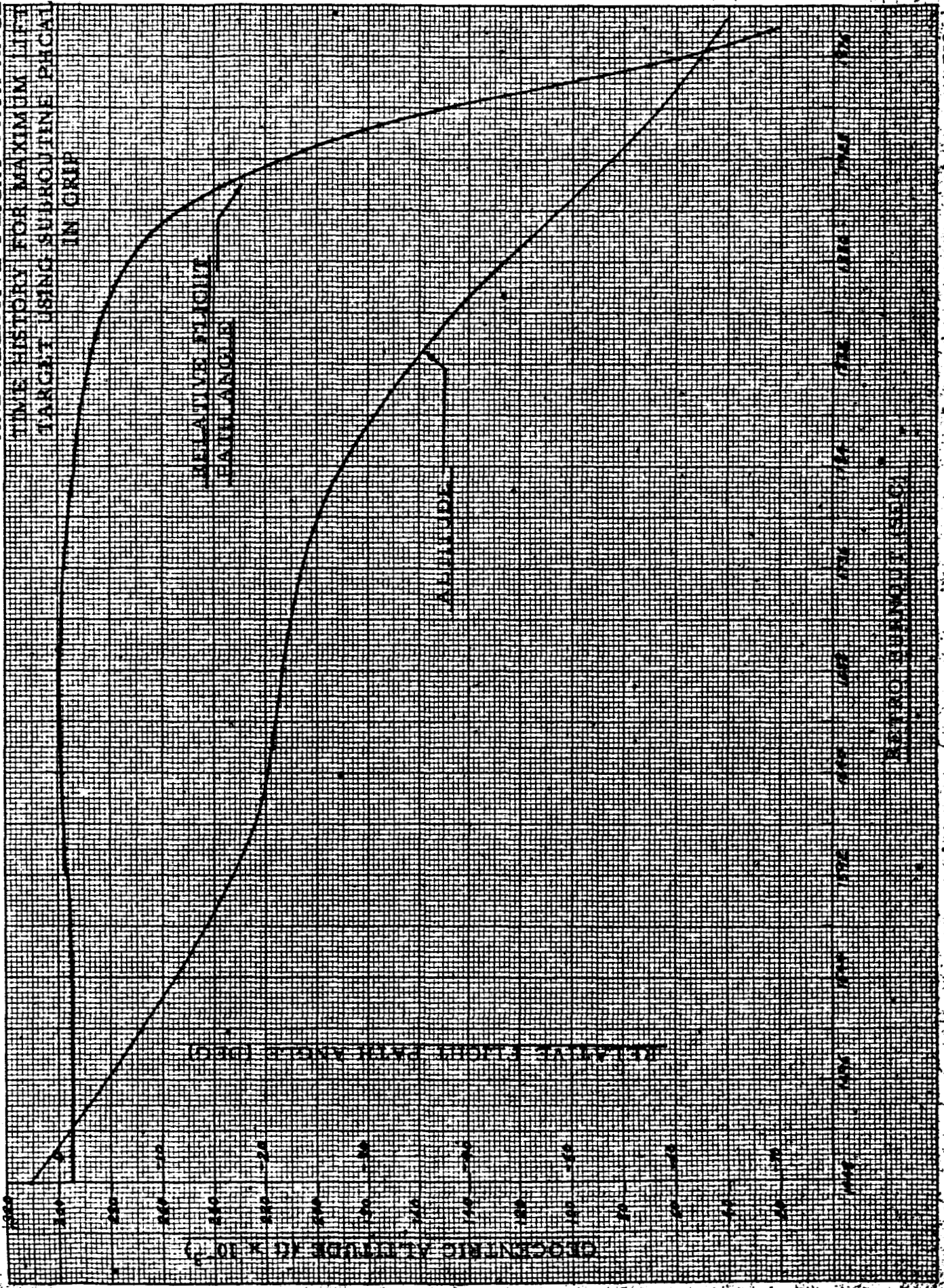
resulting actual bank angle time history. The computer is in the controlled mode until 1670 seconds after burnout. During this phase a commanded bank angle is continuously generated in the computer. Figure 4.10 shows the actual bank angle response to these commands as a negatively increasing angle. This is followed by a short period of oscillations due to the mode switching between controlled and spin. This is caused by the extreme sensitivity of the mode to the predicted ballistic capability. From 1700 seconds to 1726 seconds R_p is greater than R_n and R_c less than one mile and the vehicle spins. At 1724.4 seconds the ballistic range becomes less than the down range distance to go (R_n) and the controlled mode is entered for a period of only 4.8 seconds. Spin is again assumed at 1729.2 seconds and continues until 1760 seconds when the ballistic range once again becomes less than R_n and the controlled mode is entered. Spin is again assumed at approximately 1814 seconds and continues until the vehicle's altitude is 80,000 ft.

FIG. 10. ACTUAL BANK ANGLE
TIME HISTORY FOR MAXIMUM
LEFT TARGET USING SUBROUTINE
LOCAL IN CRIP

ACTUAL BANK ANGLE (DEG)

RETRO DRUNOUT INCL

FIG 4. 7 GEOCENTRIC ALTITUDE
AND RELATIVE FLIGHT PATH ANGLE



11FAS

FIG 1-5 RELATIVE VELOCITY
AND HEADING TIME HISTORY FOR
MAXIMUM LEFT TARGET USING
SUBROUTINE CALLED IN GRP

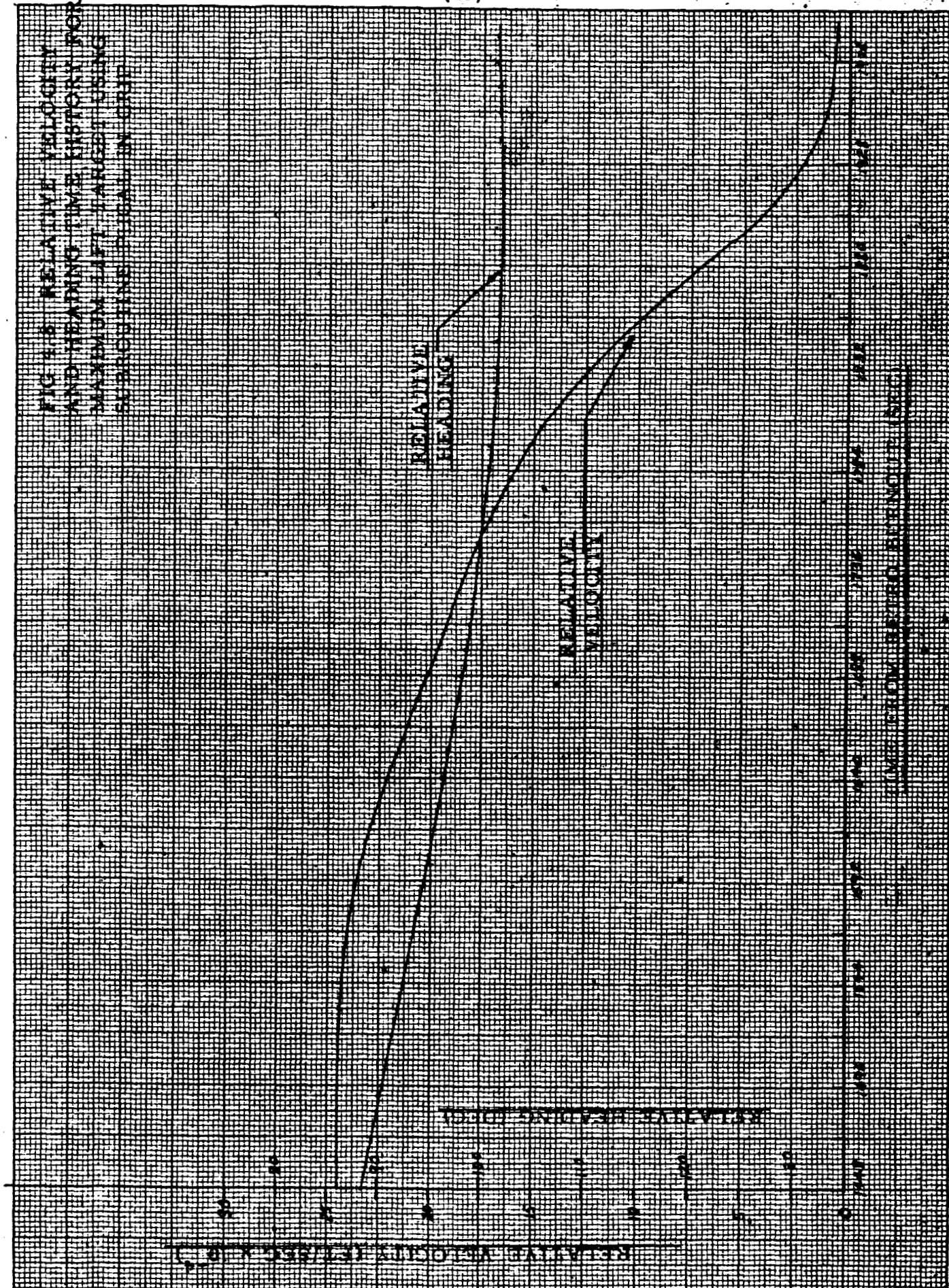
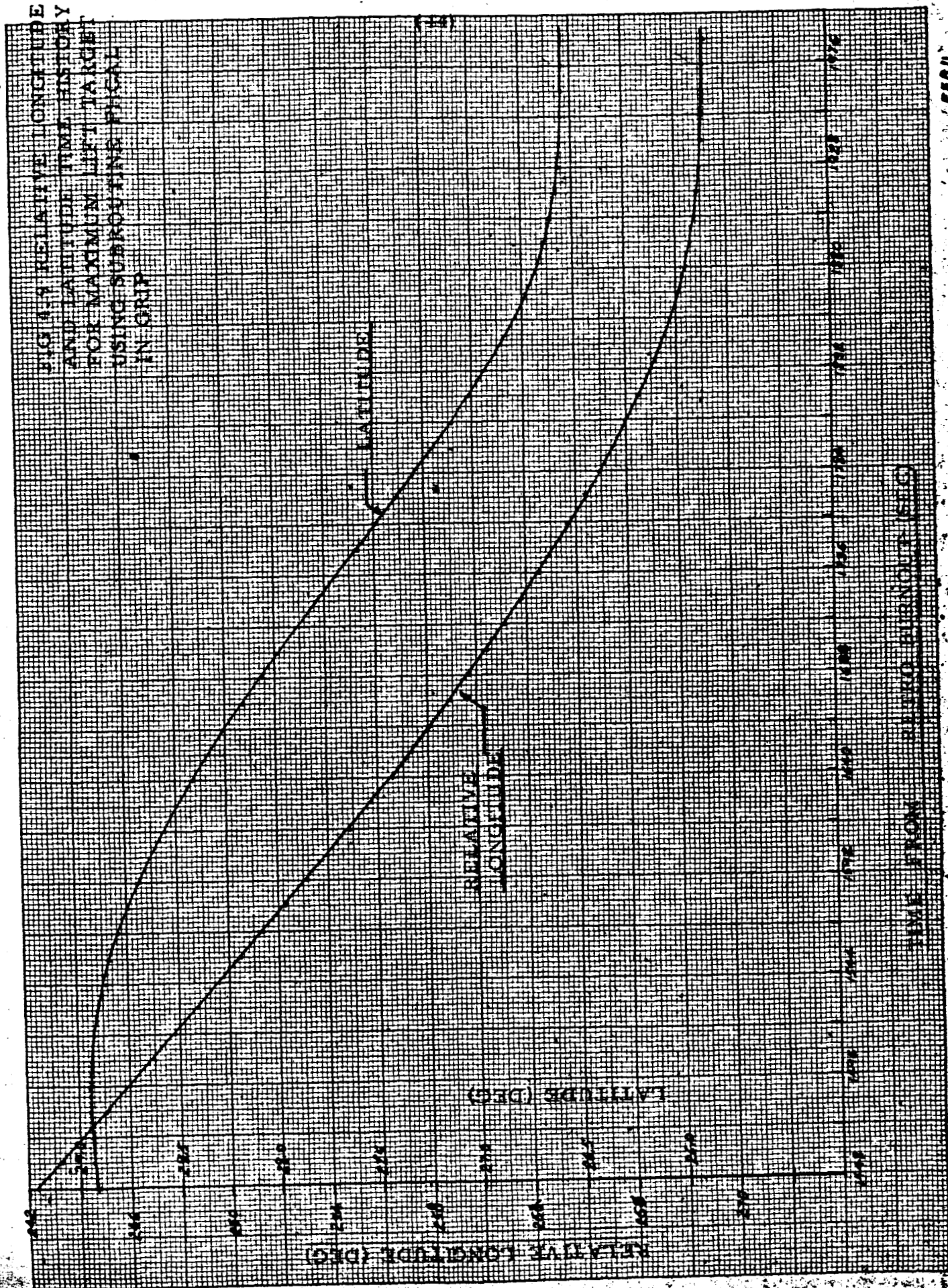


FIG 4-9 RELATIVE LONGITUDE
AND LATITUDE TIME HISTORY
FOR MAXIMUM LEFT TARGET
USING SUBROUTINE PICAL
IN GRIP



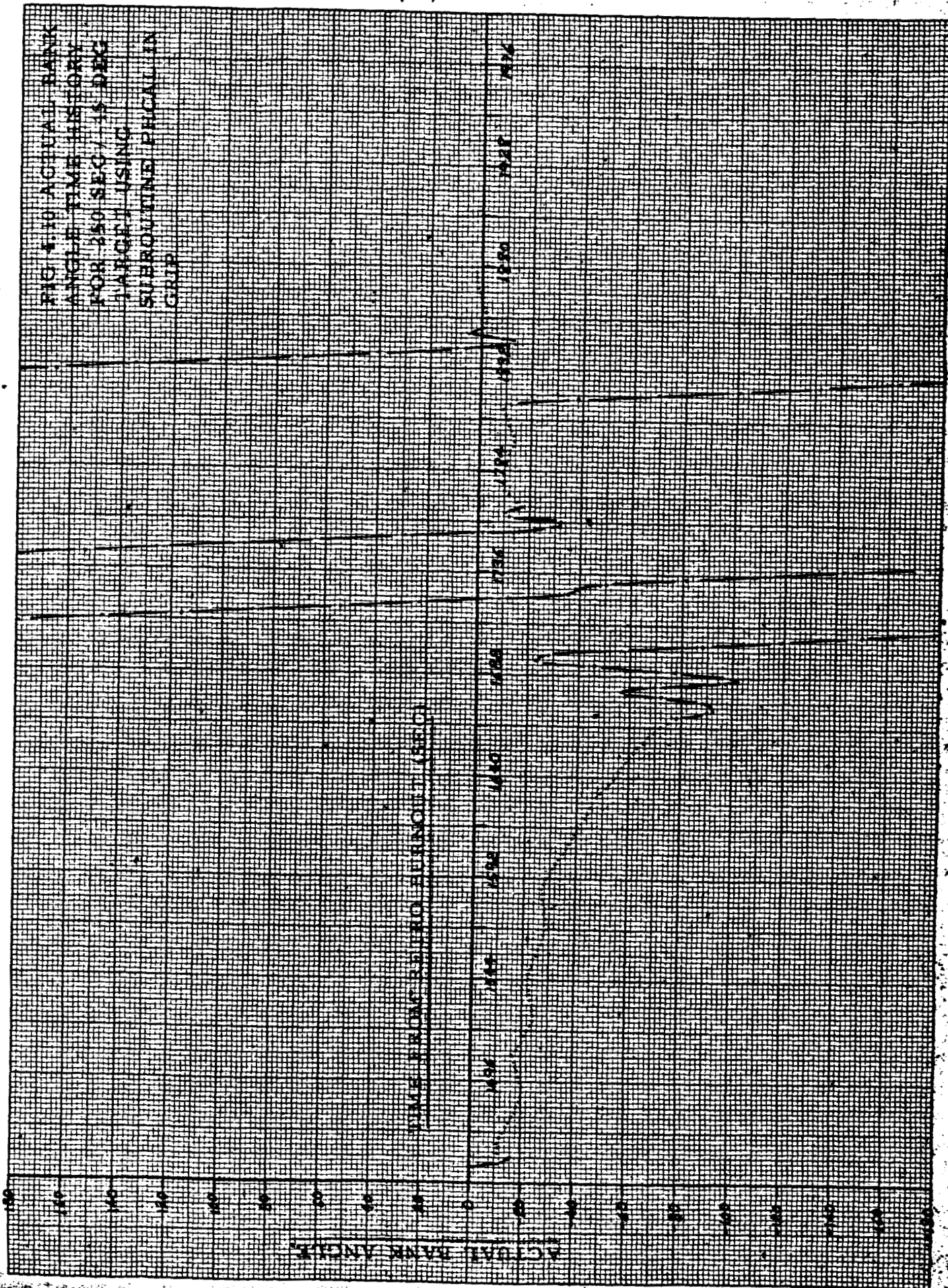
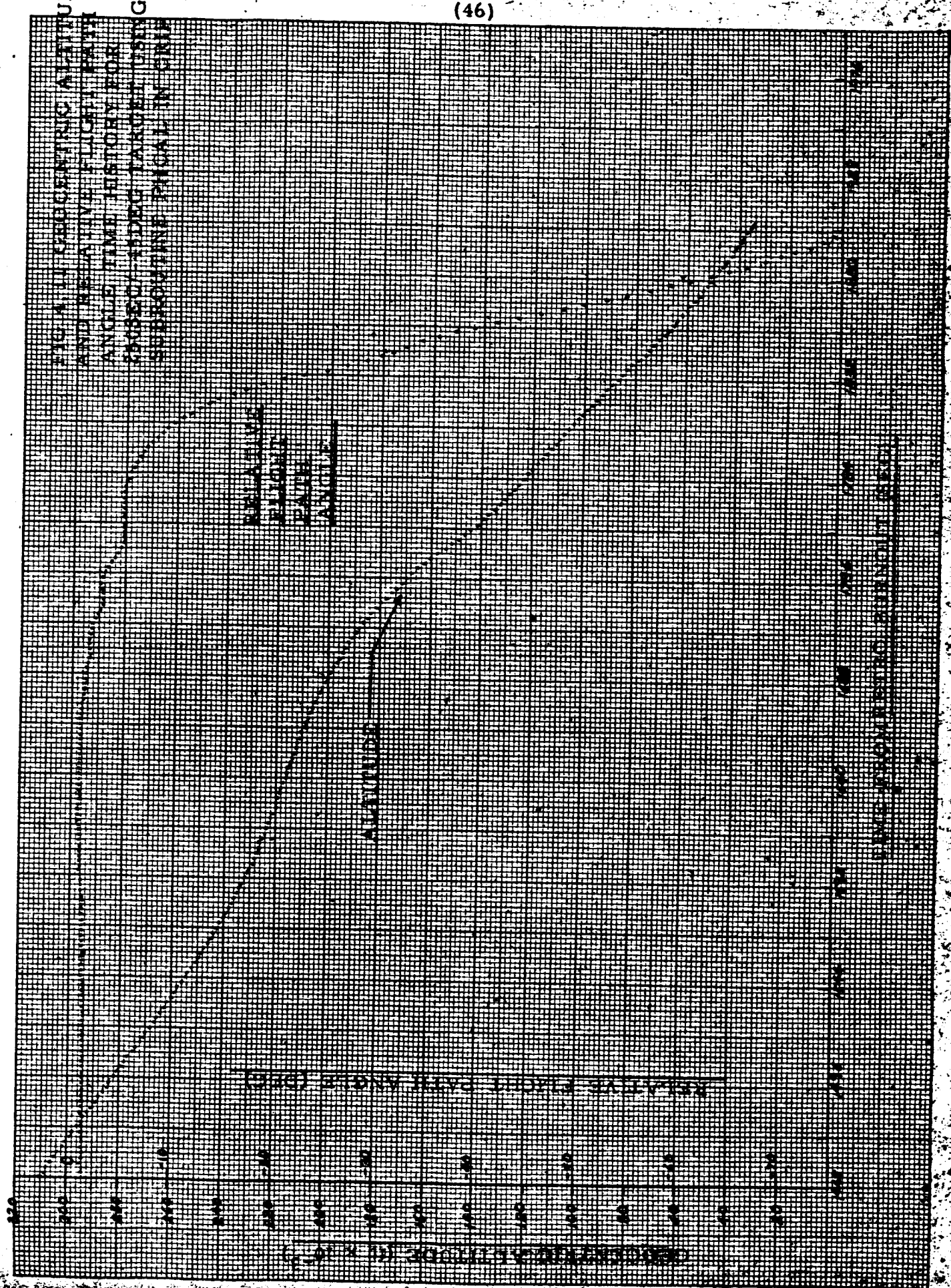
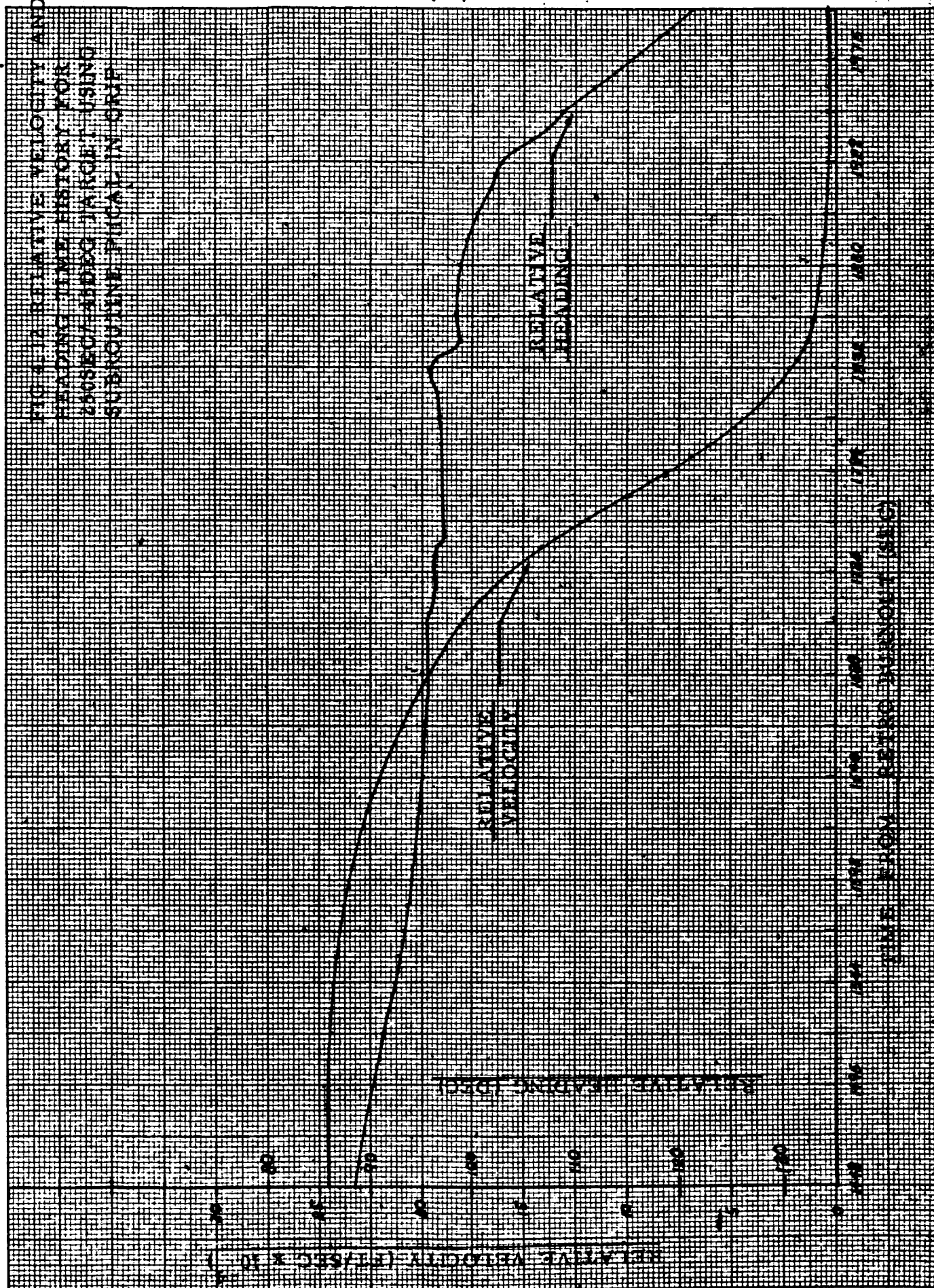
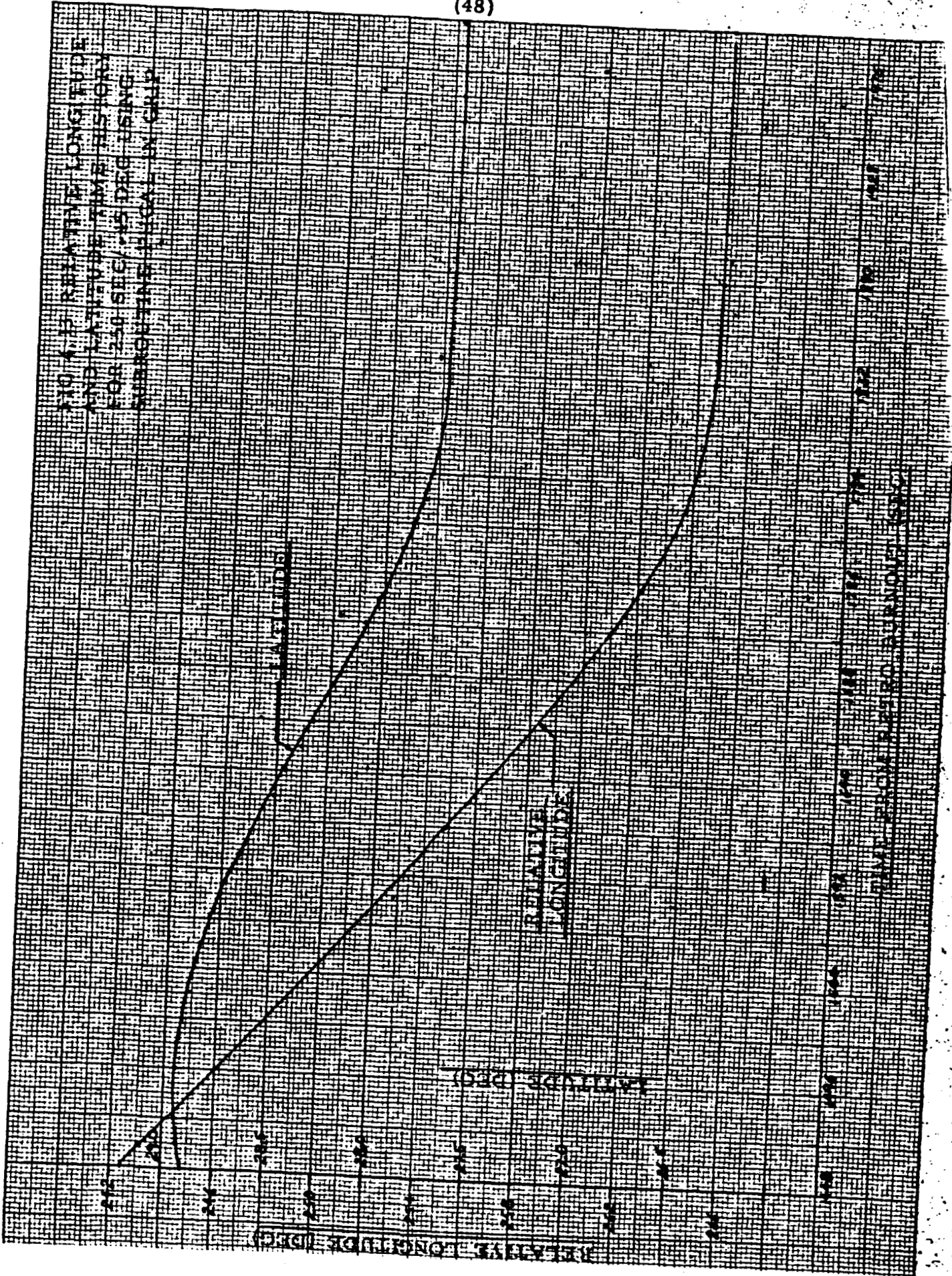


FIG. 1.11 CONCENTRIC ALTITUDE
AND RELATIVE FLIGHT PATH
ANGLE TIME HISTORY FOR
200000 MILES TARGET USING
SUBROUTINE PHCAL IN GNF



11 FEB 83





APPENDIX A: SUBROUTINE PHCAL

PHCAL is the re-entry guidance subroutine which is used in the GEMINI RE-ENTRY INTEGRATION PROGRAM (GRIP). During re-entry, the Gemini vehicle is guided to a pre-selected target by controlling the bank angle. PHCAL is used to simulate this control. It is a Fortran subroutine based upon the fourth math flow of the Gemini onboard computer and its purpose is twofold:

1. to continuously compute a commanded roll rate to drive the vehicle to the target, and
2. to simulate the vehicle's response to this commanded rate.

The subroutine also computes the bank angle at separate times through the cycle to be used by the Runge-Kutta integration routine in the main program. These functions are discussed in detail later.

A.1 Commanded Bank Angle and Roll Rate

The period of guidance begins when the sensed acceleration (XSA) becomes greater than 0.4 ft./sec^2 . This sensed acceleration is the result of averaging the specific force on the vehicle over four time cycles. This critical point is generally reached in the

range from 305 to 310 thousand feet of altitude. Above this point the bank angle is continuously driven to zero and the major portion of the guidance logic is not entered.

Once guidance has been initiated, the onboard computer uses the relative position and velocity of the vehicle together with the relative latitude and longitude of the target point to compute approximations to the down-range and cross-range distances (R_n and R_c) to the target. A quantity D , which is characteristic of the altitude of the vehicle, is calculated from the expression

$$D = -\log_{10} \left(\frac{XSA}{V_R^2} \right)$$

where V_R is the relative velocity of the vehicle. The ballistic range is then determined as

$$R_B = F_0(D) + F_1(D) \gamma_R + F_2(D) V_R$$

where F_0 , F_1 , and F_2 are obtained from tables and γ_R is the relative path angle. This range, R_B , is the minimum down range capability of the vehicle.

The quantity D also serves the function of ending the guidance regime. When D passes below a constant value the roll angle is driven to zero in preparation for deployment of the parachute or paraglider. This is done by setting the commanded bank angle to zero and letting the commanded roll rate equal the

negative of the actual bank angle. This termination of guidance occurs between 80 and 85 thousand feet of altitude.

While the vehicle is within the limits of guidance there are two modes for commanding the bank angle, the proportional mode and the spin mode. The proportional mode is entered whenever the down-range to the target is greater than the ballistic range ($R_N > R_B$), since this condition will allow the vehicle some maneuver capability. The quantity, PHICF, which is calculated as

$$\text{PHICF} = \frac{R_C}{R_N - R_B + 10}$$

is used to calculate B_C , the commanded bank angle (see Fig. A-1).

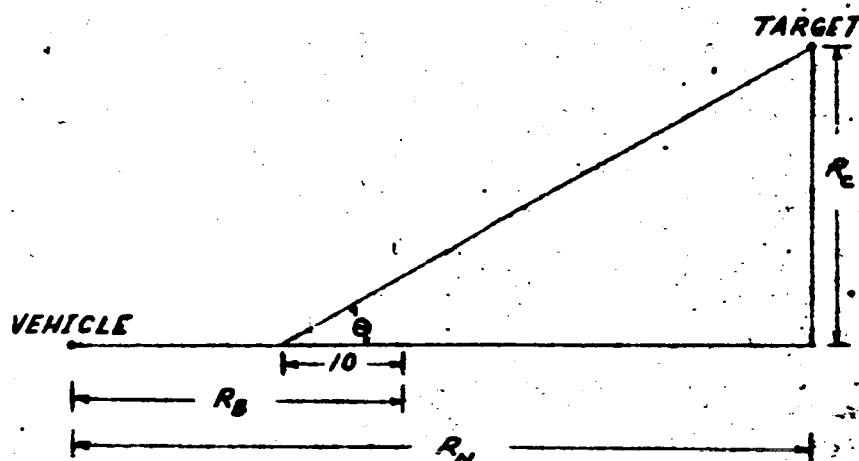


FIG. A-1

If PHICF is greater than 1 (i.e., $\theta > 45^\circ$), then B_C is set to plus or minus 90 degrees, according to the sign of R_C . If PHICF is less than 1, B_C is determined by the equation

$$B_C = \text{PHICF}^3 * \text{KR1} + \text{PHICF}^2 * \text{KR2} + \text{PHICF} * \text{KR3}$$

where $KR1$, $KR2$, and $KR3$ are constants and the range of B_C is -90 degrees to +90 degrees.

When the commanded bank angle has been determined, the bank error, B_E , is given by

$$B_E = B_C - B_A$$

where B_A is the actual bank angle. The commanded roll rate, $DPHIB$, is exactly this bank error except for the situation in which the vehicle has been spinning. In this case a logical decision is made as to whether to continue to roll in the same direction or to reverse the direction of spin to attain B_C . The direction of spin is changed only if the vehicle must rotate more than 230° in its present direction of rotation to reach the commanded bank angle. In this manner the commanded bank rate is determined for the proportional mode.

The spin mode is used whenever the ballistic range is greater than the down-range to the target ($R_B > R_N$). In this case the computer has calculated that the vehicle will overshoot the target. If the cross-range is now greater than 1 mile (the constant cross-range deadband), the commanded bank angle is set to plus or minus 90 degrees, whichever is appropriate to reduce the cross-range, and the bank error and commanded roll rate are calculated exactly as in the proportional mode. If the cross-range

is less than 1 mile the vehicle is commanded to spin by setting the commanded roll rate to plus or minus 15 deg./sec., where the sign is determined by the previous commanded rate or the actual bank angle. An indicator LCR is also set positive to indicate that the vehicle is in a commanded spin.

Regardless of the mode in which the vehicle is operating, it is important to note that the output of the computer which is used by the servos to control the vehicle is the commanded roll rate.

A.2 Conversion of Commanded Rate

Because of the fact that significant delays occur in the onboard system and also because of the deadband restrictions in the servos, it is necessary to perform a detailed simulation of the conversion of the commanded roll rate to an actual rate.

Fig. A-2 shows the input and output timing for the onboard computer over two cycles. (The cycle time is very nearly 1.2

seconds.) At time t_n the sensed acceleration is read from the accelerometers. The actual bank angle is read approximately .5 seconds later and a commanded roll rate is generated .6 seconds after the start of the cycle. It should be noted that this commanded rate is based upon the commanded angle from the previous

cycle. The actual bank angle is read again at $t_n + 1$ sec. and B_c and DPHIB are calculated and outputted at the end of the interval.

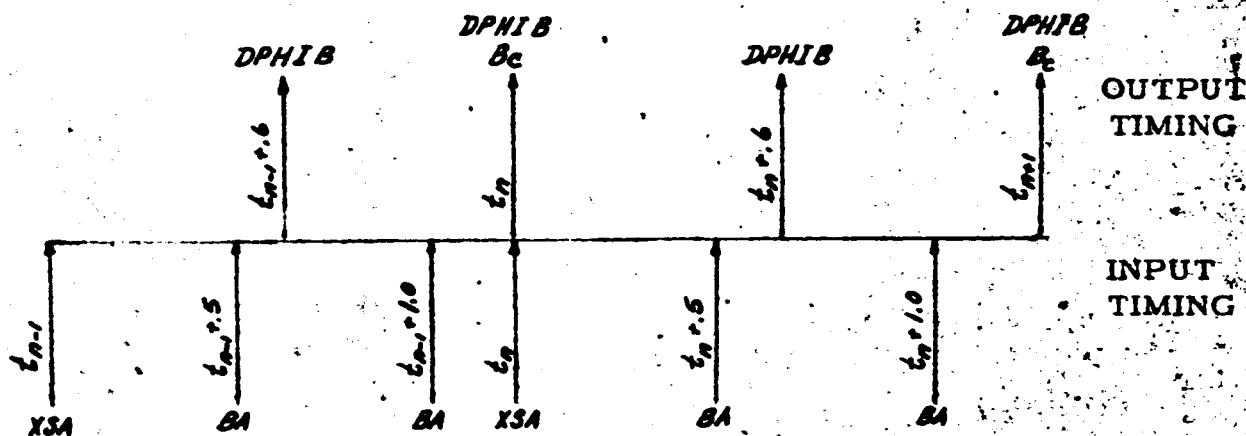


FIG. A-2

If the timing of the input and output of the above figure is studied carefully, it is seen that the commanded bank angle is outputted 1.2 seconds after the computer reads the sensed acceleration. Thus the bank angle through the n^{th} interval depends only upon the roll history of the previous interval and the sensed acceleration at the start of the $(n-1)$ st interval.

For this reason the bank angle profile for the $(n+1)$ st interval is computed during the interval just preceding. In order to do this it must be assumed that the roll history is known for the first interval and then each succeeding interval is solved in turn. This is done by assuming the vehicle begins the guidance with zero bank angle and zero roll rate, the state to

which it is driven during descent from retrofire.

In order to compute the bank angle and bank rate throughout the $(n+1)$ st interval, it is necessary to determine first whether the vehicle has been commanded to spin. The indicator LCR is used for this purpose, positive meaning a spin, negative meaning no spin. The commanded bank rate is limited to $\pm 15 \text{ deg./sec.}$, and then the rate error is computed as

$$PE = \text{DPHIB} - \text{PDOT12},$$

where PDOT12 is the actual bank rate at t_{n+1} . This rate error is computed continuously by the servos and as long as the error is greater than the deadband constant the roll jets are turned on. As soon as it passes below the deadband limit the jets are turned off.

In simulating this, the rate error is compared against the deadband limit. If $|PE| > DB$, the roll acceleration (BDD) is set equal to the average acceleration due to the roll jets and the time that the jet will remain on is calculated as

$$\tau = \frac{|PE| - DB}{|BDD|}$$

TAU and TAU1 are then calculated as τ limited to .6 and .5 seconds respectively. If $|PE| < DB$ the roll acceleration and TAU and TAU1 are set to zero. With this information together with the bank angle and bank rate at t_{n+1} we may now compute the bank angle at $t_{n+1} + .5 \text{ sec.}$ (PH15) and both the bank angle

and bank rate at $t_{n+1} + .6$ sec. (PHI6 and PDOT6). PHI5 is used to compute the commanded bank rate at $t_{n+1} + .6$ sec. and PDOT6 is used to compute the rate error at this time. PHI6 is used as output to the Runge-Kutta integrator during the next pass.

In order to compute the rate error at $t_{n+1} + .6$ sec., the indicator LCR is checked to see if the vehicle is to be spinning.

If the vehicle is not spinning the commanded rate is calculated as

$$DPHIB = PHIC - PHI5$$

and limited to ± 15 deg/sec. If the vehicle has been commanded to spin, the commanded rate is not changed. The rate error at $t_{n+1} + .6$ sec. is then calculated as

$$PE = DPHIB - PDOT6$$

As before, this error is checked against the deadband limit and the jet on-time is calculated. TAU and TAU1 are calculated as τ limited to .6 and .4 seconds respectively. With this information we may now calculate the bank angle at $t_{n+1} + 1$ sec. (PHI1), the bank angle at $t_{n+1} + 1.2$ sec. = t_{n+2} (PHI12), and the bank rate at t_{n+2} (PDOT12). PHI1 is used during the next cycle to compute the bank error and PDOT12 is used to calculate the rate error. PHI12 is the output to the Runge-Kutta integrator for the end of the interval.

A.3 Subroutine Characteristics

Because of the timing characteristics of the onboard computer

it has been necessary to use an integration step size equal to the computer cycle time of 1.2 sec. This has not caused any difficulty in the other portions of the simulation.

The routine uses an indicator (IPHI) to initialize the guidance. This should be a 1 at the beginning of each run.

PHCAL is entered three times for each integration step. The first time the guidance logic is performed and all the necessary output for the next interval is calculated. On the second and third times the appropriate roll angle is outputted to the Runge-Kutta integrator. The control within the subroutine is performed by the variable NPHI which takes on the values 1, 2, and 3 successively.

TABLE A-1 INPUT TO PHCAL

RRATE	- average angular acceleration about the roll axis due to the roll jets.
DB	- deadband for sensing bank angle error and roll rate error.
XKBE = 15 deg.	- maximum roll rate
$D_0 = 4.675$	- represents lower limit of guidance control.
SA	- specific force on the vehicle
HT	- geocentrically measured altitude
X, Y, Z	- rectangular geocentric inertial coordinates of the vehicle
$R = (X^2 + Y^2 + Z^2)^{1/2}$	
λ_R	- relative longitude of the vehicle
β_R	- relative heading from north
V_R	- relative velocity
γ_R	- relative flight path angle
λ_T	- target longitude
γ_T	- target latitude
R_G	- earth gravitational radius

SUBROUTINE PHCAL (PULL, CUVAR, X, X, X, X, X, X, X, X)

PH1=0.0

```

SUBROUTINE PHCAL(PULL,CUVAR,X,X,X,X,X,X,X)

PH2=0.0
RETURN
2 CONTINUE
XSA=(SA1+SA2+SA3+SA4)/XNN
DR=XSA
IF(XSA-.4)4.3.2
3 CONTINUE
COP=SQRTF(ANS(2)*ANS(2)+ANS(3)*ANS(3))/R*RG
SIP=ANS(4)/R*RG
B=COSF(TPS1)*SINF(TLAM-DLON/CONV)
E=SINF(TPS1)*COP-COSF(TPS1)*SIP*COSF(TLAM-DLON/CONV)
RT=60.*57.2957795*ARSINF(SQRTF(B*B+E*E))
CALL TANGLE(B,E,PSITR)
RC=RT*SINF(AZH2/CONV-PSITR)
RN=RT*COSF(AZH2/CONV-PSITR)
D=-.43429448*LOGF(XSA/VR**2)
CALL PREDI(D,VR,DFPAR,RB)
GO TO 30
4 D=0.0
30 IF(D-4.675)5.6.6
5 CONTINUE
DPHIB=-PHI1
PHIC=0.0
LCR=-1
GO TO 23
6 CONTINUE
IF(RB-RN)7.8.8
7 CONTINUE
PHICF=RC/(RN-R3+10.)
IF(PHICF)9.10.10
9 CONTINUE
LC2E=-1
PHICF=-PHICF
GO TO 11
10 CONTINUE
LC2E+=1
11 IF(PHICF-1.)12.13.13
12 CONTINUE
PHIC=PHICF*(PHICF*(-184.9553*PHICF+393.9718)-299.0165)
GO TO 14
13 CONTINUE
PHIC=-90.
14 IF(LC2E)15.15.31
15 CONTINUE
PHIC=-PHIC
31 CONTINUE
PHIE=PHIC-PHI1
PHIE=PHIE-360.*INTF(PHIE/180.)
425 IF(LCR)430.430.426
426 IF(DPHIB)428.427.427
427 IF(PHIE+XXKL)438.438.429
428 IF(PHIE-XXKL)429.438.438
429 LCR=-1
430 DPHIB=PHIE
23 CONTINUE
PHI=PHI6

```

SUBROUTINE PHCAL(PULL,CUVAR,X,X,X,X,X,X,X)

```

PH2=PHI12
IF(ABSF(DPHIB)-XKBE)4002,4000,4000
4000 DPHIB=SIGNF(15.,DPHIB)
4002 PE=DPHIB-PDOT12
IF(ABSF(PE)-DB)4003,4003,4004
4003 BDD=0.0
TAU=0.0
TAU1=0.0
GO TO 4005
4004 BDD=SIGNF(RRATE,PE)
TAU=MINIF((ABSF(PE)-DB)/ABSF(BDD),.6)
TAU1=MINIF(TAU,.5)
4005 PHI5=PHI12+.5*DOT12+.5*BDD*TAU1*TAU1+BDD*TAU1*(.5-TAU1)
PHI5=PHI5-360.*INTF(PHI5/180.)
PHI6=PHI12+.6*DOT12+.5*BDD*TAU*TAU+BDD*TAU*(.6-TAU)
PHI6=PHI6-360.*INTF(PHI6/180.)
PDOT6=PDOT12+BDD*TAU
IF(LCR)4006,4006,4007
4006 DPHIB=SIGNF(MINIF(ABSF(PHIC-PHI5),15.),PHIC-PHI5)
4007 PE=DPHIB-PDOT6
IF(ABSF(PE)-DB)4008,4008,4009
4008 BDD=0.0
TAU=0.0
TAU1=0.0
GO TO 4010
4009 BDD=SIGNF(RRATE,PE)
TAU=MINIF((ABSF(PE)-DB)/ABSF(BDD),.6)
TAU1=MINIF(TAU,.4)
4010 PHI1=PHI6+.4*PDOT6+.5*BDD*TAU1*TAU1+BDD*TAU1*(.4-TAU1)
PHI1=PHI1-360.*INTF(PHI1/180.)
PHI12=PHI6+.6*PDOT6+.5*BDD*TAU*TAU+BDD*TAU*(.6-TAU)
PHI12=PHI12-360.*INTF(PHI12/180.)
PDOT12=PDOT6+BDD*TAU
WRITE OUTPUT TAPE 6,9999,SA,RC,RN,RB,D,PHIC,DPHIB,PHI1
9999 FORMAT(13X,2HSA,13X,2HRC,13X,2HRN,13X,2HRS,14X,1HD,11X,4HPHIC,10X,
15HDPHIB,10X,5HPHI1/1X,E14.6,7E15.6)
RETURN
203 NPHI=3
ROLL=PH1
RETURN
204 NPHI=1
ROLL=PH2
ROLL=ROLL-360.*INTF(ROLL/180.)
6031 RETURN
8 CONTINUE
IF(RC-1.0)24,25,25
25 CONTINUE
PHIC=-90.
GO TO 31
24 CONTINUE
IF(RC+1.0)26,25,27
26 CONTINUE
PHIC=90.
GO TO 31
27 CONTINUE
431 IF(LCR)432,438,438

```

SUBROUTINE PHCAL(PULL,CUVAR,X,X,X,X,X,X,X,X)

432 IF(ABSF(DPHIB)-XKBE/2.)433,433,434

433 IF(PHI1)435,435,436

434 IF(DPHIB)435,435,436

435 DPHIB=-XKBE

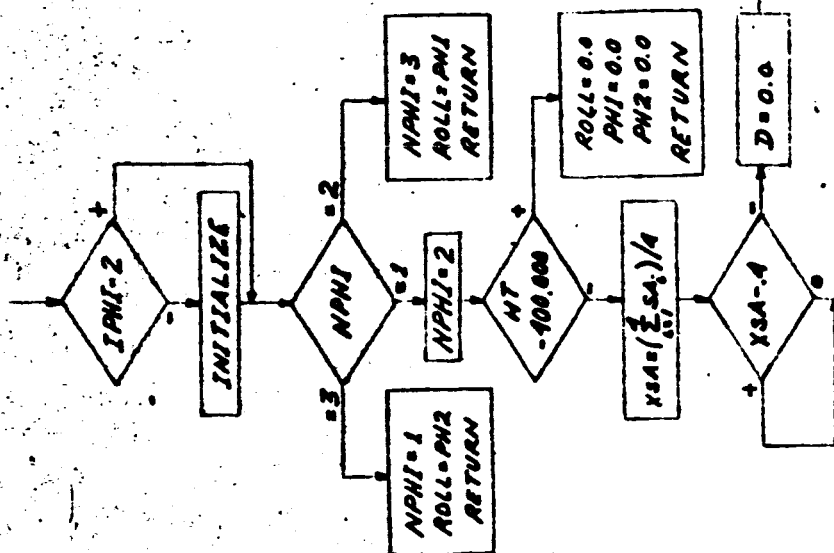
GO TO 437

436 DPHIB=XKBE

437 LCR=+1

438 GO TO 23

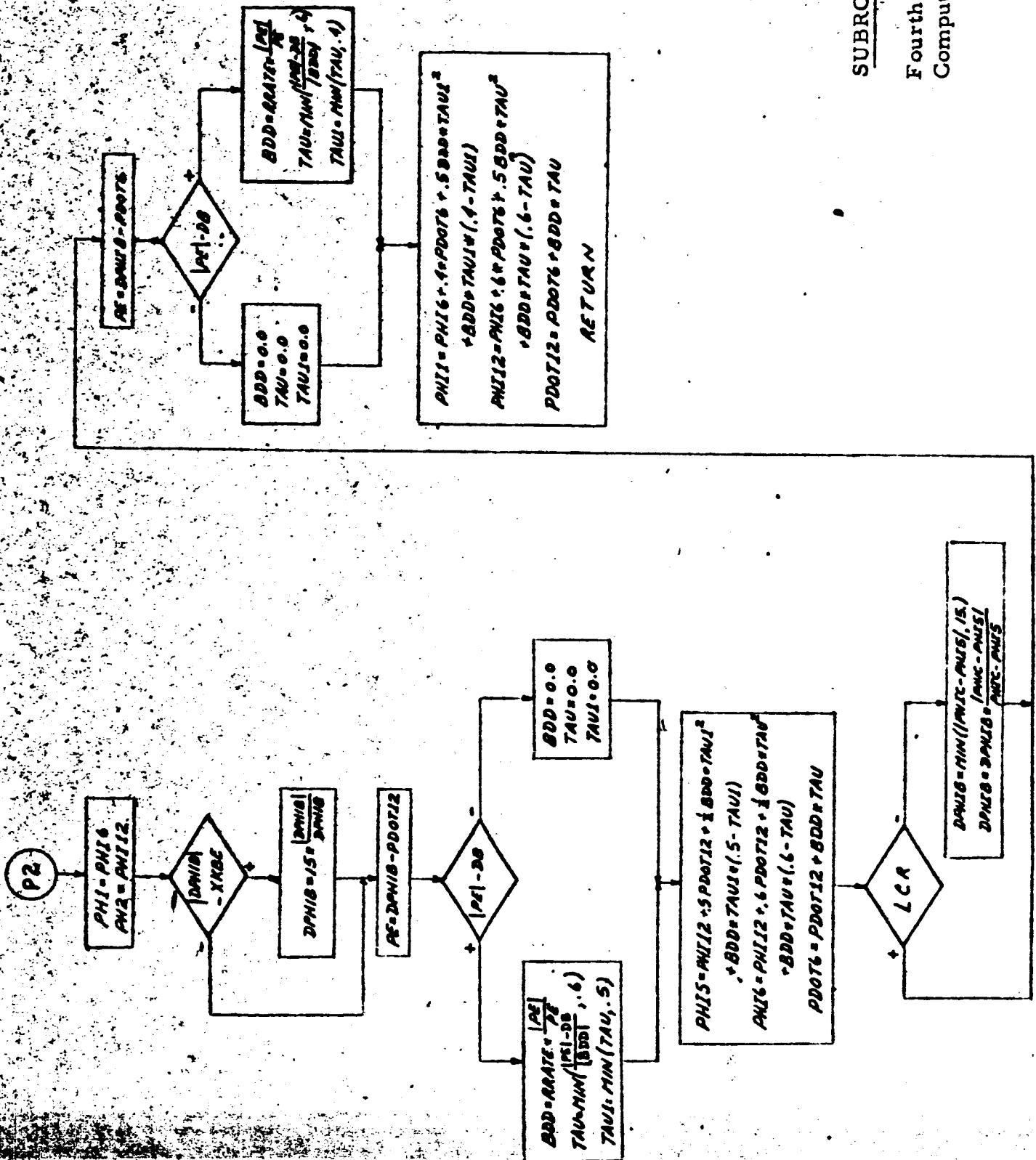
END(0.0.0.1.0.0.1.0.0.1.0.0.0.0.0)



$$\begin{aligned} \cos \psi &= \frac{(x^2 + y^2)^{1/2}}{R} \\ \sin \psi &= \frac{z}{R} \\ B &= \cos \psi_T \sin(\lambda_T - \lambda_A) \\ E &= \sin \psi_T \cos \psi - \cos \psi_T \sin \psi \cos(\lambda_T - \lambda_A) \\ AT &= 60 \times \frac{180}{\pi} \sin^{-1}(B^2 + E^2)^{1/2} \\ \beta_T &= \tan^{-1}(B/E) \\ R_E &= R_T \sin(\beta_A - \beta_T) \\ R_A &= R_T \cos(\beta_A - \beta_T) \\ D &= -109_{10} (SA/V_A^2) \\ R_B &= F_B(D) \cdot F_1(D) \cdot F_2(D) \cdot V_A \end{aligned}$$

SUBROUTINE PHCAL

Fourth Gemini Onboard
Computer Math Flow



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