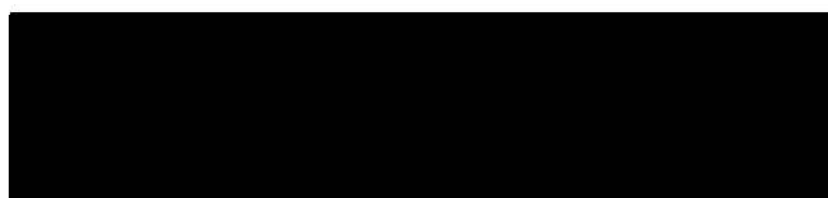


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APOLLO

GUIDANCE AND NAVIGATION

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R-532
Volume I of II
REENTRY GUIDANCE
FOR APOLLO

by
Raymond Morth
January 1966



INSTRUMENTATION
LABORATORY

CAMBRIDGE 39, MASSACHUSETTS

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The publication of this report does not constitute approval by the National Aeronautics and Space Administration of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

R-532
REENTRY GUIDANCE FOR APOLLO

ABSTRACT

The design of the reentry steering for the Apollo spacecraft is discussed in detail.

Error performance is the critical design factor. A great deal of effort has been spent to find a system that would steer properly in spite of navigation errors. The most significant error is in the initial indicated rate-of-climb. To achieve this error performance a computed reference trajectory is used during the critical supercircular phase, with control gains that have been chosen on a statistical basis to minimize the miss distance.

The many other factors which affected the design are presented. Some of these are requirements on the trajectory by the heat shield and monitor system, and limitations on the attitude maneuvers by the roll control system fuel.

The performance of the automatic self-contained system using a digital computer is presented. Guidance to all possible points throughout the entry corridor is demonstrated.

The detailed computer logic for the Apollo Guidance Computer is also presented.

by Raymond Morth
January 1966

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Instrument Error Performance

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PROLOGUE

Since "Apollo Reentry Guidance", R-415, was written several changes have occurred. These changes as well as more complete performance data are the subject of this report.

The most significant change is the reduction of the lift-to-drag ratio (L/D) of the Apollo command module from .5 to .3. This is a profound change in that the vehicle's performance characteristics have been sharply reduced. No longer is a 5000 nautical mile range possible for entries near the undershoot (10 g) limit. The maximum range possible for a .3 L/D vehicle is about 2500 nautical miles in this case. This reduced range capability affects the entire Apollo mission, putting stronger requirements on such things as the number of landing sites, and the time of the lunar month for return to earth. The entry steering design is also affected, with more accurate ranging required in the early phases because the final phase has less capability to correct for deviations.

It was felt since R-415 is essentially out of date, that this report should be made self-contained, repeating some of the material in R-415.

I INTRODUCTION

A large amount of experience in reentry from orbit has been gained in the Mercury and Gemini programs. To date, there has been essentially no guidance during the reentry phase, though the Gemini spacecraft has a reentry guidance system, yet the results have been satisfactory. This raises the question: Is reentry guidance necessary for the Apollo mission? The answer is an emphatic yes. The main reason lies in the dynamics of reentry at escape velocity. Although escape velocity is only 40% greater than orbital velocity, the sensitivity of reentry range to variations in the reentry flight path angle is several orders of magnitude greater than that for the orbital case. (See Section II for a detailed discussion.) Thus a ballistic entry or a constant L/D entry would impose unreasonable accuracy requirements on the preceding phase. Further, even if such accuracy were possible, large landing point errors would be caused by non-standard atmospheric conditions and variations in the spacecraft aerodynamic characteristics. Because, here again, the range sensitivity to these variations is significantly higher than in the orbital case.

The guidance system must be self-contained because of radio black-out which is caused by an ion sheath surrounding the vehicle. Though there are means of penetrating this sheath such as by injecting water and using extremely high radio frequencies, these methods are as yet unproved, and it would be unwise to rely on their timely development.

The two objectives of the reentry guidance are, in order of importance:

1. safe return to the surface of the earth, and
2. landing point control.

These objectives must be achieved in spite of non-ideal equipment performance and non-standard environmental conditions.

To achieve a safe return the vehicle must be in the reentry "corridor", i.e. the entry angle must be large enough so that capture by the atmosphere

is assured but not so large so that excessive acceleration will result, (see fig. 1-1.) The midcourse guidance phase has first responsibility to attain this corridor.

The reentry guidance then must achieve the landing site while avoiding excessive g-loads at one extreme and a prolonged ballistic flight at the other. There is a real chance of the latter since longer ranges are attained by exiting from the atmosphere at slightly less than satellite velocity. Should this exit velocity exceed satellite velocity there would be an extended elliptical flight from half way to almost all the way around the earth. This would be highly undesirable since there are limited supplies of power and oxygen, to say nothing about the recovery problem from an unpredictable point on the earth.

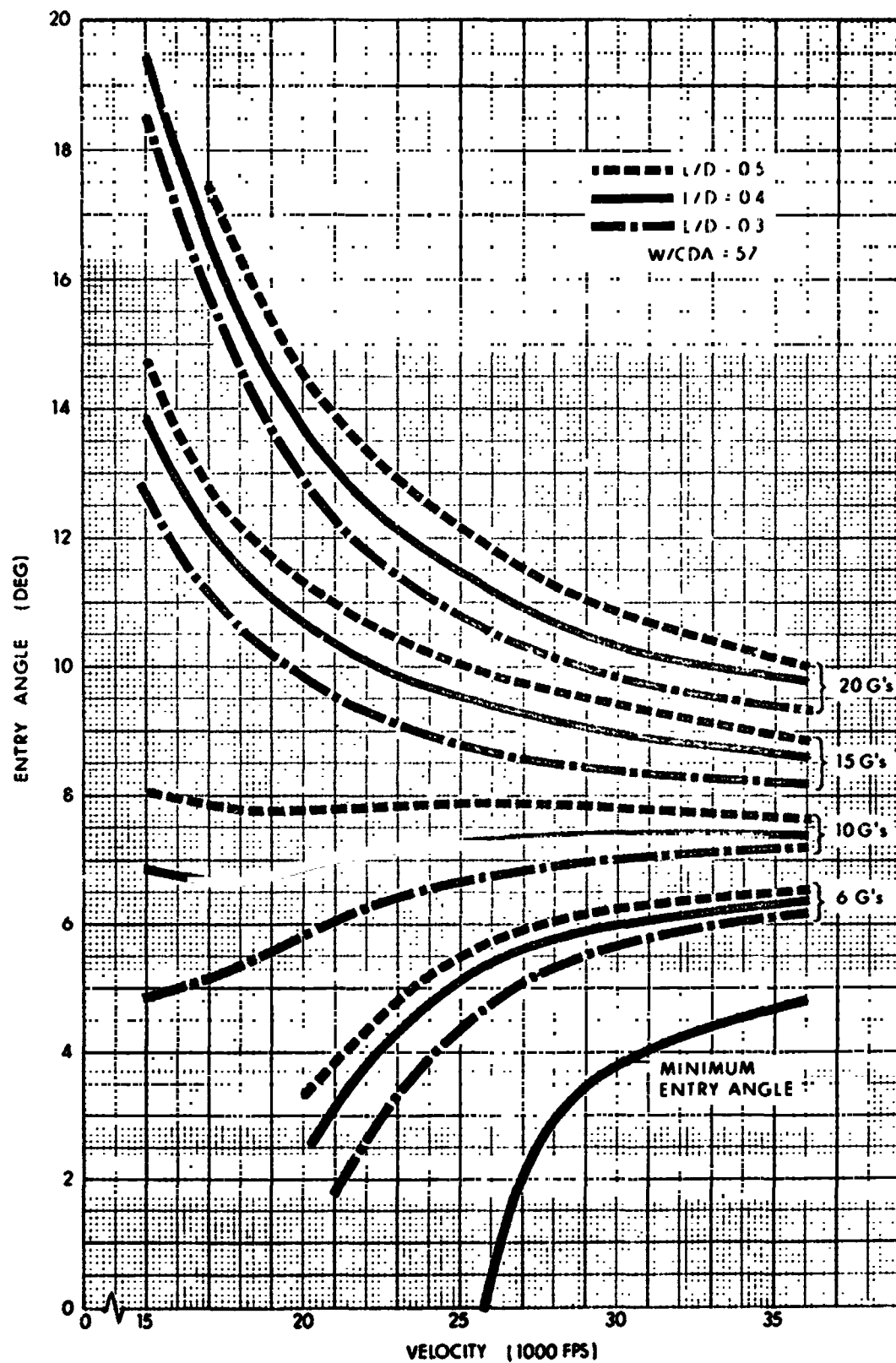


Fig. H Limit entry angle.

II CAPABILITIES AND REQUIREMENTS

The Apollo command module is a wingless, axially symmetric reentry vehicle constructed so that its center of gravity is displaced from its axis of symmetry. The c.g. offset causes the vehicle to trim to a low angle of attack, about 20 degrees, providing the lift for trajectory control. The trajectory is controlled by rolling the vehicle about the wind axis with hypergolic reaction control jets, so that the lift may be directed anywhere in a plane perpendicular to the velocity vector.

A major vehicle design problem has been to provide sufficient center of gravity offset so that the vehicle lift-to-drag ratio, L/D , will be large enough. At present the L/D is about .3. As the following charts will show, further reduction of the L/D would seriously degrade the mission.

Shown in fig. 2-1 are maximum range capabilities for a series of low L/D vehicles which hold lift up throughout the reentry trajectory. Range is plotted against the initial flight path angle. The first point to note from this figure is that long range capability is due more to initial energy than to lifting capability. All vehicles, even the ballistic vehicle ($L/D = 0$), can achieve a very large range if they enter at the right flight path angle. But the sensitivity of range to initial flight path angle is very large as seen by the slopes of the solid lines. For example, a ballistic vehicle going 4000 nautical miles has a sensitivity of about 10,000 nautical miles per milliradian. This sensitivity decreases with both increasing L/D and decreasing range, but for ranges greater than 1500 n.m. the sensitivities are too great to permit an open-loop guidance system.

The dotted line in fig. 2-1 shows the cases which have a maximum acceleration of 10 g's. This line shows the increase in allowable initial flight path angle with increasing L/D . Further, the figure shows the range penalty for decreasing L/D . At the 10 g limit, about 2500 n.m. is the maximum possible range with an L/D of .3 while over 6000 n.m. is possible with an L/D of .4.

The minimum possible range is determined by the maximum g level that can be tolerated as well as by the initial entry angle. Figure 2-2 shows

2-2

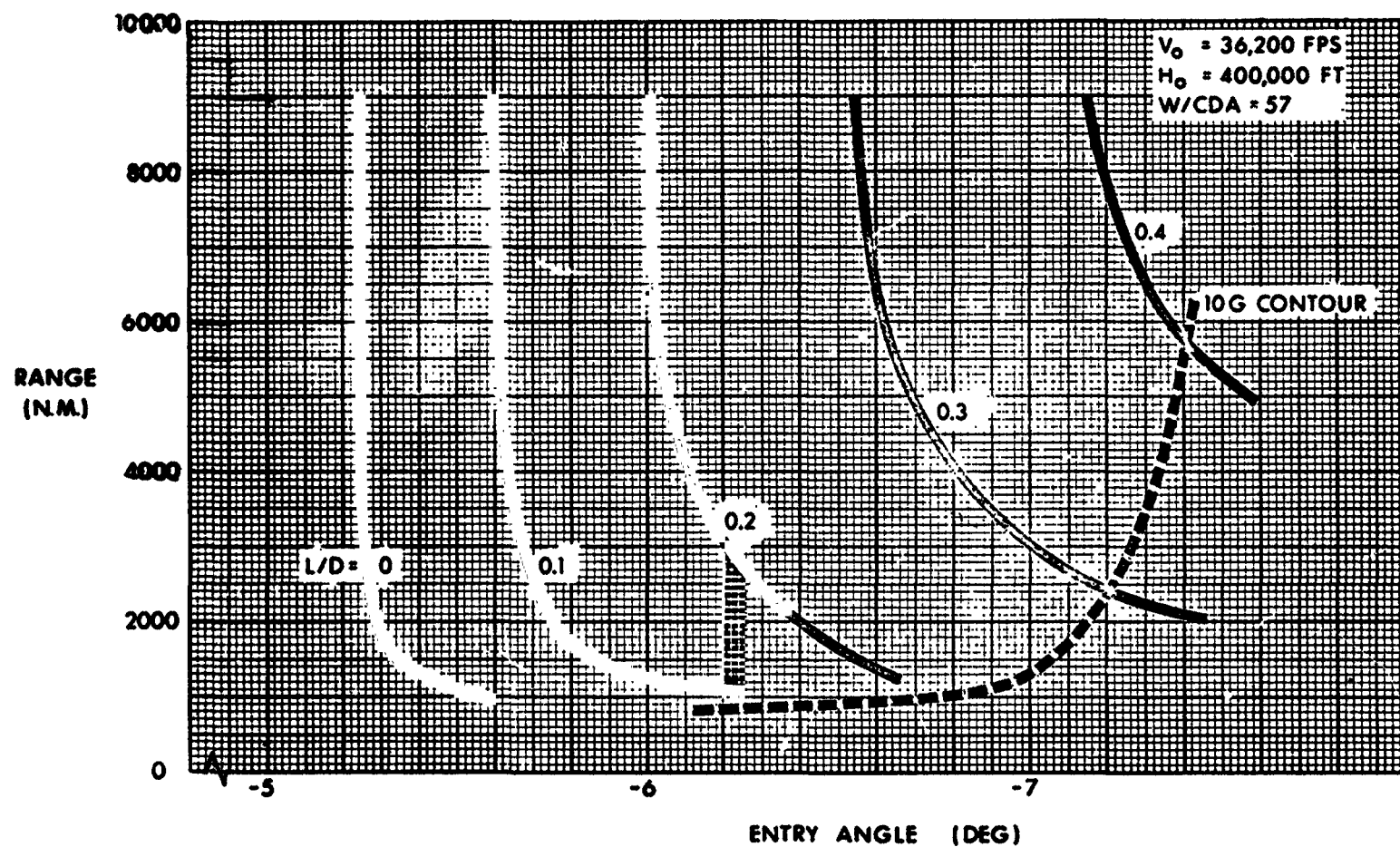


Fig. 2-1 Range for constant 4/0 entry.

a measure of this minimum range. This range was attained by directing the lift down after the initial pull-out modulating this lift direction by a g-limiter logic so that a 10 g limit will not be exceeded.

The maximum lateral range is shown in fig. 2-3 which plots the entry "foot print" for three values of L/D . That the lateral range is quite small emphasizes the fact that ranging capability is due to initial velocity (or energy) rather than aerodynamic characteristics. Note that the lateral range capability for $L/D = .3$ is roughly half that for $L/D = .4$.

The next three charts show the vehicle capabilities for initial velocities less than satellite velocity. The curve for $L/D = .3$ can be considered a maximum range capability and the $L/D = 0$ curve can be considered a minimum range capability. At these velocities there is not a significant range reduction attained by lifting down. The next curve shows the time of flight for the $L/D = .3$ cases. These curves have been useful to the designer of the powered steering for the abort cases.

Design Requirements

The several requirements on the guidance system are listed below

1. Guide to all possible landing sites over the entry corridor
2. Do this with a 3 sigma accuracy of 15 n.m. in track and range
3. Choose those trajectories recognizable by a simple monitor
4. Choose trajectories that are compatible with the heat shield
5. Use only vehicle lift directed by a reaction control system with limited fuel
6. Do all this with a self-contained system, because of radio black-out

Vehicle capabilities dictate a range requirement of 2500 n.m. maximum, and 1500 n.m. minimum for all entry angles. Note again that this maximum range is reduced from the previous 5000 n.m. value which was possible with the higher L/D .

The accuracy requirement is largely a requirement on the initial condition uncertainties. The errors accumulated during entry due to both the steering and navigation meet this requirement easily. There is some possibility of reducing unusually large initial errors by monitoring the drag build-up. This is discussed in Appendix E.

The monitor function is to detect a guidance system failure. This is particularly difficult in some cases where the failure might result in a ballistic phase starting at just above satellite velocity. Since the monitor system has simple instruments which are supposed to be more reliable, the guidance system is constrained to generate trajectories in which "good" and "bad" is more easily detected.

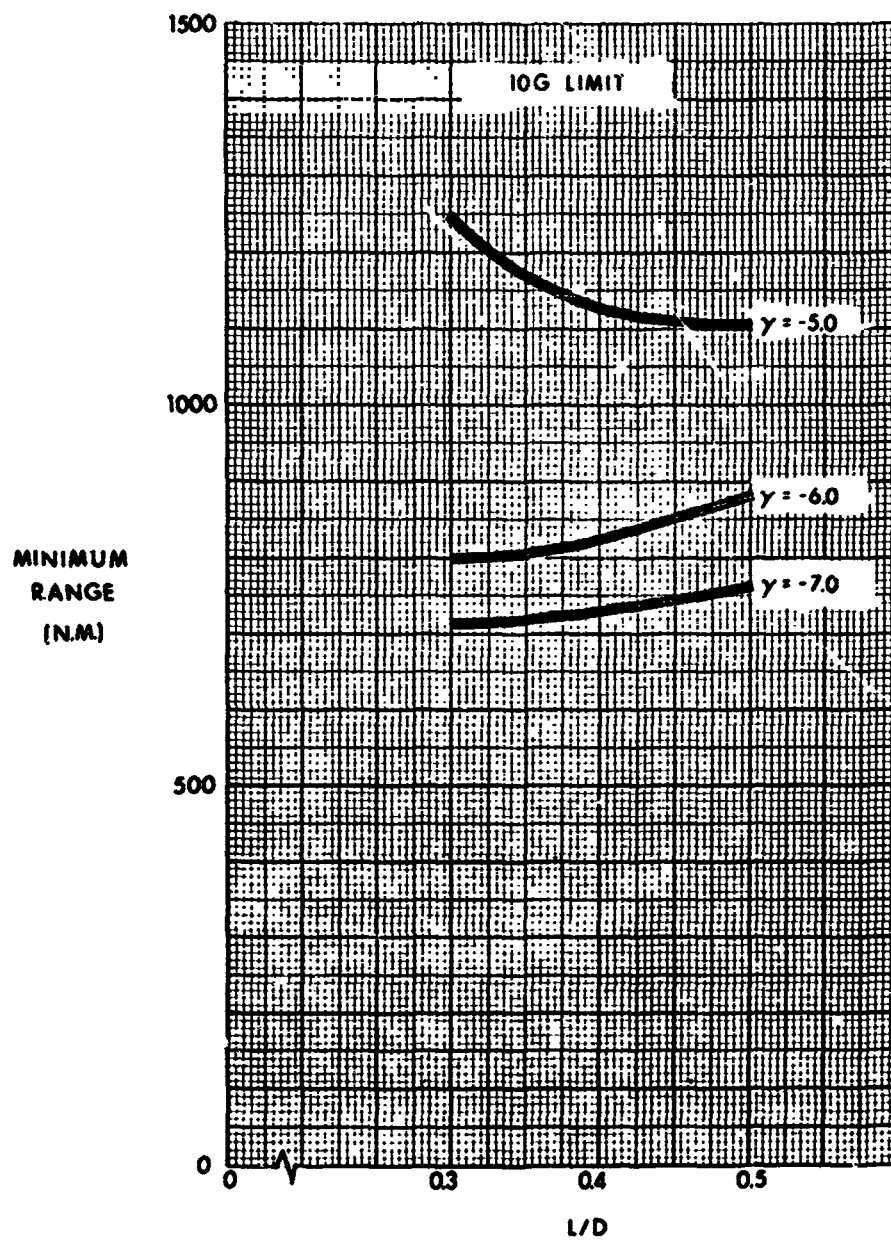


Fig. 2-2 Minimum possible range.

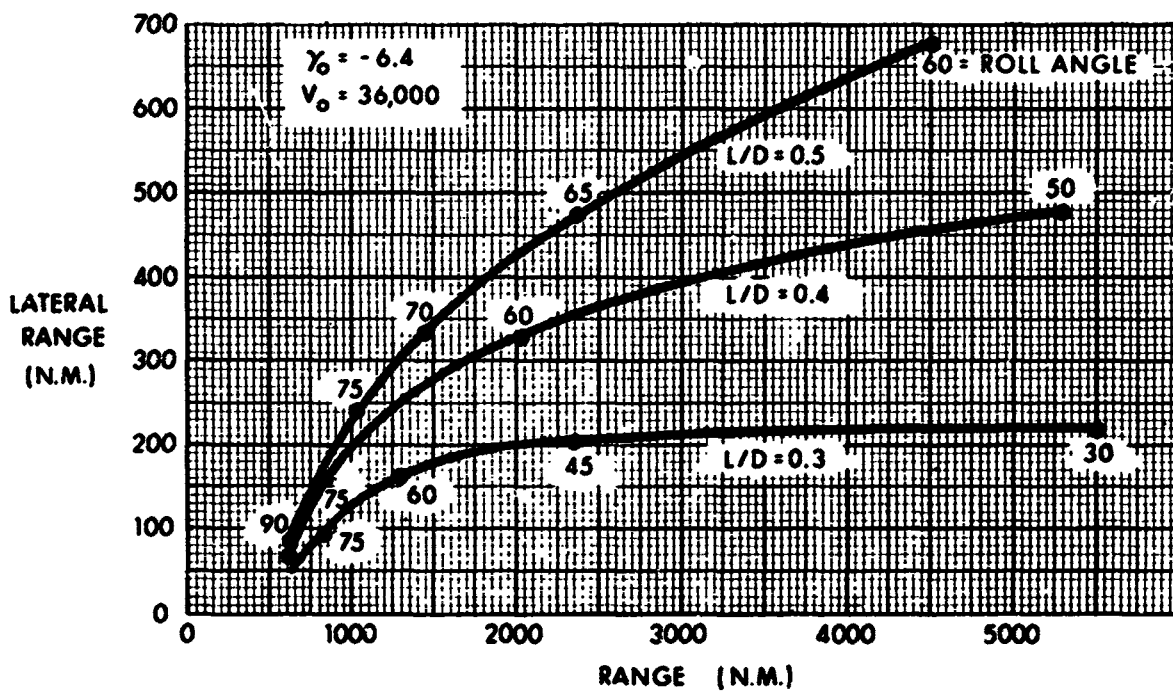


Fig. 2-3 Maximum lateral range.

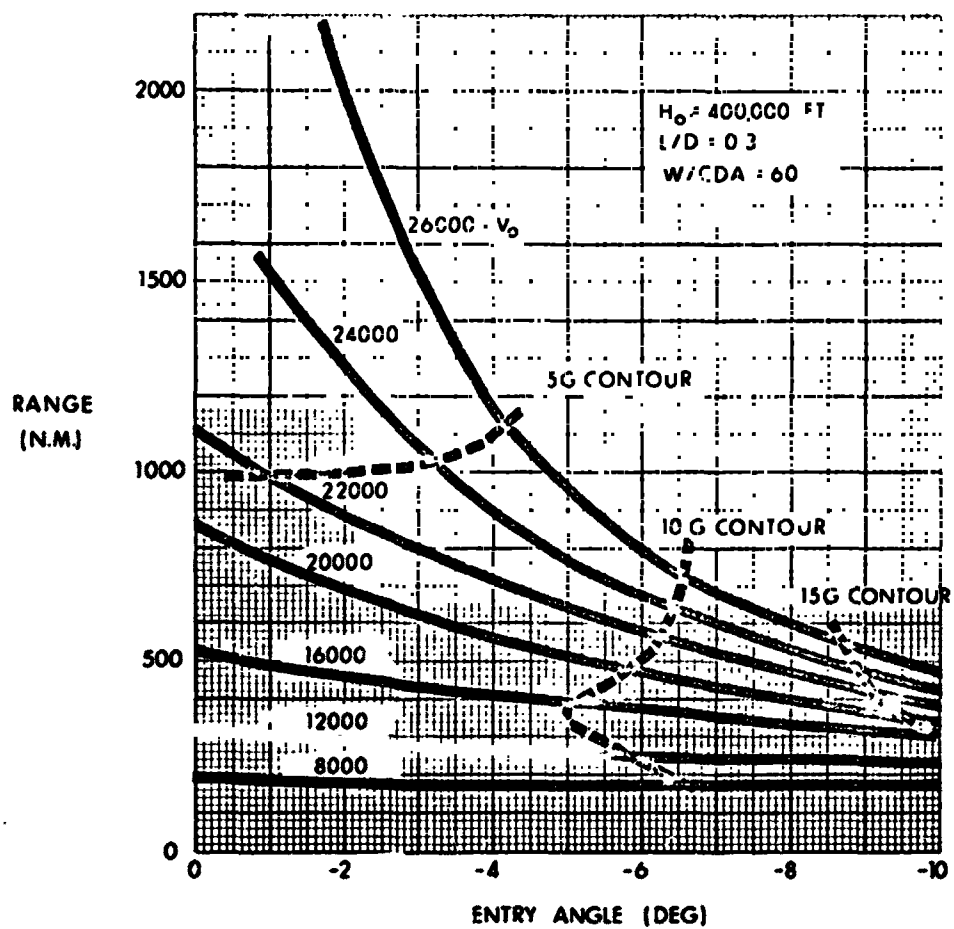


Fig. 2-4 Maximum Range for $L/O = 0.3$

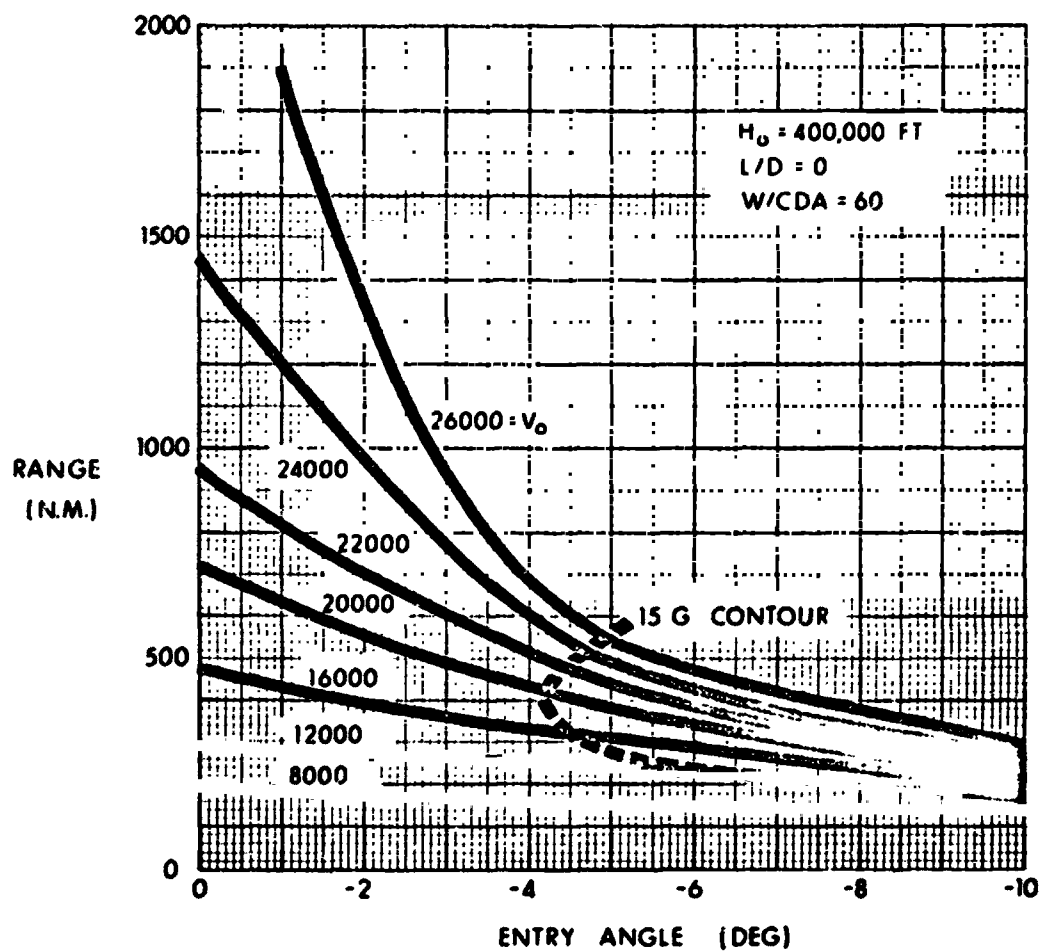


Fig. 2-5 Ballistic Range.

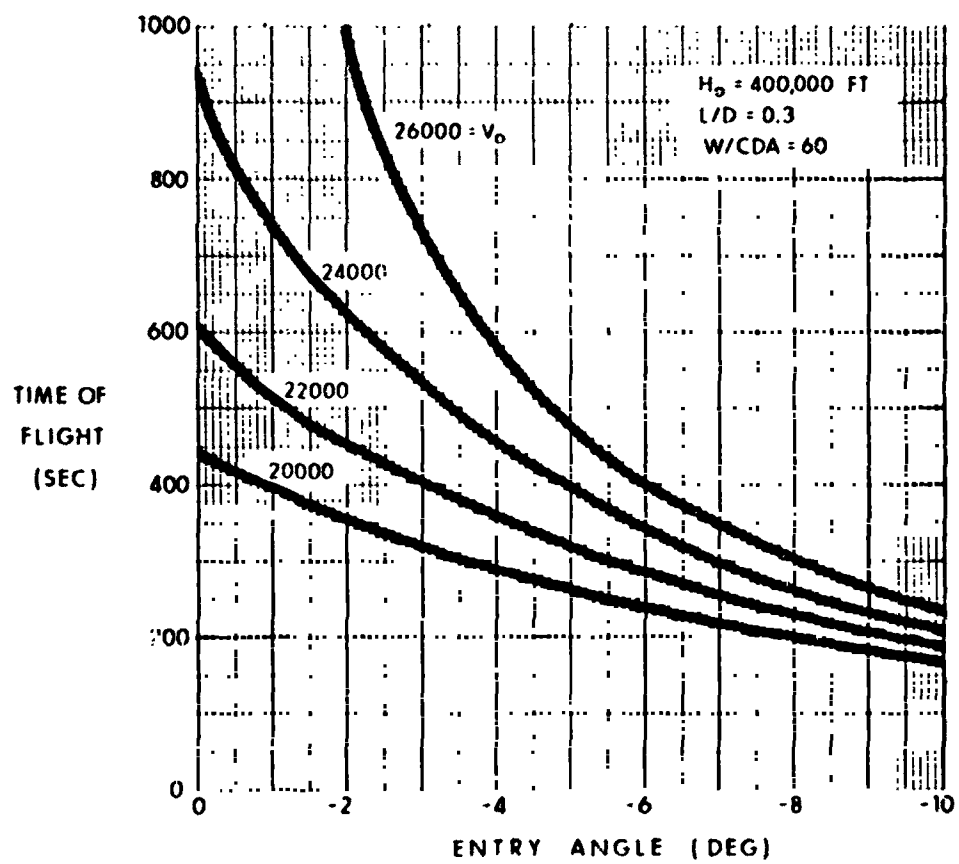


Fig. 2-6 Time of Flight

III DESIGN GOALS

To meet these requirements several goals were set forth to evaluate the various designs that evolved. These are

1. Have large error handling capability
2. Use explicit techniques where possible
3. Adapt to the digital computer which is shared with several other mission phases

The main design goal was to synthesize a system which would steer correctly in spite of large errors in the form of initial condition uncertainties and gyro and accelerometer errors, as well as adapt to large deviations in the atmosphere and vehicle aerodynamic characteristics. Two distinct types of errors are encountered. The first is a navigation error, or lack of knowledge of position and velocity. This type of error is largely uncontrollable. That is, there is not much chance of reducing the position or velocity error without more measurements. The final miss will be at least the initial uncertainty propagated through the entry trajectory by the navigation equations. However, as described in Appendix E, very large uncertainties can be reduced by monitoring the acceleration build-up.

A second and more serious error is designated a "steering error". This error is a miss of the indicated target due to improper control action based on imperfect data. Early in the flight, more particularly in the critical up-control phase, an imperfect altitude rate signal, for example, will cause a range deviation so large that the final phase cannot correct for it. That is, in the critical early portion of the flight an error will cause the vehicle to fall outside the "foot print" and a huge miss results.

The central goal of this steering design was to find a scheme to reduce this "steering error". As will be described, a self-generated reference trajectory in the critical up-control phase has this effect. The reference trajectory in a sense weights all the input variables, thus not allowing any one variable to cause a large deviation.

Secondly, gains to control to this reference trajectory have been chosen to minimize the miss distance in the presence of noisy inputs. This is done on a statistical basis and is described in more detail in Reference 8. This type of performance criterion, i.e. maximum adaptability to errors, would appear to be more desirable than most of the criteria seen in the optimal control literature today. Much more work can be done along these lines on the entry problem.

IV GUIDANCE DESCRIPTION

General

A typical entry is shown in fig. 4-1 to illustrate the main features of the steering design. This is an acceleration versus velocity plot such as has been proposed for the monitor display.

Initially the vehicle is at point (1). Starting at point (1), the lift is directed up. Then the acceleration builds up and the velocity decreases until a point near peak acceleration, detected by a threshold altitude rate, is reached, point (2). Variations in this initial policy will be described in the detailed discussion. At point (2) a constant drag control is started. At the same time a range prediction is made. This calculates the range for constant L/D flight starting at present drag and velocity, and continuing the flight at constant L/D. Constant drag control is maintained until the range prediction is within 25 n.m. of the desired range. When this occurs, point (3), control is shifted to a self-generated reference trajectory that goes to the edge of the atmosphere, point (4). A ballistic phase is then maintained until the acceleration again builds up, point (5). Finally, steering to the landing site is accomplished by using a prestored reference trajectory, shown as a dotted line.

Very short ranges omit the up-control portion, and very long ranges omit the constant drag portion. Special cases such as an abort from orbit would start directly in the final phase.

Heating and monitor considerations led to selecting this type of trajectory. A high heating rate is desirable because it leads to a low integrated heat load, and the heat load sizes the heat shield. A trajectory with a constant drag portion tends to have a high heat rate because the initial stay in the atmosphere is prolonged. The reduction in heat load is more dramatic in the shallow entries where the constant drag level is larger than the drag at pull-out. In the limit, a trajectory in which the up-control portion is delayed as long as possible would have the least heat load. This extreme delay is not practical, of course, since there would be great danger of falling short of the target.

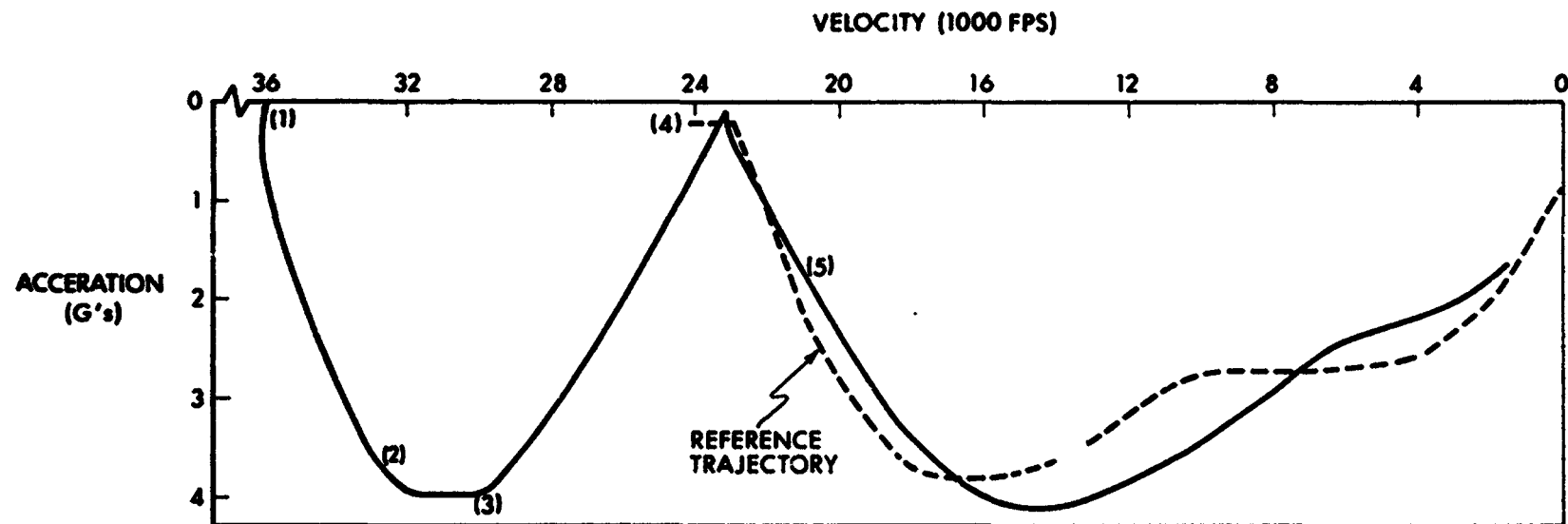


Fig. 4-1 Typical entry trajectory.

The monitor function is to detect uncontrolled skip-outs at greater than satellite velocity. The trajectory in which the up-control portion has been delayed is more easily distinguished from an uncontrolled skip-out than is one with no delay. This is true whether the monitoring function is accomplished by means of a trace on an acceleration-velocity plot as has been proposed by North American Aviation, or by a meter displaying rate of change of acceleration with velocity, dA/dV , as has been proposed by the Ames laboratory of NASA. Since the maximum range has been decreased to 2500 n.m., the monitor task has been greatly simplified. This is because the exit velocity for a 2500 n.m. trajectory is much less than that for a 5000 n.m. trajectory.

Input Variables

The input variables to the steering equations are fixed by the inertial measurement unit which is shared with other mission phases. The basic input is integrated acceleration generated by the PIPA-s (Pulsed Integrating Pendulous Accelerometers). This along with the initial condition of position and velocity, the target location, and the location of the earth North Pole vector, $\bar{U}_Z$, are the basic inputs.*

There are several choices on how to rearrange these basic inputs. The derived variables that have been chosen are:

- D = total acceleration
- T = time from start of entry
- $\bar{R}$ = position vector
- $\bar{V}$ = velocity vector
- $\bar{R}_T$ = target vector
- $\dot{R}$ = altitude rate

Acceleration is preferred to altitude. The acceleration provides a measure of the pressure altitude, and is less susceptible to variations in atmospheric density and vehicle aerodynamic characteristics. Also, no requirement is made on the inherently divergent altitude channel of the inertial measurement unit.

* Notation peculiar to this report is in Appendix I.

All the other choices are straight-forward except for that of altitude rate. The altitude rate signal is subject to large biases because the direction of the position vector is not known precisely. See the detailed discussion in Appendix D. The alternative, rate of change of drag with velocity (dA/dV) is a noisy signal. The noise is due both to vehicle oscillations and the quantization in the PIPA-s. Shown in fig. 4-2 is an estimate of this noise level due to vehicle oscillations. The amplitude of the oscillation is mainly a function of the dead zone in the rate damper channel of the Stabilization and Control System (SCS).

Altitude rate is chosen as the lesser of two evils. The steering equations have been designed to accomodate large biases in this signal. Many schemes that were studied would have a large miss because of this error. The drag rate signal did not cause unusually large steering errors but did cause excessive roll control system fuel consumption particularly at the lower drag levels. The vehicle would alternate between zero and 180 degrees roll angle following the noise on the drag signal. A fairly sophisticated filter was required to smooth this signal.

The drag rate information is better used to correct the bias in the smoother altitude rate signal. One possibility for this is described in Appendix F.

Computer Logic

The flow graph in fig. 4-3 shows the computer logic. This logic is entered every two seconds, and flow is directed to the appropriate branch by the mode selector. The final result is a roll command sent to the SCS by means of the coupling and display unit (CDU).

The Initialization Section, entered once at the start of entry, does the necessary initialization of variables, switches, etc.

The Navigation Section updates the position and velocity vectors with acceleration data by using the so-called "average-g" integration.

The Targeting Section calculates the range and lateral range to the landing site which is projected ahead by the earth rotating through an estimated time of flight.

4-5

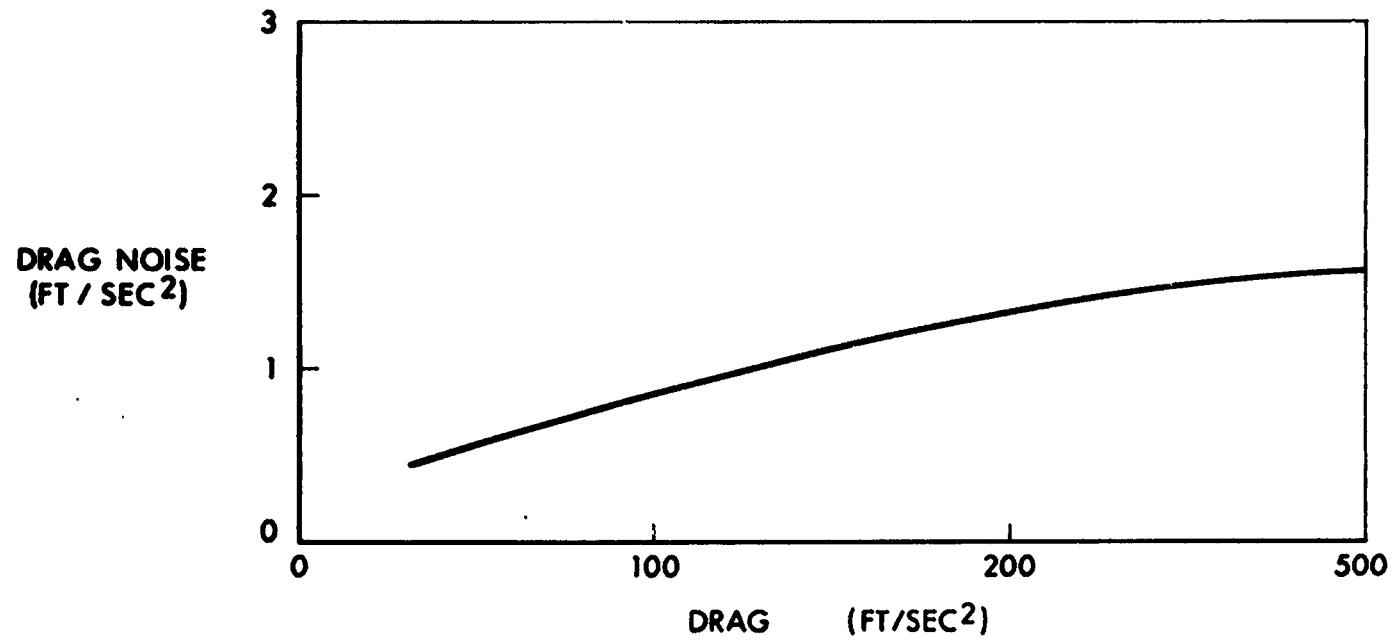


Fig. 4.2. Drag noise due to angle of attack oscillations

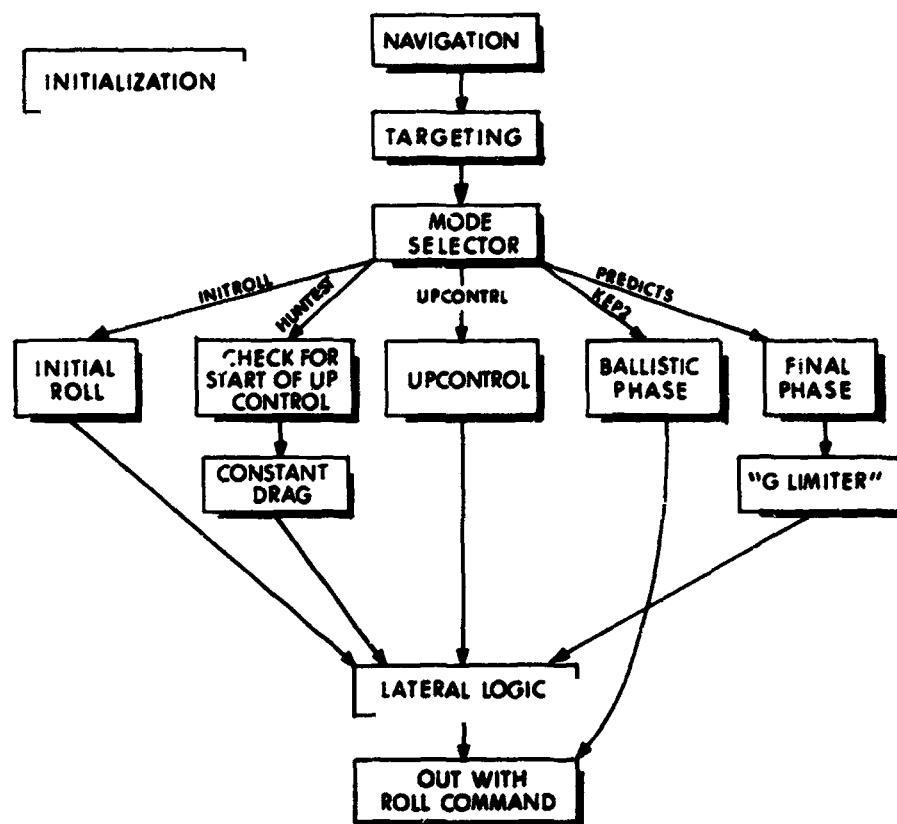


Fig. 4.3. Computer Logic

The Mode Selector selects the appropriate branch. In the diagram, the branches are arranged from left to right as they would be selected in time-sequence by the Mode Selector.

The Initial Roll Section holds constant roll angle, down-lift for shallow entries and up-lift for steep entries, until safe capture by the atmosphere is assured and ranging starts.

The Hunttest Section checks to see if the predicted range of a constant L/D flight from present velocity and acceleration equals the desired range. If the predicted range is long, the Constant Drag section is entered. If the predicted range is within 25 n.m. of the desired range, the Up-control Section is entered.

In the Up-control Section the vehicle is steered to the edge of the atmosphere by using a self-generated reference trajectory.

The Constant Drag Section holds constant acceleration with a simple linear proportional control.

The Ballistic Phase Section holds a constant roll command. Pitch and yaw commands are also generated because the aerodynamic stability is inadequate in this low dynamic pressure region.

The Final Phase Section steers to the landing site by using a prestored reference trajectory.

The G-Limiter Section modifies the roll commands where needed so that the limit acceleration will not be exceeded.

The Lateral Logic Section periodically switches the roll command from one side to the other so that one control variable, roll angle, can control both range and lateral range.

Initialization

The Initialization Section sets up the computation cycle by setting certain initial variables and branches in the logic. The input to this section are the initial position and velocity vectors, the initial target vector all in earth-centered inertial coordinates, and the corresponding timing mark. Also as an input is an initial estimate of the entry angle so that the initial roll attitude may be set.

The vectors $\bar{R}_{TE}$, $\bar{U}_{TR}$, and $\bar{W}_E$ are calculated so that the target position may be updated with the earth's rotation. Also, an initial calculation is made of the range, THETA, and the lateral range, LATANG.

The lateral logic parameter is set so that the initial lift will be toward the target.

$$K2ROLL = -SGN(LATANG)$$

The address of the starting phase is set to INITROLL. At INITROLL the decision is made if the particular trajectory is an abort case.

Other parameters are set to their initial values of zero. These are all the switches and K1ROLL.

Navigation

The "average-g" method of navigation is used to update position and velocity. The main idea is that the average gravity acceleration over the time interval is used to incorporate the velocity increment measured by the PIPA-s.

The computation cycle proceeds as follows: first the velocity increment is read as $\bar{D}ELV$. Then the position vector is updated by using the gravity acceleration corresponding to the position vector at the start of the computation cycle.

$$\bar{R} = \bar{R} + \bar{T}EM DT$$

where

$$\bar{T}EM = \bar{V}I + DT \bar{G}/2 + \bar{D}ELV/2$$

The gravity acceleration at the end of computation cycle is then computed using this position vector.

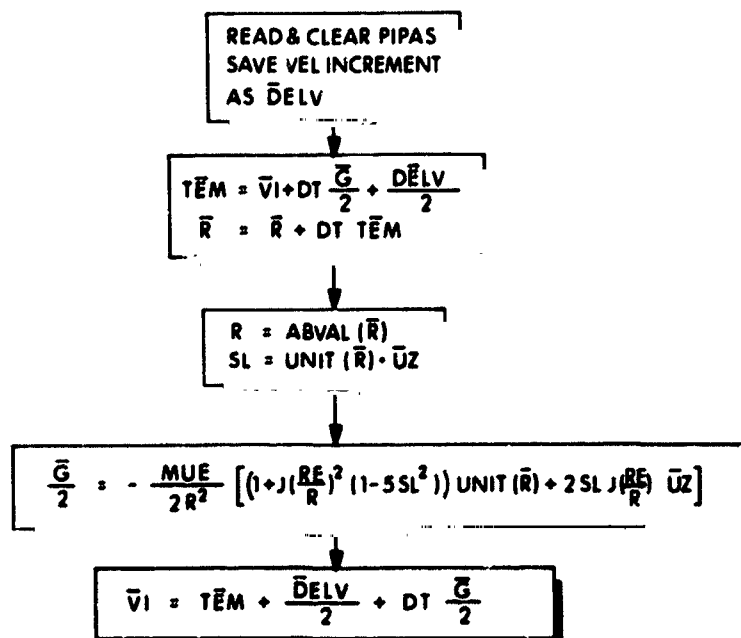


Fig. 4.4. "Average-g" Navigation

$$\bar{G} = -\mu E / 2 R^2 ((1 - J(RE/R)^2 (1 - 5 SL^2)) \text{UNIT}(\bar{R}) + 2 SL J(RE/R)^2 \bar{U}Z)$$

where

$$R = \text{ABVAL}(\bar{R})$$

SL = sine of Geocentric Latitude

$$= \text{UNIT}(\bar{R}) \cdot \bar{U}Z$$

Note that the second spherical harmonic coefficient, J, is used to represent the oblate earth. Finally, the velocity is calculated using the average of the two gravity acceleration vectors by

$$\bar{V}I = \bar{T}EM + \bar{D}ELV/2 + DT \bar{G}/2$$

A thorough discussion of this method is given by R. Bairnsfather in Reference 7, where he presents the effects of round-off and truncation on computational accuracy. The errors due to these effects are shown to be in the order of a few feet for the average entry trajectory.

He also shows that the errors introduced in computing velocity by the approximate representation of the oblate earth are less than the eight decimal digit precision of a double precision AGC number.

Targeting

This section processes the position and velocity vectors generated by the Navigation Section to get the range and lateral range to the landing site as well as certain control parameters.

The control parameters are

$$V = \text{ABVAL}(\bar{V}), \text{ total velocity either relative or inertial}$$

$$VSQ = V^2 / VSAT^2, \text{ normalized square of velocity}$$

$$LEQ = (VSQ - 1) GS, \text{ gravity plus centripetal accelerations}$$

$D = ABVAL(DELV)/DT$, total acceleration

$\dot{R} = \bar{V} \cdot \text{UNIT}(\bar{R})$, altitude rate

$\bar{UNI} = \text{UNIT}(\bar{V} * \text{UNIT}(\bar{R}))$, unit normal to trajectory plane

Initially the velocity vector is calculated as the inertial value, V_I . But late in the flight, when V is less than V_{MIN} , the velocity vector is calculated as a velocity relative to a fixed altitude above the rotating earth by

$$\bar{V} = \bar{V}_I - KWE \bar{U}_Z * \text{UNIT}(\bar{R})$$

This decision is marked by the switch RELVELSW. At the same time, the target is no longer projected ahead through an estimated time of flight, but the range is calculated to the instantaneous location of the target. At these low velocities it does not make sense to chase a target going at earth rate, but rather we steer in coordinates fixed to the rotating earth.

The target vector is rotated through an angle WT by the equation

$$\bar{U}_{RT} = \bar{U}_{RT0} + \bar{U}_{TR} (\cos WT - 1) + \bar{R}_{TE} \sin WT$$

where

$\bar{U}_{RT0}$ = initial target vector

$\bar{R}_{TE} = \bar{U}_Z * \bar{U}_{RT0}$

$\bar{U}_{TR} = \bar{R}_{TE} * \bar{U}_Z$

Figure 4-6 is the appropriate diagram. $\bar{U}_{RT0}$, $\bar{U}_{TR}$, and $\bar{R}_{TE}$ are set up in the Initialization Section.

The angle, WT , through which the initial target vector is rotated is based on the time of flight which is estimated in one of three different ways. Initially, at supercircular velocities

$$WT = WIE (KTETA \text{ THETA} + T)$$

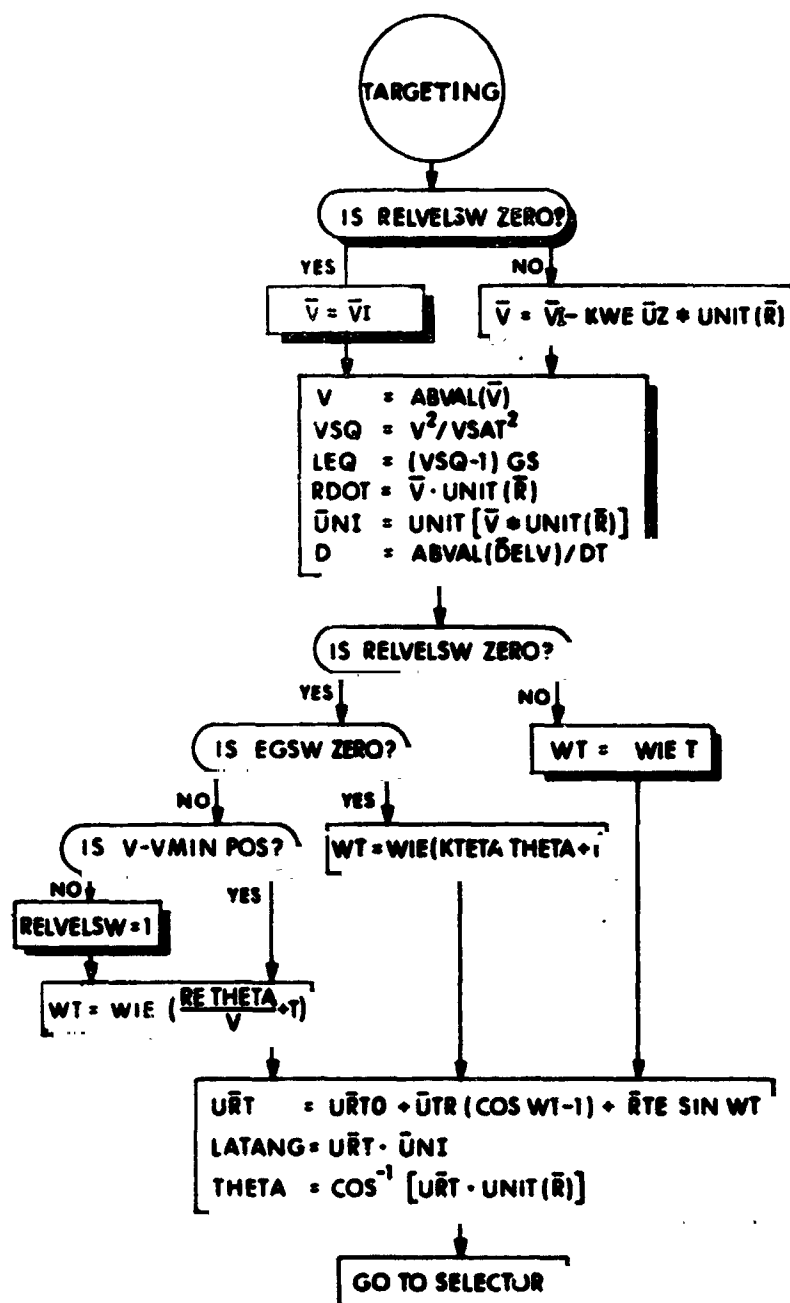


Fig. 4.5. Targeting

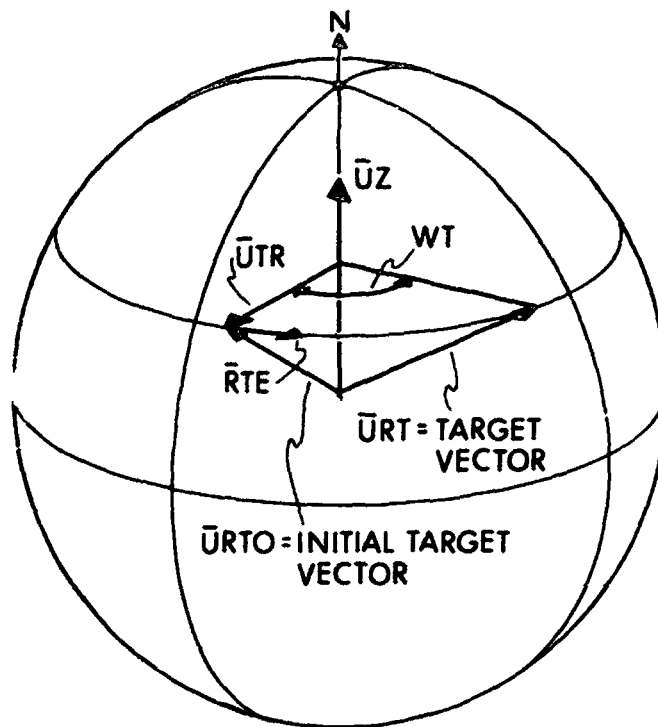


Fig. 4-6 Projection of target vector through estimated time of flight.

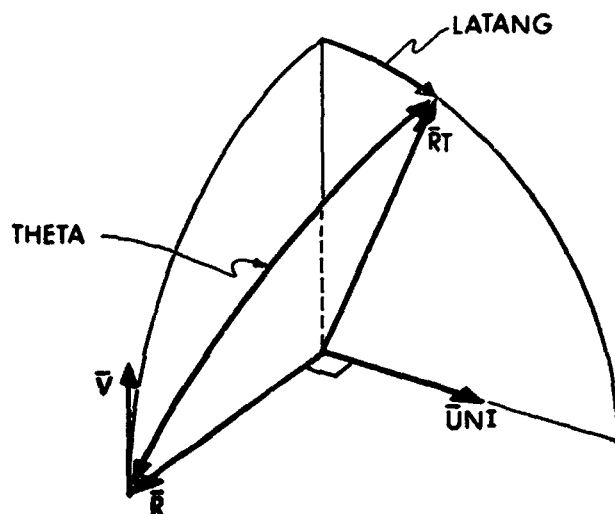


Fig. 4-7 Range and lateral range.

The time of flight is approximately proportional to the range-to-go. This assumes flight at constant velocity, $KTETA$ approximately equals $RE/VSAT$. An examination of the guided trajectories in Section V shows that this assumption is reasonable.

During the first part of the final phase

$$WT = WIE (THETA RE/V + T)$$

The time of flight is calculated assuming the rest of the flight will be at the present velocity. It is no longer fair to assume flight at satellite velocity.

Finally, when relative velocity is used near the very end of the flight, the target is not projected ahead. That is, we steer the present position of the target by using $WT = WIE T$.

The lateral range is calculated by

$$LATANG = \bar{U}RT \cdot \bar{U}NI$$

Small angles are assumed since the right hand side of the above equation defines the sine of the lateral range.

The range is calculated by

$$THETA = ARCCOS(\bar{U}RT \cdot UNIT(\bar{R}))$$

See fig. 4-7. If we go past the target, detected by $\bar{R}T \cdot \bar{R} \cdot \bar{U}NI$ less than zero, the steering is disabled and a 180 degree roll is called. This logic is performed only in the final phase.

The range formula is unambiguous for ranges up to 180 degrees. If ranges greater than half way around the earth are ever contemplated, additional logic would be required to allow for this possibility. Likewise the lateral logic would have to be changed since all great circles converge at a point 180 degrees away from the present point.

The ARCCOS function is not very accurate for arguments near one. The algorithm for this function has been modified to improve the accuracy by making use of the triple precision result of a double precision multiplication. Let x equal the argument of the ARCCOS. If $1-x$ is less than $1/16384$, i.e. the high order part is zero, the quantity $1-x$ is shifted left 13 places and the ARCCOS is approximated by

$$\text{ARCCOS}(x) = \text{SQRT}(2(1-x))$$

Initial Roll

The Initial Roll Section holds a constant roll attitude until the sensible atmosphere is detected (at .05 g). At this time INRLSW is set to one so that this branch will not be entered again. Then up-lift is called and the final phase is entered if the velocity is low, less than VFINAL. If the velocity is high, a test is made to determine the position in the entry corridor. Down-lift is called if the entry is shallow. This is detected when the velocity is greater than

$$V_{\text{FINAL}} - K_{44} (\dot{R}/V)^3$$

This curve, shown in fig. 4-8a, is parallel to the overshoot boundary curve defined at the .05 g level.

As described in Appendix D, a shallow entry angle is accompanied by a positive $\dot{R}$ error. This error would indicate an even shallower entry. The test, therefore, would call for the proper lift direction even in the presence of very large errors.

This lift direction is then maintained until the acceleration exceeds K_A . Then the L/D command is set to LAD. This command is held until the altitude rate is less than a threshold altitude rate, VRCONTROL, at which time the next phase is started.

K_A is fixed at 2 g's for lunar entries and .2 g's for the 202 case, but may vary for some of the other flight tests.

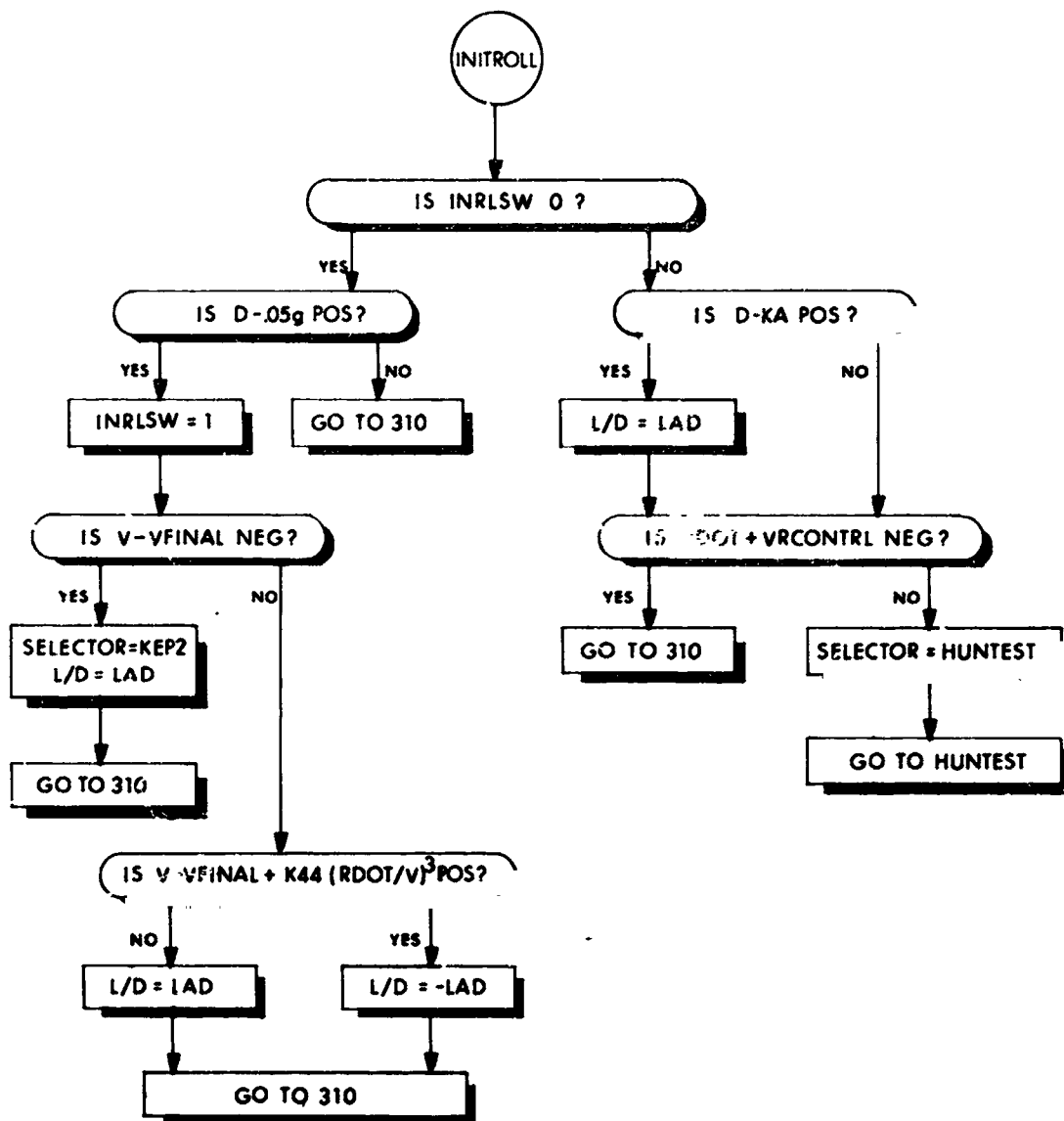


Fig. 4.8. Initial Roll

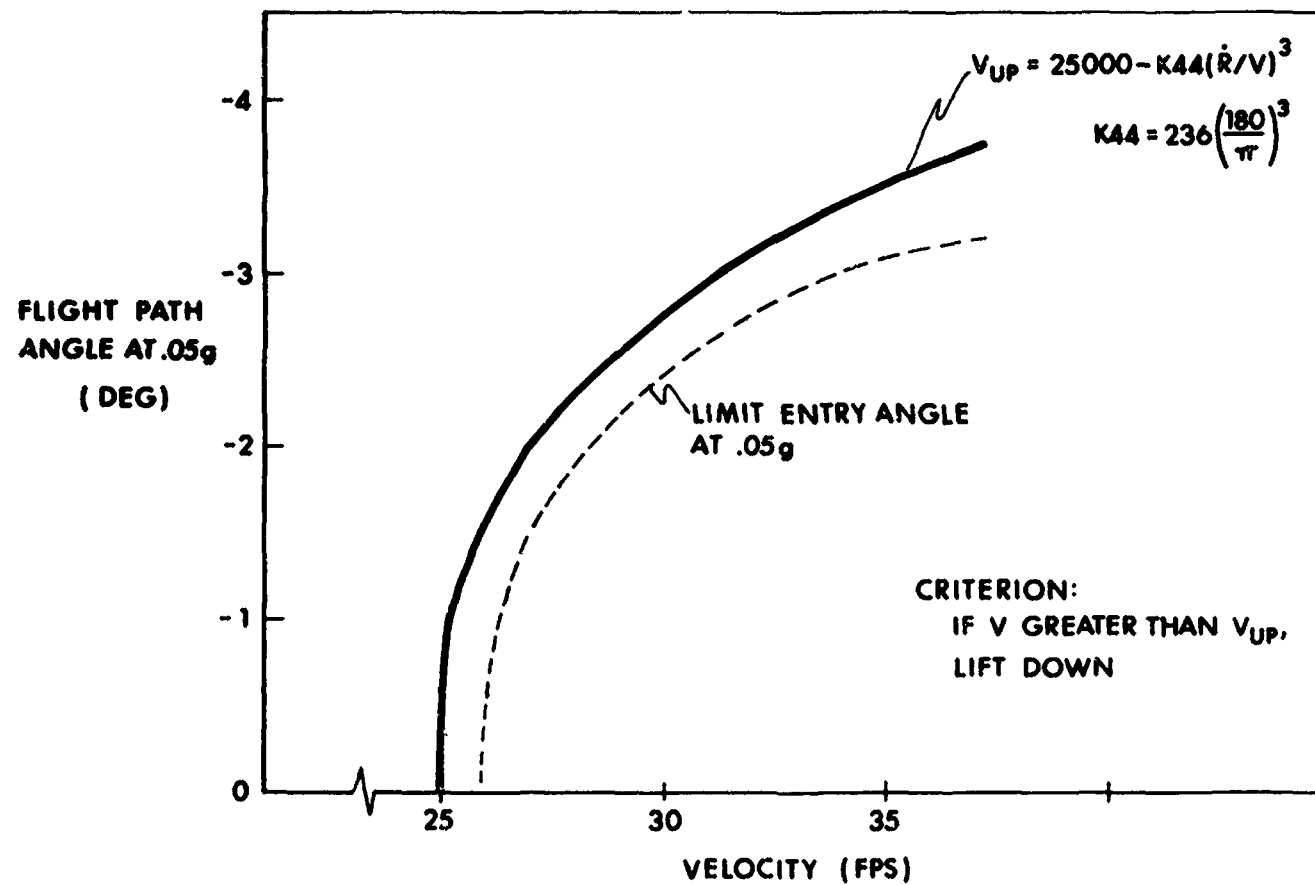


Fig. 4-8a. Criterion for Up- or Down-Lift

A more sophisticated policy is being considered for this phase. This policy would examine the acceleration build-up to determine where the vehicle is in the entry corridor, and then direct the lift accordingly. So far however, the simple roll policy appears to be adequate.

Huntest

The Huntest Section checks to see if a constant L/D policy from present conditions will give the desired range. If so, range control is started using a self-generated reference trajectory. If the range is longer than the desired range, control is shifted to a constant drag controller. The reference trajectory, which approximates constant L/D flight, is a parabola relating drag and velocity. The predicted ranges are represented by simple approximate formulae.

The first "subtask" of this section is to project ahead from present conditions to a point having zero altitude rate. This point is a possible starting point for the up-control phase and has a starting velocity V_1 , and a starting acceleration A_0 . If R is negative the starting velocity is calculated assuming flight at maximum L/D until $\dot{R} = 0$.

$$V_1 = V + \dot{R}/LAD$$

The same assumption is used to calculate A_0 , see Appendix A.

$$A_0 = (V_1/V)^2 (D + \dot{R}^2/(2 HS LAD))$$

If R is positive, flight at nominal L/D is assumed from zero $\dot{R}$, and LEWD is used in place of LAD in the two equations above.

This refinement was needed for the 202 mission in which this part of the trajectory is flown at low dynamic pressure and hence for a long time period. The nominal entry for a lunar mission is at a much higher dynamic pressure, and in this case these corrections will be quite small.

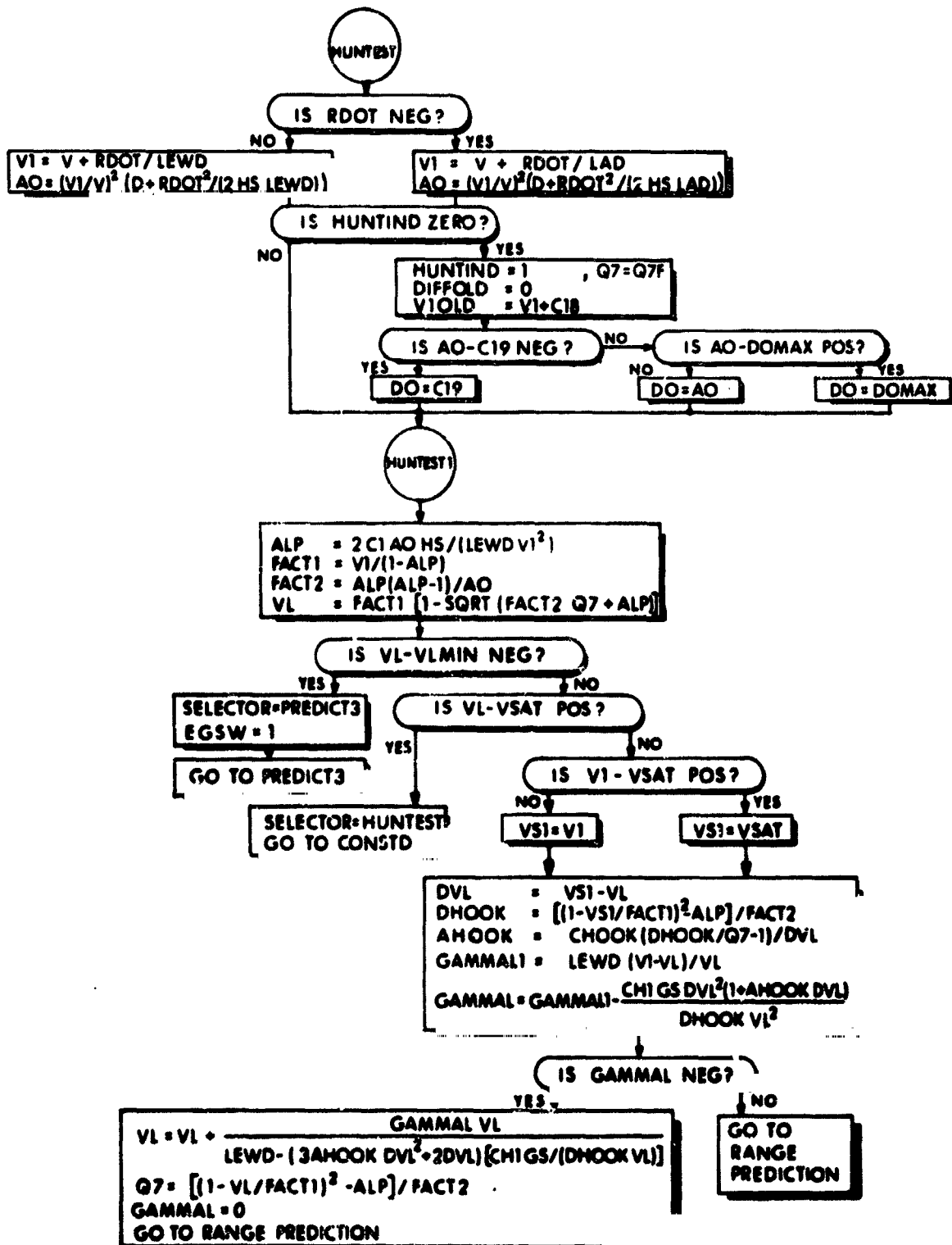


Fig. 4-9. Hunttest

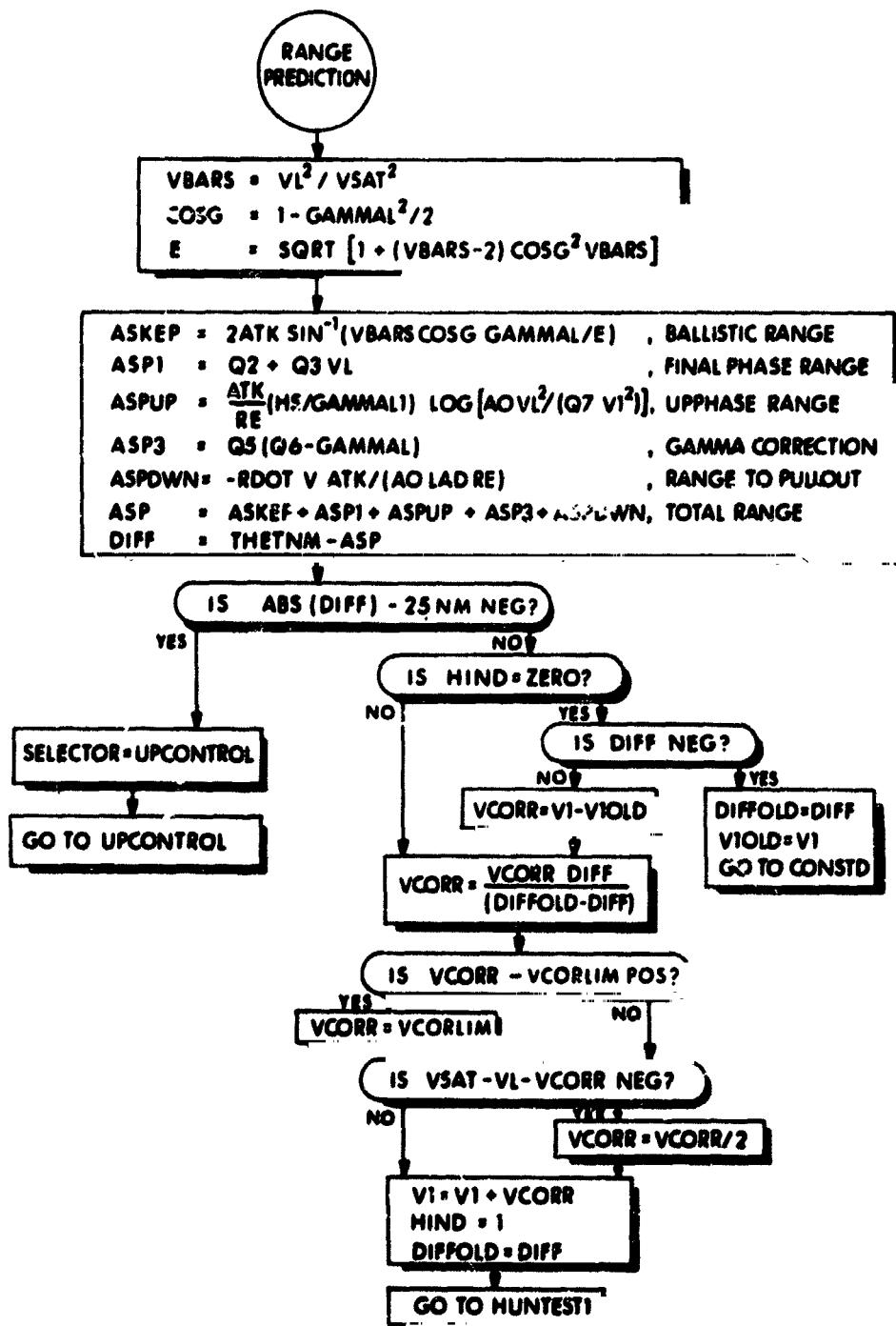


Fig. 4-10. Range Prediction

The next "subtask" of this section is to establish the drag level for the constant drag controller. This is D or C19, whichever is larger, with a maximum value of DOMAX. HUNTIND is a switch to allow this calculation only one time, the first pass through this section. Very short ranges could call for a higher drag level than C19, and logic has been written to allow for this possibility. So far, the logic has not been needed and therefore has not been included.

Next, the exit velocity, VL, is related to the initial velocity and the initial and final drag levels by the relation

$$VL = FACT1(1 - \sqrt{FACT2 Q7 + ALP})$$

where

$$ALP = 2 C1 A0 HS / (LEWD V1^2)$$

$$FACT1 = V1 / (1 - ALP)$$

$$FACT2 = ALP(ALP - 1) / A0$$

$$C1 = \text{shaping constant}$$

As shown in Appendix A, this relation holds for constant L/D flight if the gravity plus centripetal acceleration is negligible, a good approximation near satellite velocity.

If the exit velocity is too low, less than VLMIN, the program control is shifted to the final phase, PREDICT3. If the exit velocity is greater than satellite velocity, VSAT, program control is shifted to the constant drag controller.

The altitude rate at exit is calculated by a simple linear relation with velocity, with a correction to allow for the neglected centripetal and gravity accelerations.

$$GAMMAL = LEWD(V1 - VL) / VL - CH1 GS DVL^2 (1 + AHOOK DVL) / (DHOOK VL^2)$$

where

$$DHOOK = ((1 - VS1 / FACT1)^2 - ALP) / FACT2$$

$$AHOOK = CHOOK(DHOOK / Q7 - 1) / DVL$$

$$DVL = VS1 - VL$$

$$VS1 = VSAT \text{ or } V1, \text{ whichever is lower}$$

$$CH1, CHOOK = \text{shaping constants}$$

If the gravitation acceleration effect is too great, GAMMAL can be negative, indicating that the desired exit condition cannot be reached. In this case, the exit velocity, VL, is adjusted to the zero flight path angle condition by

$$VL = VL + GAMMAL VL / (\dot{dR}/dV)$$

where

$$\dot{dR}/dV = LEWD - CH1 GS(3 AHOOK DVL^2 + 2 DVL)/(DHOOK VL)$$

And the acceleration at exit, Q7, is adjusted to correspond to this new VL by

$$Q7 = ((1 - VL/FACT1)^2 - ALP)/FACT2$$

These two variables (GAMMAL and VL) are enough to calculate the predicted range ASP as the sum of five components, each represented by simple approximate formulae, derived in Appendix G.

$$ASP = ASPDOWN + ASPUP + ASKEP + ASP1 + ASP3$$

$$\begin{aligned} ASPDOWN &= \text{range to pull-out (where } R = 0) \text{ in n.m.} \\ &= - R V ATK / (A0 LAD RE) \end{aligned}$$

$$\begin{aligned} ASPUP &= \text{range to exit in n.m.} \\ &= (ATK HS / (RE GAMMAL1)) \ln(A0 VL^2 / (Q7 V1^2)) \end{aligned}$$

$$\begin{aligned} ASKEP &= \text{ballistic range in n.m.} \\ &= 2 \arcsin(VBARS \cos G GAMMAL / E) \end{aligned}$$

where

$$VBARS = VL^2 / VSAT^2, \text{ normalized exit velocity squared}$$

$$\cos G = 1 - GAMMAL^2 / 2$$

$$E = \sqrt{1 + (VBARS - 2) \cos G^2 VBARS}$$

$$\begin{aligned}\text{ASP1} &= \text{final phase range in n.m.} \\ &= Q2 + Q3 \text{ VL}\end{aligned}$$

$$\begin{aligned}\text{ASP3} &= \text{correction to final phase for flight path angle in n.m.} \\ &= Q5(Q6 - \text{GAMMAL})\end{aligned}$$

If the difference between the predicted and desired ranges, DIFF, is less than 25 n.m., control is shifted to the up-control section. If no iteration has been called, HIND = 0, and the predicted range is too great, DIFF is negative, then control is shifted to the constant drag controller. DIFF and V1 are saved to aid in a possible future iteration.

If HIND = 1, an iteration has been indicated. This iteration is started when the desired range is more than 25 n.m. greater than the predicted range. In this case the starting velocity, V1, is altered to cause the predicted and desired range to agree.

$$V1 = V1 + \text{VCORR}$$

where

$$\text{VCORR} = \text{VCORR DIFF} / (\text{DIFFOLD} - \text{DIFF})$$

The VCORR on the right hand side of the last equation is either the last velocity correction or V1OLD - V1 on the first pass through the iteration. No correction greater than 1000 fps is allowed so that the iteration will be well-behaved. Also, the velocity correction is halved if it appears that the exit velocity may exceed satellite velocity on the next pass through the iteration.

Usually no iteration is involved. It is only on the steep entry long range case that an iteration is called. In this case, the very first pass through this section gives too short a predicted range, and V1 must be increased until the range is great enough.

There is some consideration of changing the iteration cases to an iteration on LEWD rather than V1. It is more reasonable to raise the nominal L/D at the present starting point than to find a different starting point where we should have been. At this time it is not decided if the additional programming required is warranted.

Up-control

The Up-control Section steers the vehicle along a self-generated reference to suitable conditions at the edge of the atmosphere. In this section, sensitivity to errors was the determining design factor. The reference trajectory technique was found to be less sensitive to altitude rate errors. This reference is self-generated allowing the desired flexibility. Optimum gains were chosen on a statistical basis to follow this reference. These optimum gains were chosen to minimize the effects of errors.

Drag is the independent variable of this reference. Other designs had velocity as the independent variable. There is no double value in the reference near exit velocity if drag is the independent variable. A second advantage is that the system response is faster to a commanded velocity than to a commanded drag level, thus a tighter control can be maintained.

Also, there is no iteration in most cases to get this reference. This gives better response than did previous systems because the actual starting condition for the up-control phase is closer to the reference starting condition.

The central equation is

$$L/D = LEWD - KB2 F1(KB1 F1 (\dot{R} - RREF) + V - VREF)$$

where

L/D = commanded lift-to-drag ratio in vertical plane

$LEWD$ = reference L/D

$KB1, KB2$ = optimum constant gains

$F1 = (D - Q7)/(A0 - Q7)$

$VREF = FACT1(1 - \sqrt{FACT2 D + ALP})$

$RREF = LEWD(V1 - VREF) + RCORR$

$RCORR = CH1 GS((VS1 - VREF)^2 + AHOOK(VS1 - VREF)^3)/(DHOOK VREF)$

Prior to implementing this equation certain tests are made. First, as is common programming practice, tests are made at the start to see if the phase is over. If the drag is less than $Q7$, the minimum drag, the ballistic

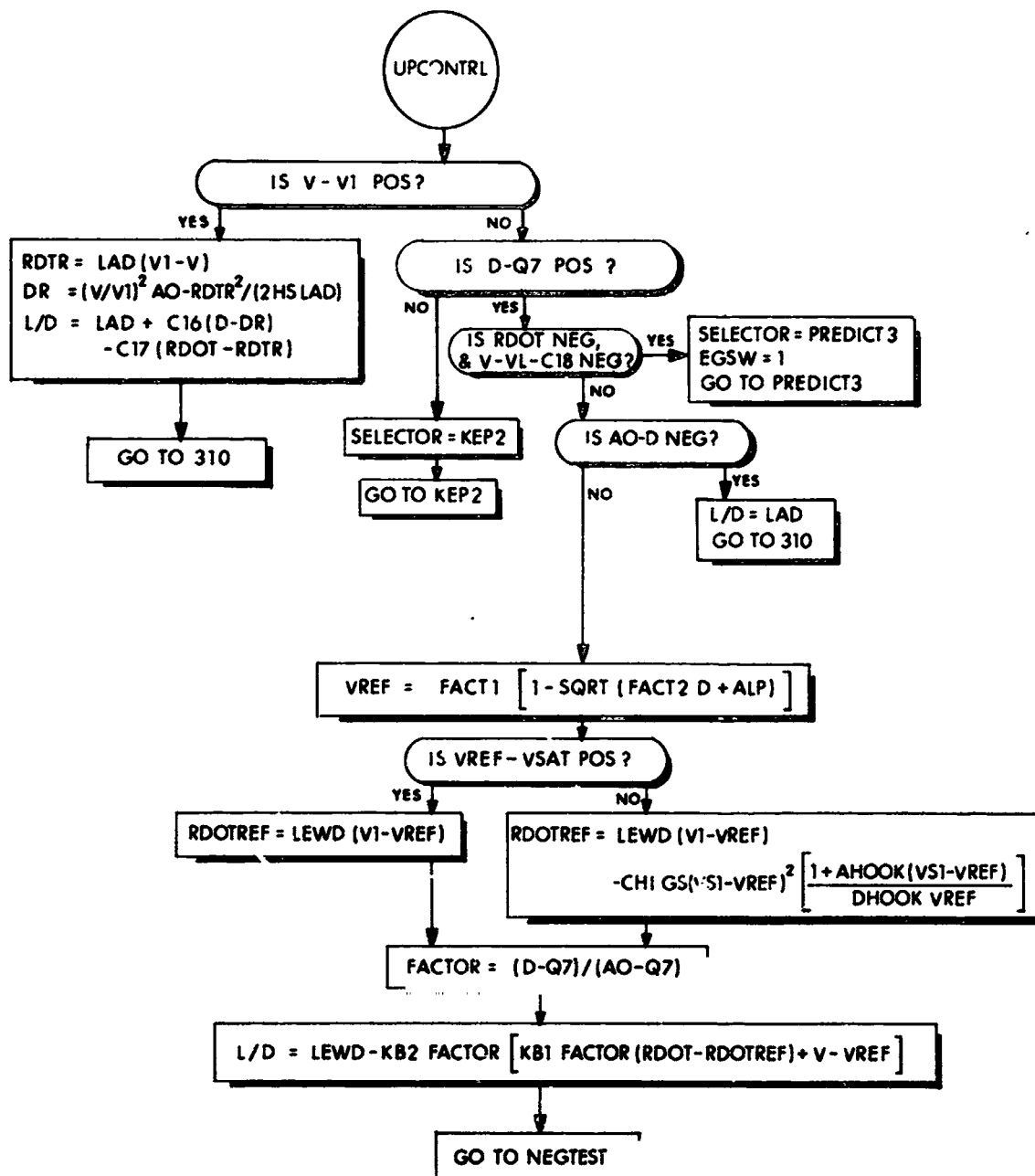


Fig. 4-11. Up-control

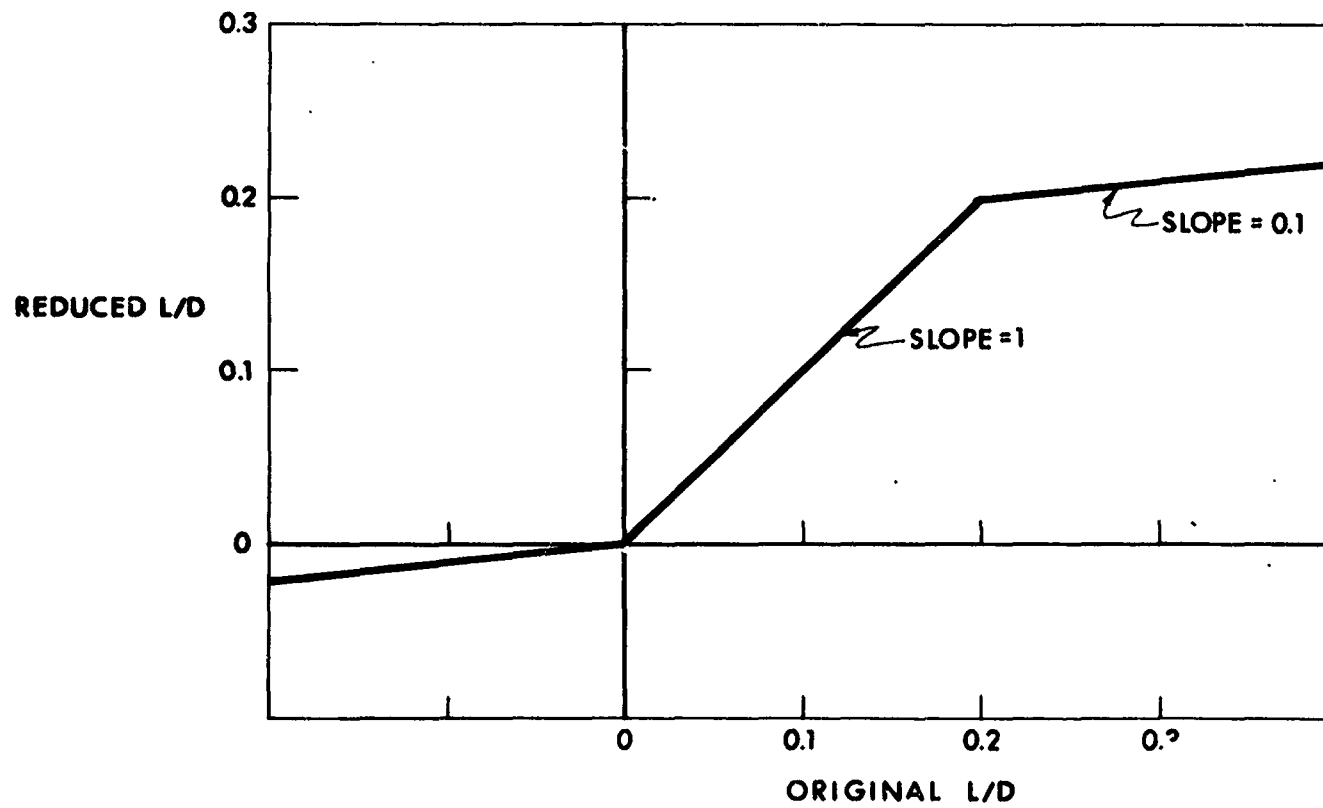


Fig. 4-12. Circuit to Reduce Gain for Large Commands

phase is started. If the altitude rate is negative and the velocity less than $V_L + C18$, the final phase is started. Other tests call for full positive lift if the drag is greater than the starting drag, $A0$, because the reference is not defined at these high drag levels.

The method used to determine the optimum form of Eq. 1, along with the optimum gain parameters, $KB1$, and $KB2$, is described in detail in Reference 8. The objective was to find varying gains, multiplying $(\dot{R} - RREF)$ and $(V - VREF)$ so that exit conditions would result in minimum dispersion at the target. The sources of error considered were uncertainties in altitude rate and velocity and deviations in atmospheric scale height. The optimization procedure consisted of the following four steps. First, an approximate set of equations of motion were derived, in which drag, rather than time, is the independent variable. Second, these approximate equations were linearized about a reference trajectory. Third, a set of linear equations (variance equations) which describe the statistical behavior of the system for an ensemble of cases were derived from the former set. Finally, a computer program containing the variance equations was used to vary the gains in an iterative steepest-descent, fashion so that the projected dispersion at the target was minimized. The resulting gains are optimal for one particular range (2500 n.m.) , but work well for all ranges.

The optimum gains are high values and can lead to a roll angle history with several switches between zero and 180 degrees. To smooth this response, reduced gains are used for large error signals. Figure 4-8 shows the nonlinear circuit that is used.

A short segment of control is made if the velocity is above the starting velocity $V1$. This causes the vehicle to follow a trajectory as if the L/D were LAD , the maximum value. This is done so that there will be no long open loop segment at maximum L/D , a possible problem at the lower drag levels. The control is very similar to the constant drag control.

$$L/D = LAD + C16 (D - DR) - C17 (\dot{R} - RDTR)$$

where

$$RDTR = LAD (V - V1)$$

$$DR = (V1/V)^2 A0 - (V - V1)^2 LAD / (2 HS)$$

Still another test, NEGTEST, will not allow L/D to be negative if the drag level exceeds C20. This is to preclude a lateral switch, rolling through the full down-lift attitude. At these high drag levels, such a maneuver could cause the vehicle to fall short of the target.

Constant Drag

The constant drag controller holds the drag level to D0 with three terms,

$$L/D = -LEQ/D0 + C16 (D - D0) - C17 (\dot{R} + 2 HS D0 / V)$$

The first term, $-LEQ/D0$, is the L/D required for equilibrium. The second term, $C16(D - D0)$, is a constant gain on the drag difference. The third term, $-C17 (\dot{R} + 2 HS D0 / V)$, is a constant gain on the difference between R and R for constant drag.

The gain C16 is designed to give a 90 second period to the equivalent second order system. For fixed frequency this gain should be inversely proportional to the square of drag. The damping gain, C17, is designed to give a damping ratio of .7. This gain should be inversely proportional to the drag level for fixed damping ratio. The governing equation by which these gains were derived can be found by taking perturbations about equilibrium of the constant drag level and neglecting certain terms. See Appendix F. The perturbation equation is

$$\delta \ddot{D} (2D/V + C17 D) + \delta \dot{D} + (C16 \beta D^2 - \beta(V^2/R - G)) \delta D = 0$$

where

$$\delta D = D - D0$$

The natural divergence at supercircular velocities can be noted, as well as the drag dependence of the natural frequency and damping ratio.

Should constant drag control be desired over a wide range of constant drag levels, this drag dependence of the gains could be used.

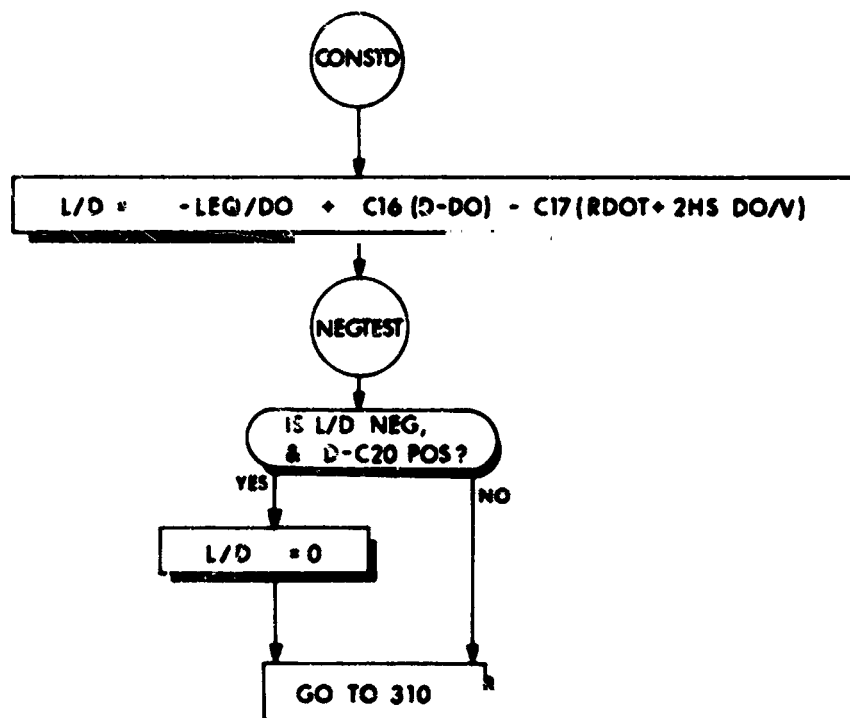


Fig. 4-13. Constant Drag Control

Ballistic Phase

The ballistic phase controls the vehicle attitude in all three axes by commanding gimbal angles. The last roll command generated in the previous phase is held constant. The pitch is commanded to an assumed 20 degree angle of attack with respect to a calculated relative velocity vector. Yaw is commanded to zero sideslip angle with respect to the relative velocity vector. These pitch and yaw commands are generated continuously throughout entry. But the SCS ignores the pitch and yaw commands if the acceleration exceeds .05 g's.

A triad at the relative velocity vector is calculated by

$$\bar{U}VA = \text{UNIT}(\bar{V} - KWE \bar{U}Z * \text{UNIT}(\bar{R}))$$

$$\bar{U}YA = \text{UNIT}(\bar{U}VA * \bar{R})$$

$$\bar{U}NA = \text{UNIT}(\bar{U}YA * \bar{U}VA)$$

A triad at the navigation base is then calculated by

$$\bar{U}BY = \bar{U}YA \cos(\text{ROLLC}) + \bar{U}NA \sin(\text{ROLLC})$$

$$\bar{U}BX = -\text{UNIT}(\bar{U}BY * \bar{U}VA) \sin(13) - \bar{U}VA \cos(13)$$

$$\bar{U}BZ = \bar{U}BX * \bar{U}BY$$

See fig. 4-14.

This triad ($\bar{U}BX, \bar{U}BY, \bar{U}BZ$) is supplied to the subroutine CALCGTA which generates the gimbal angle commands (OGC, MGC, IGC). See Reference 11.

The final phase is started when the acceleration exceeds $Q7 + .5$ fps.

Final Phase

The final phase is based on a stored nominal trajectory. This nominal is made up of six fifteen point tables with velocity as the independent variable. As stated before, the analytic approach is preferred because it has greater

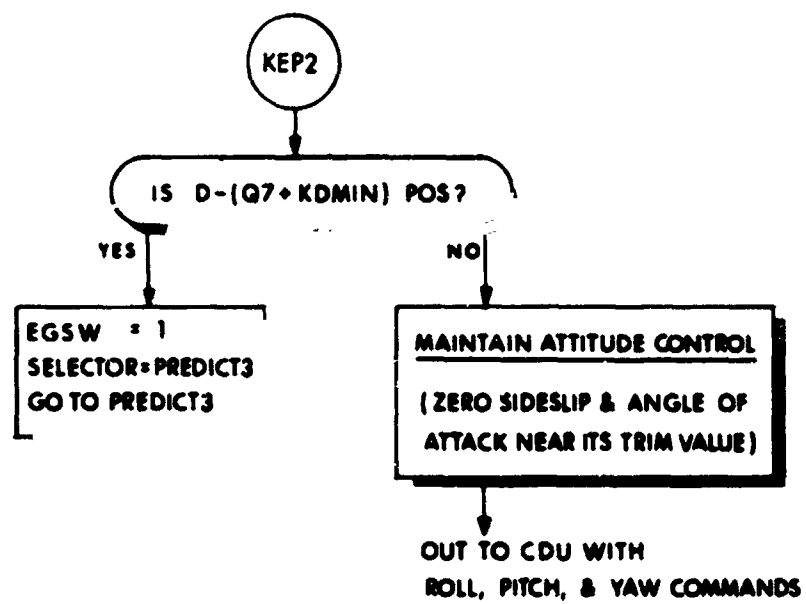


Fig. 4-14. Ballistic Phase

ATTITUDE CONTROL PHASE

Calculates commanded gimbal angles (OGC, MGC, IGC) by computing desired orientation of Nav Base with respect to relative velocity vector.

$$\bar{U}VA = \text{UNIT}(\bar{V} - KWE \bar{U}Z * \text{UNIT}(\bar{R}))$$

$$\bar{U}YA = \text{UNIT}(\bar{U}VA * \bar{R})$$

$$\bar{U}NA = \text{UNIT}(\bar{U}YA * \bar{U}VA)$$

$$\bar{U}BY = \bar{U}YA \cos(\text{ROLLC}) + \bar{U}NA \sin(\text{ROLLC})$$

$$\bar{U}BX = -\text{UNIT}(\bar{U}BY * \bar{U}VA) \sin(13) - \bar{U}VA \cos(13)$$

$$\bar{U}BZ = \bar{U}BX * \bar{U}BY$$

Call CALGTA with ($\bar{U}BX$, $\bar{U}BY$, $\bar{U}BZ$)

Return with (OGC, IGC, MGC).

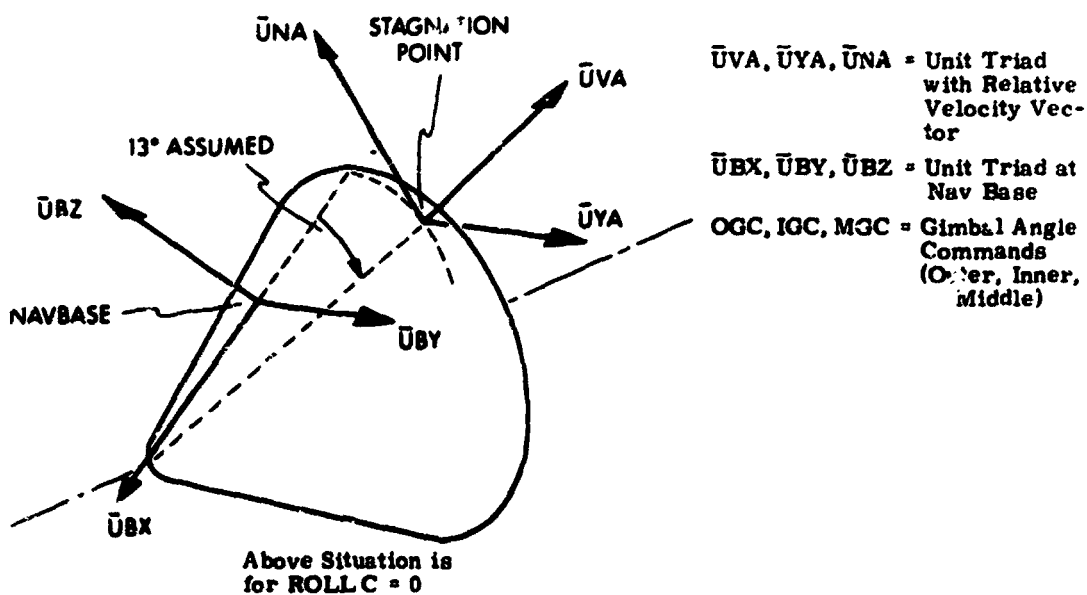


Fig. 4-15

flexibility in adapting to off-design conditions. As a matter of fact, previous designs used simple analytic formulae based on the equilibrium glide concept, but with the present low L/D, equilibrium glide flight is no longer a good approximation. Were some analysis available to represent a near-ballistic vehicle as is the Apollo command module, this would certainly be preferred.

On the other hand, the range calculation is simpler for a vehicle of low capability. Since the vehicle has a smaller band of possible ranges, the analysis need only represent this smaller band. That is, the linear perturbation theory is pushed less far out of the linear range.

The central equation is

$$L/D = LOD + 4 (THETNM - PREDANGL)/F3$$

where

LOD = nominal L/D = .18

THETNM = desired range in n.m.

PREDANGL = predicted range in n.m.

F3 = dRANGE/d(L/D)

The predicted range, PREDANGL, is obtained from a stored table with corrections for drag and altitude rate.

$$PREDANGL = RTOGO(V) + F2(V)(R - RDOTREF(V)) + F1(V)(D - DREF(V))$$

The prestored tables are shown in fig. 4-16. The details of the reference generation are described in Appendix F. Essentially, the reference is a two-dimensional trajectory over a spherical non-rotating earth. The reference L/D is chosen at .18 so as to be in the center of capability for a .3 L/D vehicle. The partial derivatives to provide the drag and altitude rate corrections are solved from linear perturbation equations (the adjoint set) also described in Appendix C. Linear interpolation is used between the stored points. A dummy point is stored at each end to guarantee good behavior of the interpolation. The last eight points of $F3 = dRANGE/d(L/D)$ are multiplied by two. This is to provide reduced gain near the end of the

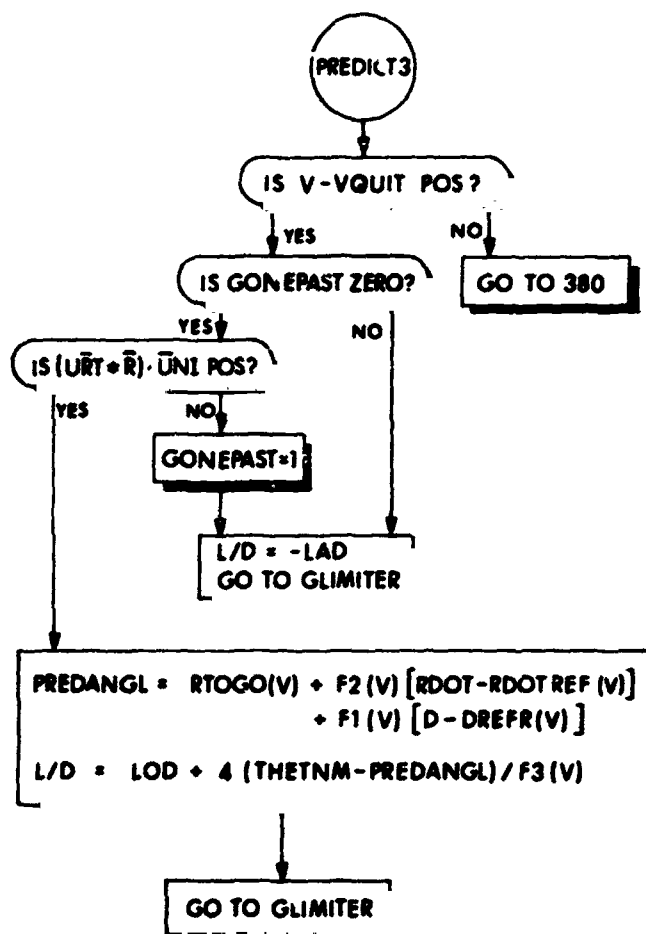


Fig. 4-16. Final Phase

VREF	RDOTREF	DREFR	DR/DRDOT F2	DR/DA F1	RTOGC	DR/DL/D F3
FPS	FPS	FPSS	NM/FPS	NM/FPSS	NM	NM
0	-331	34.1	0	-.02695	0	1
337	-331	34.1	0	-.02695	0	1
1080	-693	42.6	.002591	-.03629	2.7	6.44 x 2
2103	-719	60.	.003582	-.05551	8.9	10.91 x 2
3922	-694	81.5	.007039	-.09034	22.1	21.64 x 2
6295	-609	93.9	.01446	-.1410	46.3	48.35 x 2
8531	-493	98.5	.02479	-.1978	75.4	93.72 x 2
10101	-416	102.3	.03391	-.2372	99.9	141.1 x 2
14014	-352	118.7	.06139	-.3305	170.9	329.4
15951	-416	125.2	.07683	-.3605	210.3	465.5
18357	-566	120.4	.09982	-.4956	266.8	682.7
20829	-781	95.4	.1335	-.6483	344.3	980.5
23090	-927	28.1	.2175	-2.021	504.8	1385
23500	-820	6.4	.3046	-3.354	643.0	1508
35000	-820	6.4	.3046	-3.354	643.0	1508

Fig. 4-17. Final Phase Reference

flight to conserve reaction jet fuel. The higher gain is needed at the start of the phase to control large deviations from the nominal. Linear perturbation theory underestimates the range contribution of large positive deviations of $\dot{R}$. A high gain is needed at the start of this phase to control these cases. An alternate way that has been considered is to include an additional range term proportional to $\dot{R}^2$.

The steering is disabled when the velocity is very low, less than VQUIT. This again is to conserve reaction jet fuel.

Lateral Logic

The lateral logic shifts the lift vector from one side of the vertical to the other. This is done so that one control variable, roll angle, can control both lateral and longitudinal range. A variable dead-zone is calculated of allowable lateral range at the target. Then if this dead-zone is exceeded, the lift is directed to the other side so as to decrease the lateral range.

To this end, the lateral range dead-zone is calculated by the simple approximation $Y = K_{LAT} VSQ$. K_{LAT} is chosen so that Y represents about half the vehicle's lateral range capability.

A bias term, Y_{BIAS} , is added to Y so that there are fewer switches near the end of the flight. When the vehicle's projected lateral range at the target, $LATANG$, exceeds this Y and is increasing, lift is directed to the other side by changing the sign of $K2ROLL$. The sign convention is such that positive roll angle causes positive lateral range.

A special case occurs when the roll angle is within 15 degrees of full positive or full negative lift. In this case, a 15 or 165 degree roll is called if the roll would decrease the lateral range. In this case also, there is a switch if $LATANG$ exceeds $Y/2$.

Also, special provision is made to roll in the shortest direction during a switch. This condition is detected by a negative L/D , and is accomplished by using $K1ROLL$.

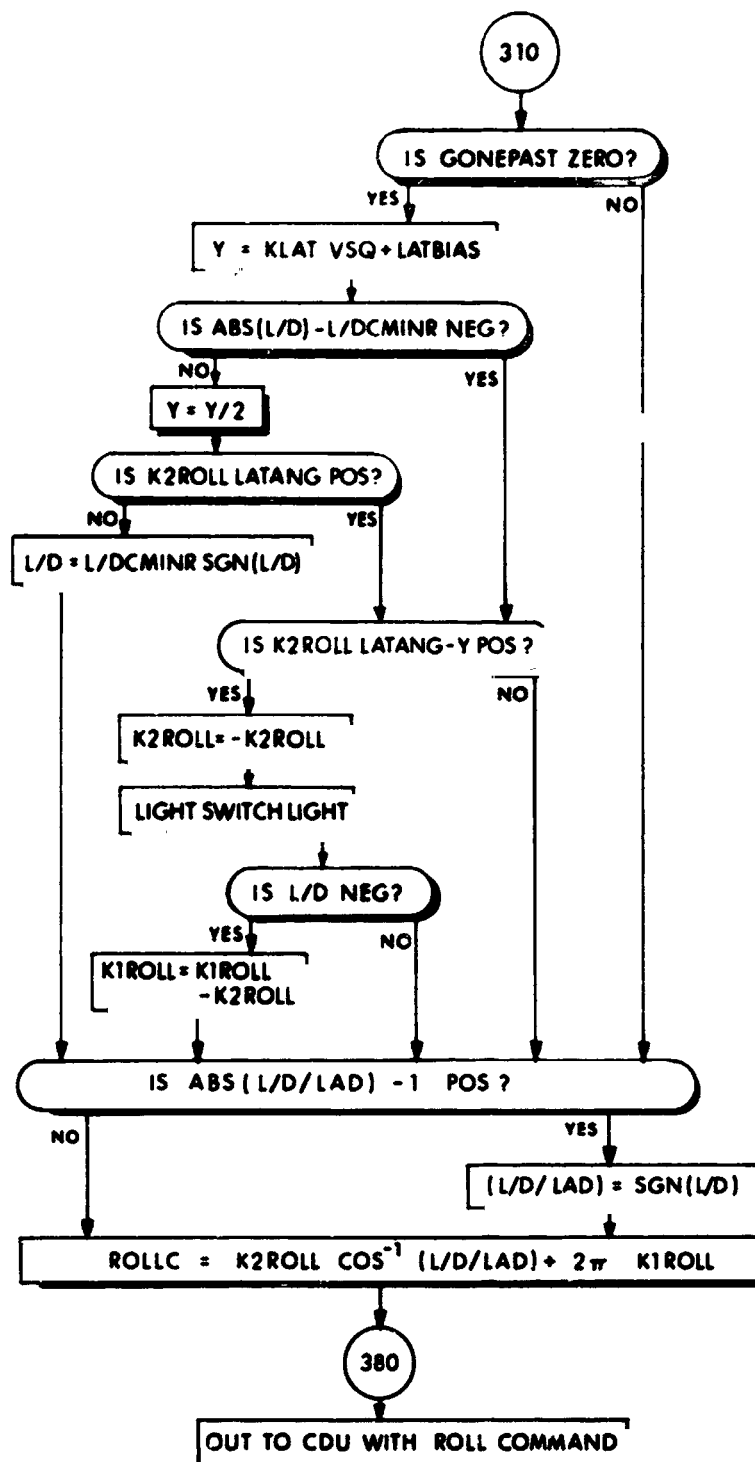


Fig. 4-18. Lateral Logic

In the lateral logic the effect of the low vehicle L/D is also seen. The dead-zone Y must be designed for the minimum expected L/D, and with a higher L/D more lateral switches will occur.

G-Limiter

The g-limiter overrides the commanded roll angle if the g-limit will be exceeded. If the altitude rate exceeds a limit altitude rate, $\dot{R}_1$, full positive lift is called. This limit altitude rate, derived in Appendix H, is

$$\dot{R}_1 = -\text{SQRT}((2 \text{ HS GMAX}/V)^2 + 2 \text{ HS LAD}(\text{GMAX}-D) + 2 \text{ HS LEQ}(\text{GMAX}-D)/\text{GMAX})$$

If the vehicle has this limit altitude rate full positive lift will result in a peak acceleration of GMAX.

No test for g-limiting is made if the drag is less than GMAX/2. And of course full positive lift is called if the drag is greater than GMAX.

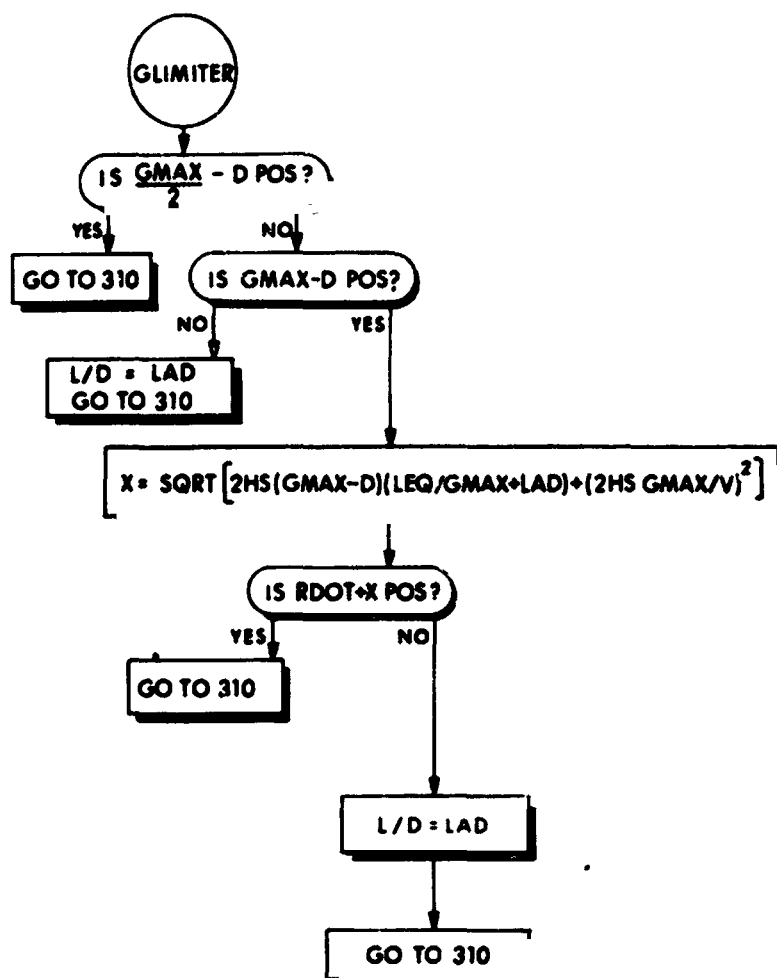


Fig. 4-19. G-limiter

V GUIDANCE PERFORMANCE

Steering Performance

Shown in fig. 5-1 is the guided entry for the nominal reentry for the lunar mission.

The initial conditions are .

$H_0 = 400,000$ ft.

$V_0 = 36,200$ fps

$\gamma_0 = -6$ degrees

Range = 2000 n.m.

Latitude = -12.7 degrees

Longitude = 122.9 degrees East

Azimuth = 61 degrees

The trajectory is terminated at 25,000 ft. near the point of chute deployment.

The vehicle is described by $L/D = .34$, $W/CDA = 66$ psf.

The 1962 ICAO model atmosphere is used. The trajectory is generated with a 4 degree of freedom simulation. The SCS model is the North American Aviation design which includes a 20 deg/sec limit roll rate. The guidance parameters are tabulated in fig. 6-1.

Figure 5-1a shows the altitude, velocity, acceleration and range from start of entry as a function of time.

More interesting is fig. 5-1b which shows the roll angle, lateral range = LATANG, lateral switch limit = Y, and reaction control fuel for the roll channel.

The roll angle time history is the key to the significant events. At point (1), the start of entry, a roll to -15 degrees is made to decrease the initial LATANG which was about 80 n.m. Initially the trajectory plane contained the target, but the target was calculated to rotate about 80 n.m. out of this plane during the estimated time of entry.

At point (2) the altitude rate is less than 700 fps and the constant drag control is started.

At point (3) the reference trajectory has been established and zero roll is called to null out the negative altitude rate that was a part of the constant drag phase.

Point (4) is the start of the reference trajectory.

Point (5) is the first lateral switch. LATANG is seen to change direction. This is after an intersection with the -Y curve which is not shown.

Point (6) marks the start of the final phase. There is a slight discontinuity in LATANG as a different calculation is made of the estimated time of flight.

Points (7), (9), (10), and (11) are lateral switches in the final phase.

Point (8) marks the start of using relative velocity rather than inertial velocity. The limit cycle operation of the SCS can be seen here as well as between points (5) and (6).

The total roll fuel is about 60 seconds of burn.

Eight other trajectories are shown in figs. 5-2 to 5-9 completing a set of three entry angles and three ranges.

The maximum range of 2350 n.m. corresponds to a total range traversed 2500 n.m. when the effect of the earth rotation is included. The minimum range of 1500 n.m. is close to the minimum possible for a shallow entry into a thin atmosphere. The shallow entry angle of -5.2 degrees is near the skip-out boundary for a .3 L/D vehicle entering a thin atmosphere. The steep entry angle of -6.7 degrees is dictated by a maximum possible range for a .3 L/D vehicle entering a more-dense atmosphere.

Tabulated are summaries of these trajectories plus the trajectories with L/D variations to .3 and .4 and with altitude rate errors of ± 200 fps. The extreme atmosphere cases of shallow entry into a thin atmosphere and steep entry into a thick atmosphere are also tabulated. Other trajectories with atmospheric variations are not shown since the entry angle variation has the same effect as the atmospheric variation.

The significant parameters that are tabulated are

RANGE = inertial range from start of entry n.m.

VEL. = velocity at start of entry, fps

GAMMA = flight path angle at start, deg.

ERV = altitude rate error, held constant, fps

SQA = atmospheric density factor, see NASA TN D-612

MISS = steering miss only, n.m.

FUEL = roll fuel for dual system, seconds

dQCONV/dT = convective heat rate at stagnation point

Btu/sq.ft/sec

$$= .79323374 \text{ RN}^{-1/2} (\rho / \rho_c)^{3/2} (VA/1000)^{3.15}$$

dQRAD/dT = radiative heat rate at stagnation point,

Btu/sq.ft/sec

$$= 7.5 \text{ RN} (\rho / \rho_o) (VA/10000)^{12.5}$$

RN = nose radius = 1 ft

VA = relative velocity, fps

5-4

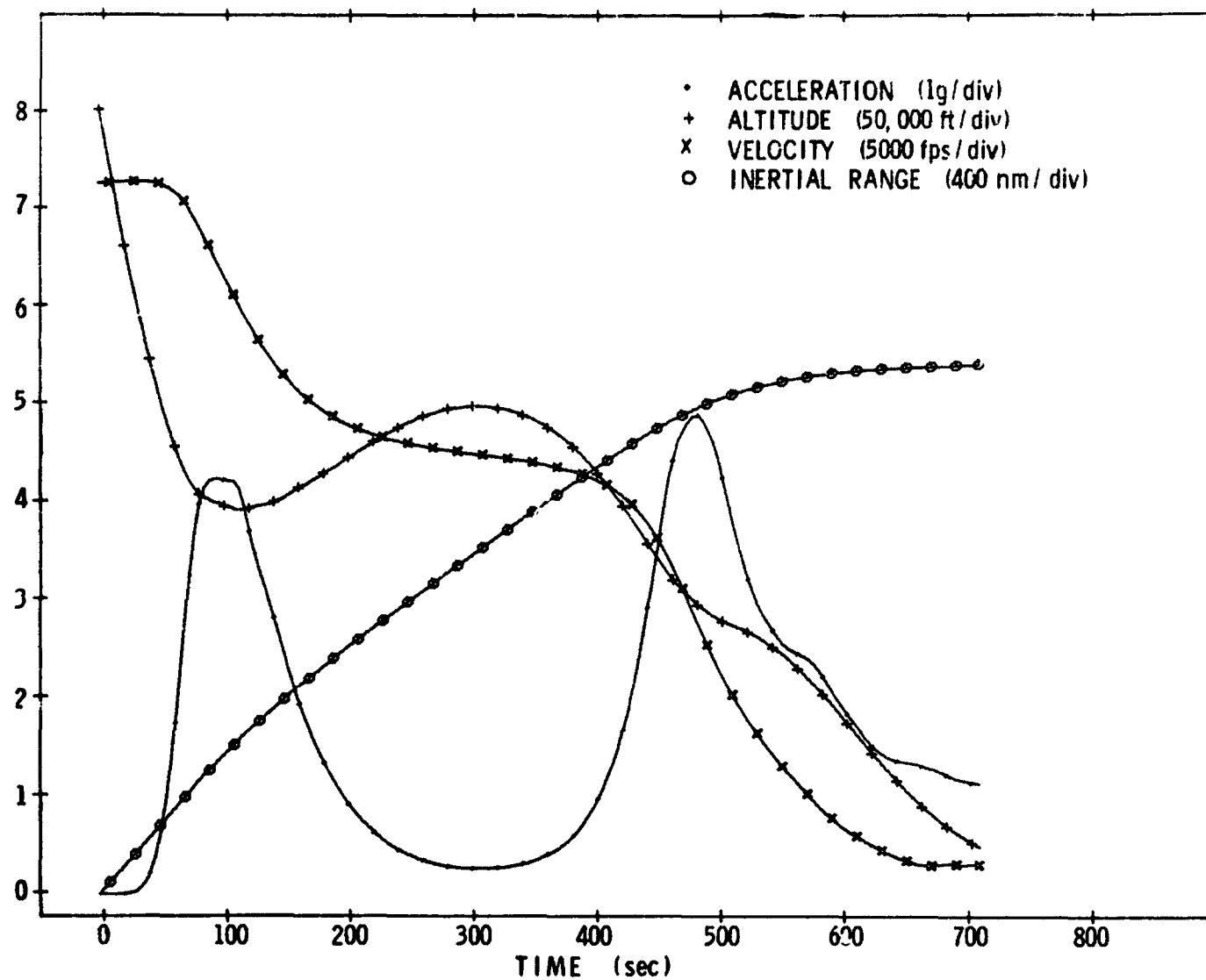


Fig. 5-1a 2000 n.m., - 6 Degree Entry

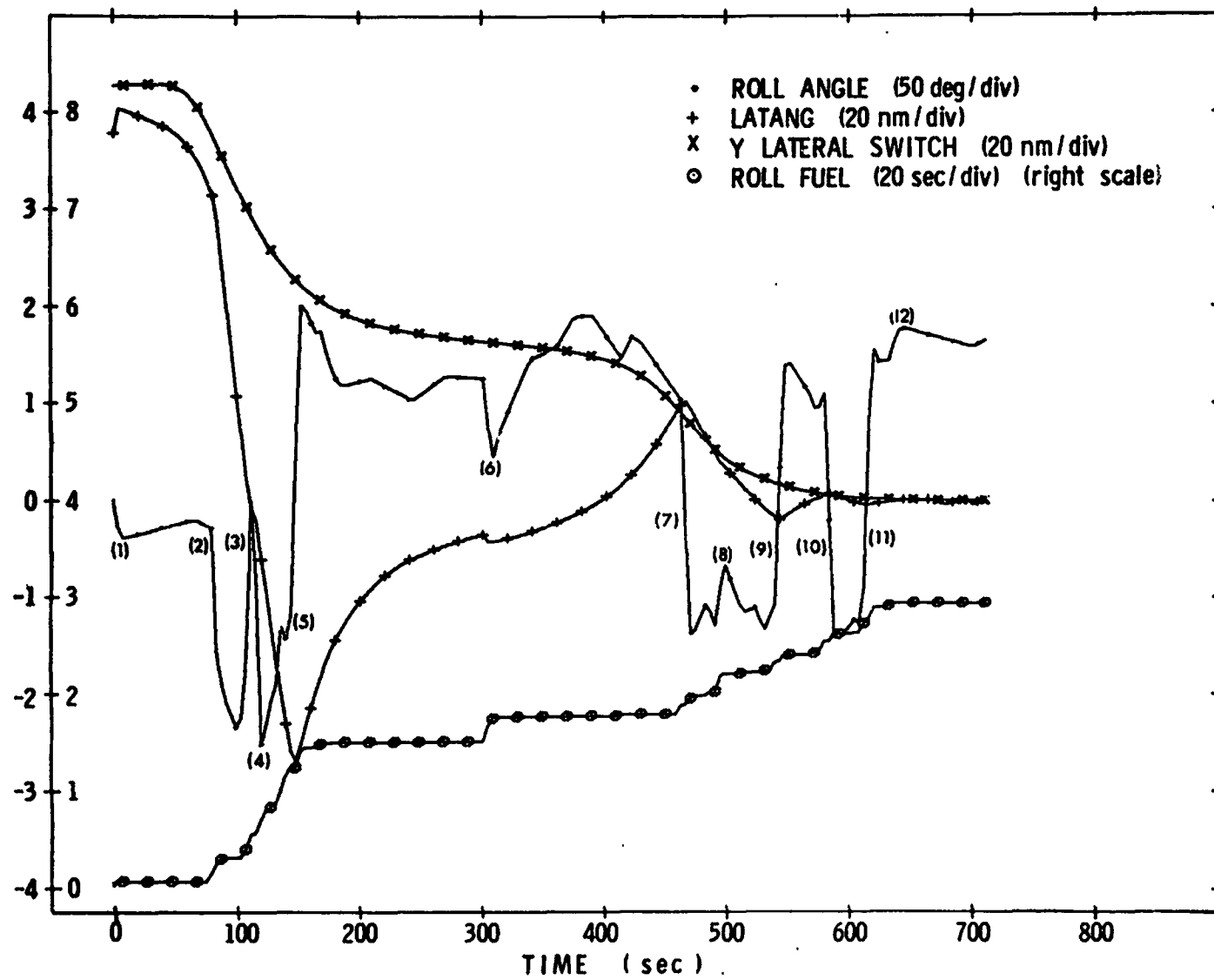


Fig. 5-1b 2000 n.m., -6 Degree Entry

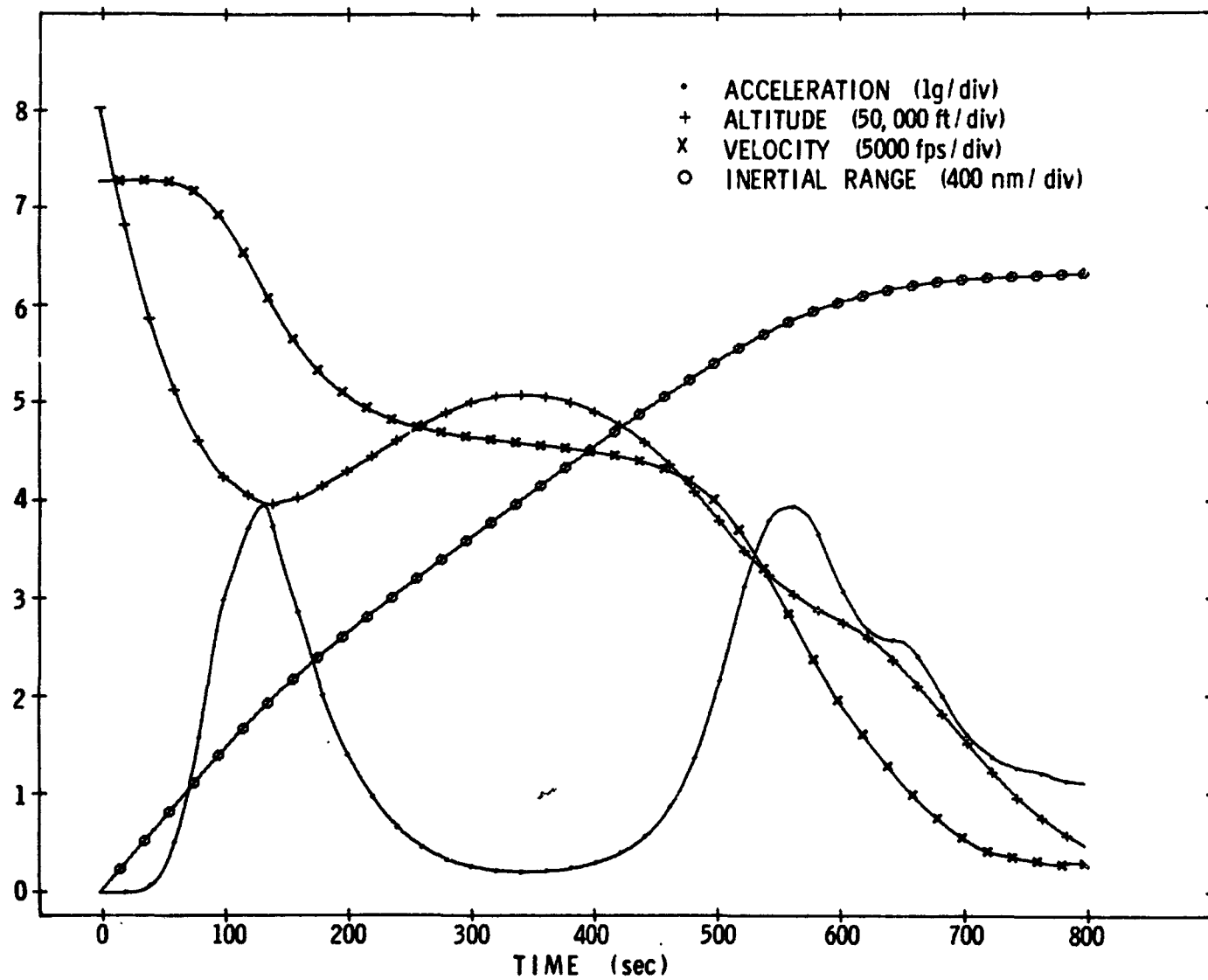


Fig. 5-2a 2350 n.m., -5.2 Degree Entry

5-7

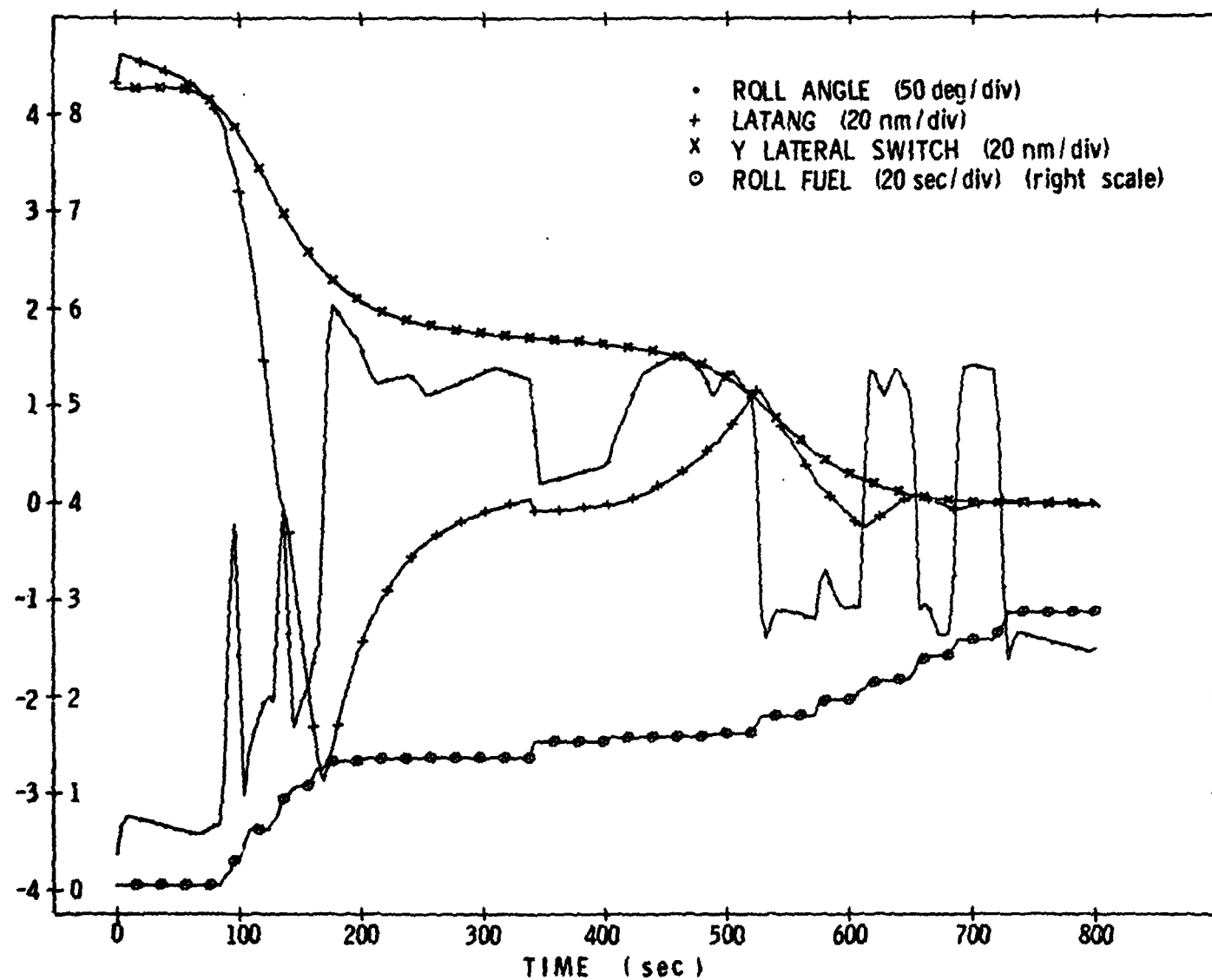


Fig. 5-2b 2350 n.m., -5.2 Degree Entry

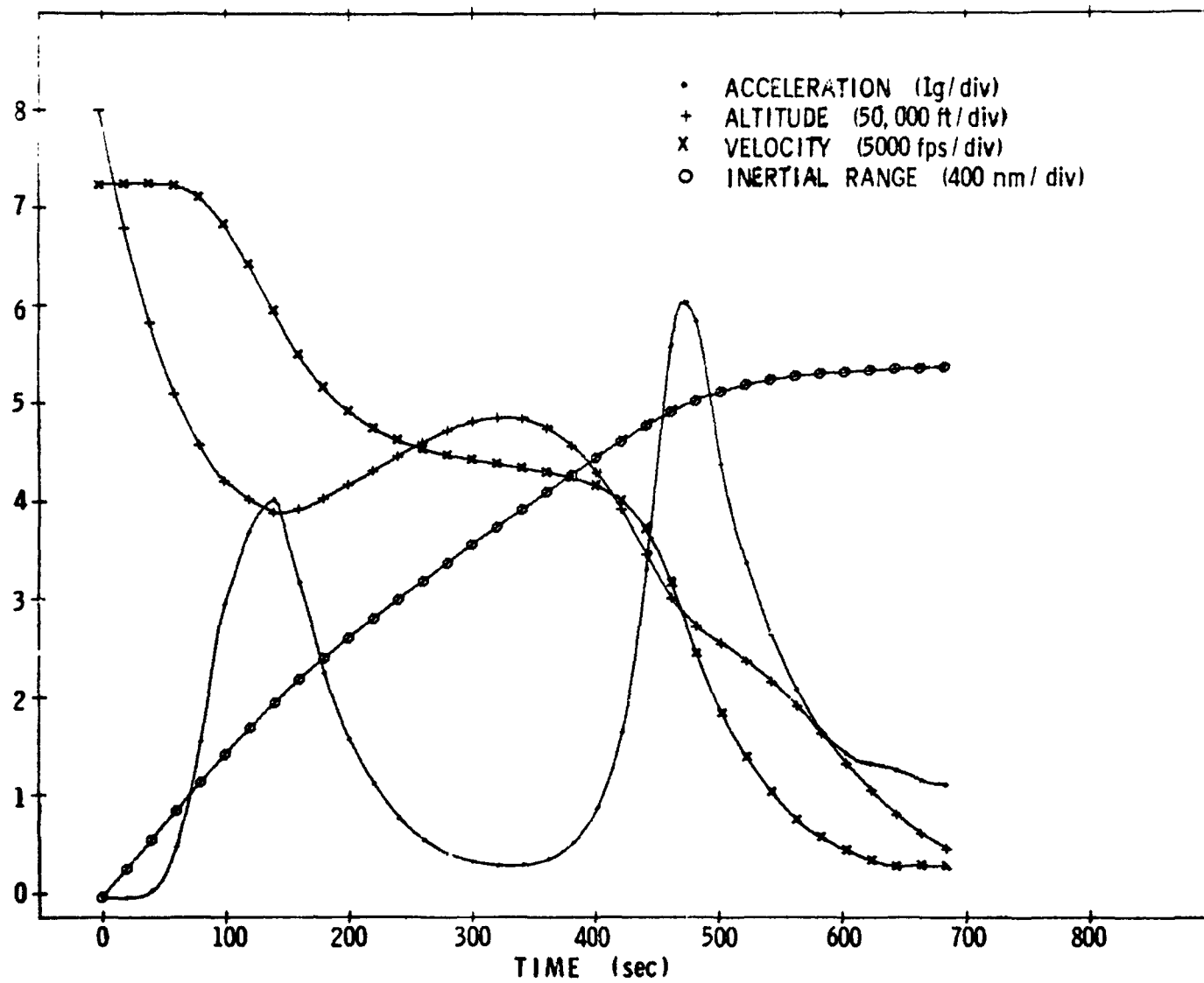


Fig. 5-3a 2000 n.m., -5.2 Degree Entry

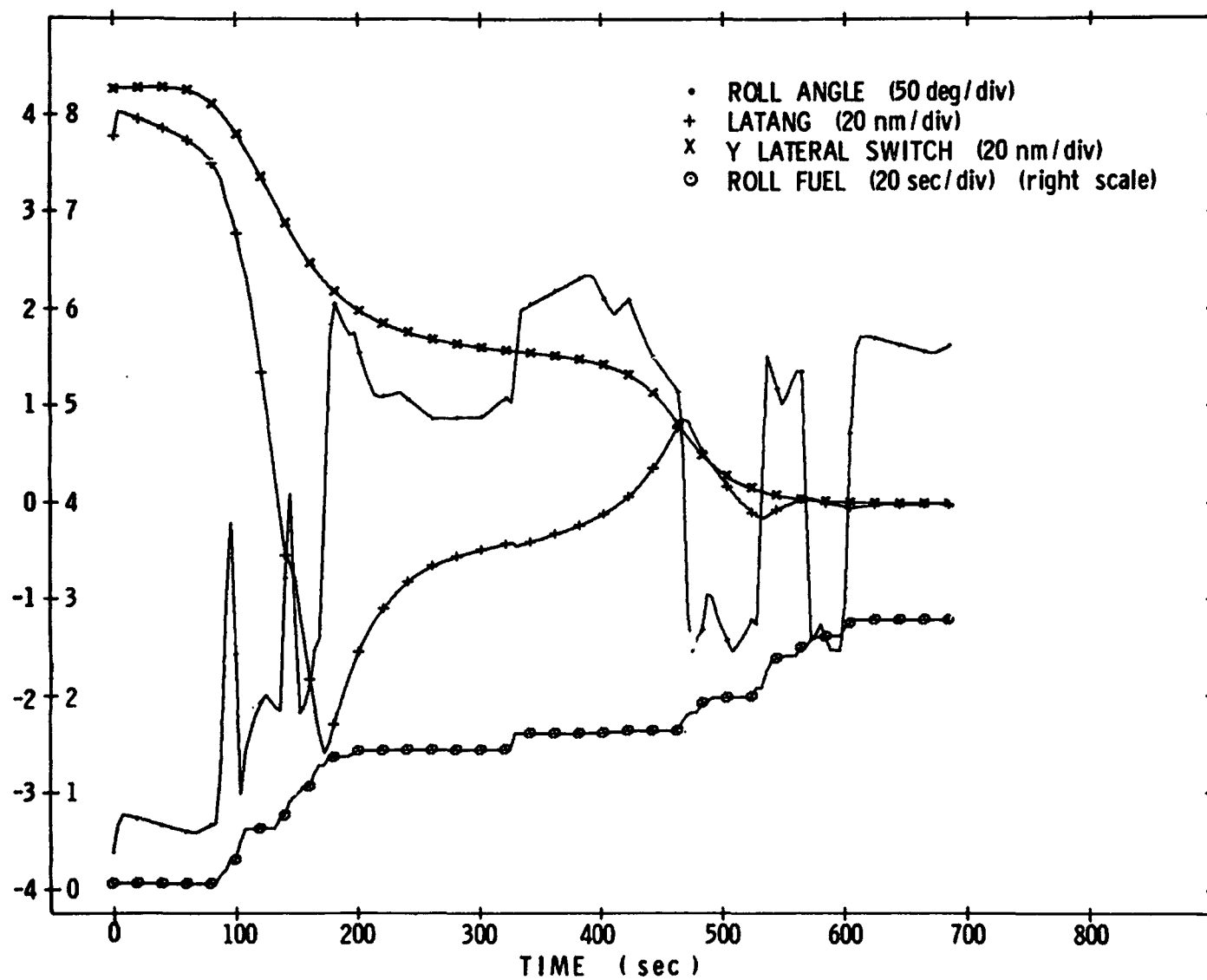


Fig. 5-3b 2000 n.m., -5.2 Degree Entry

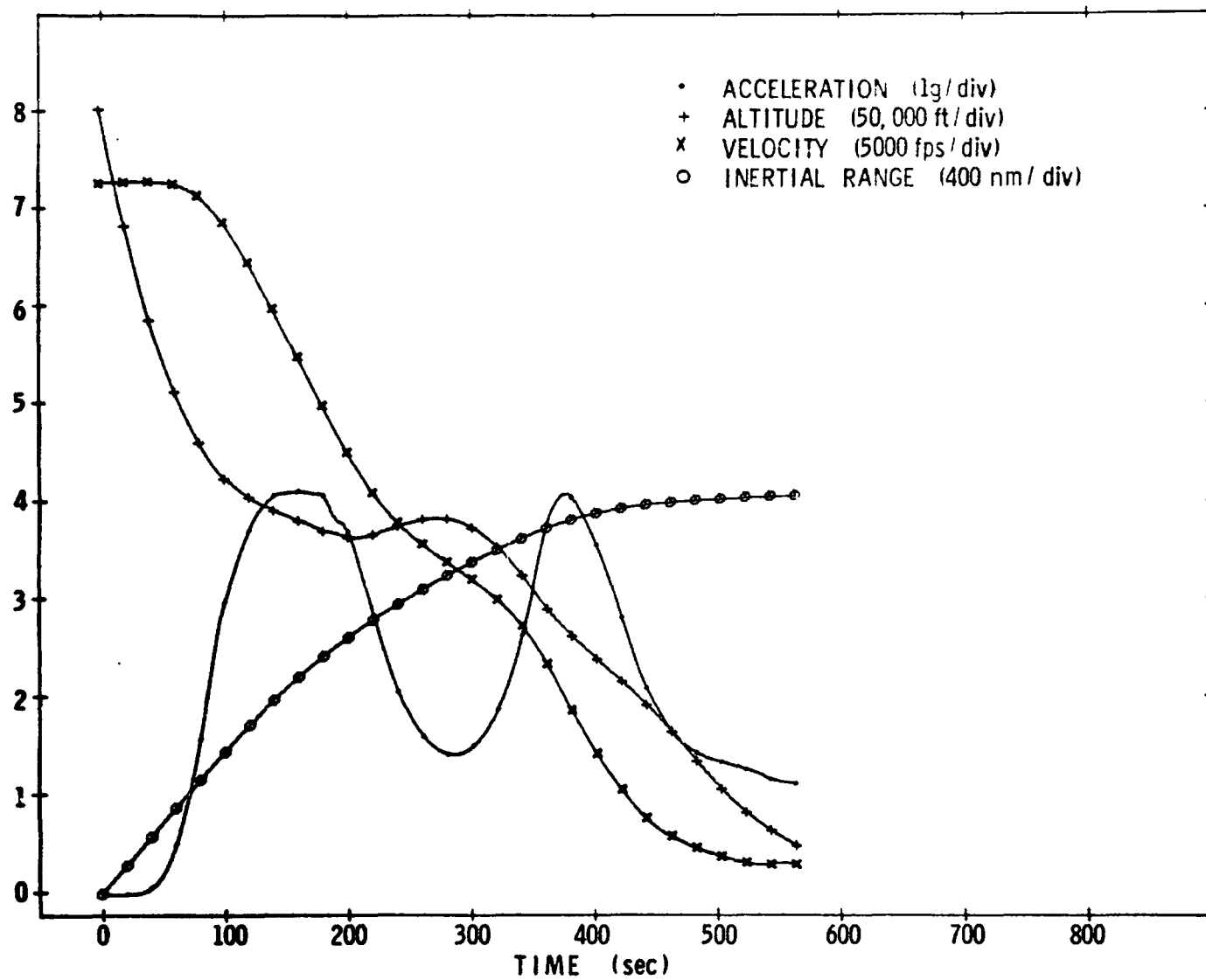


Fig. 5-4a 1500 n.m., -5.2 Degree Entry

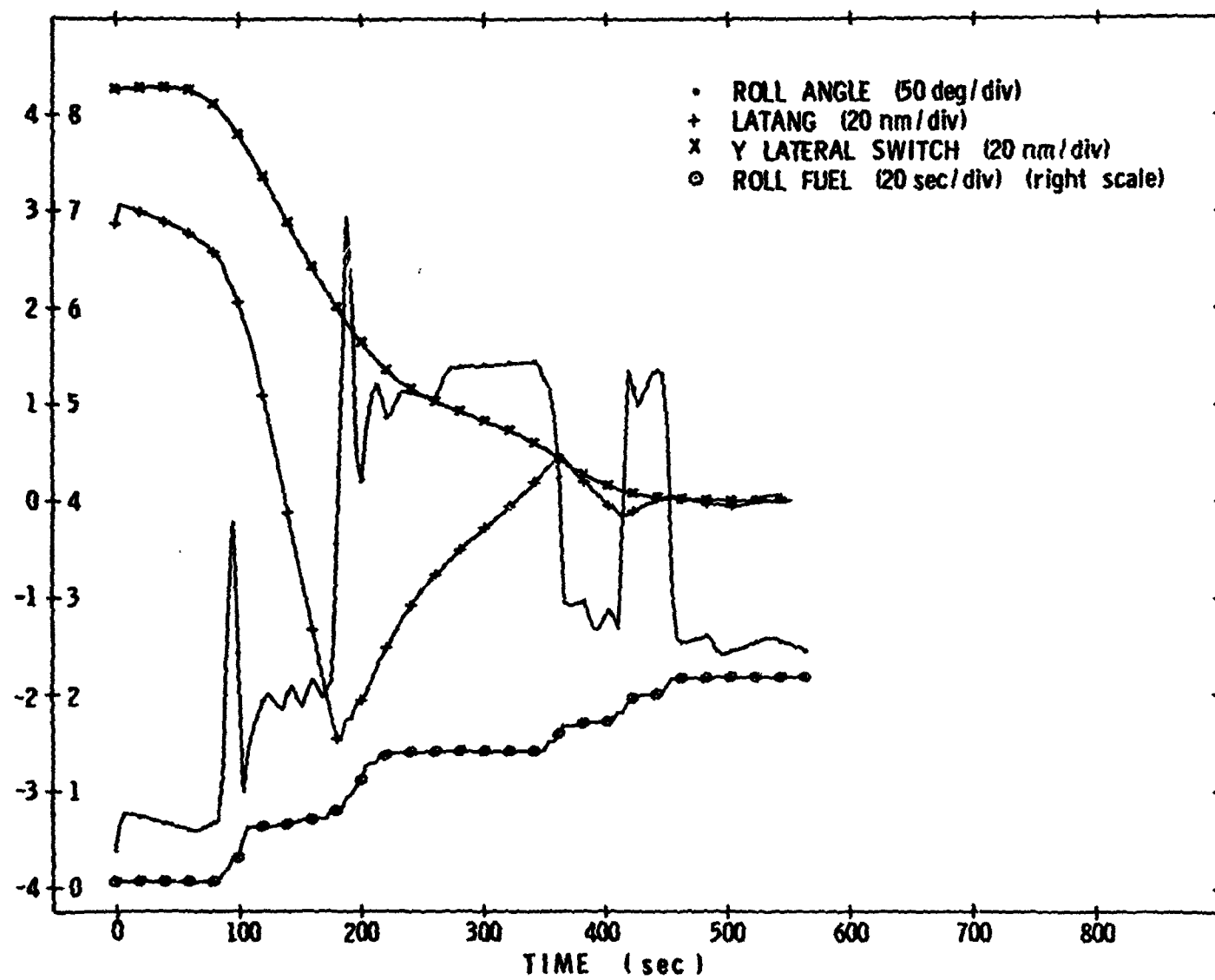


Fig. 5-4b 1500 n.m., -5.2 Degree Entry

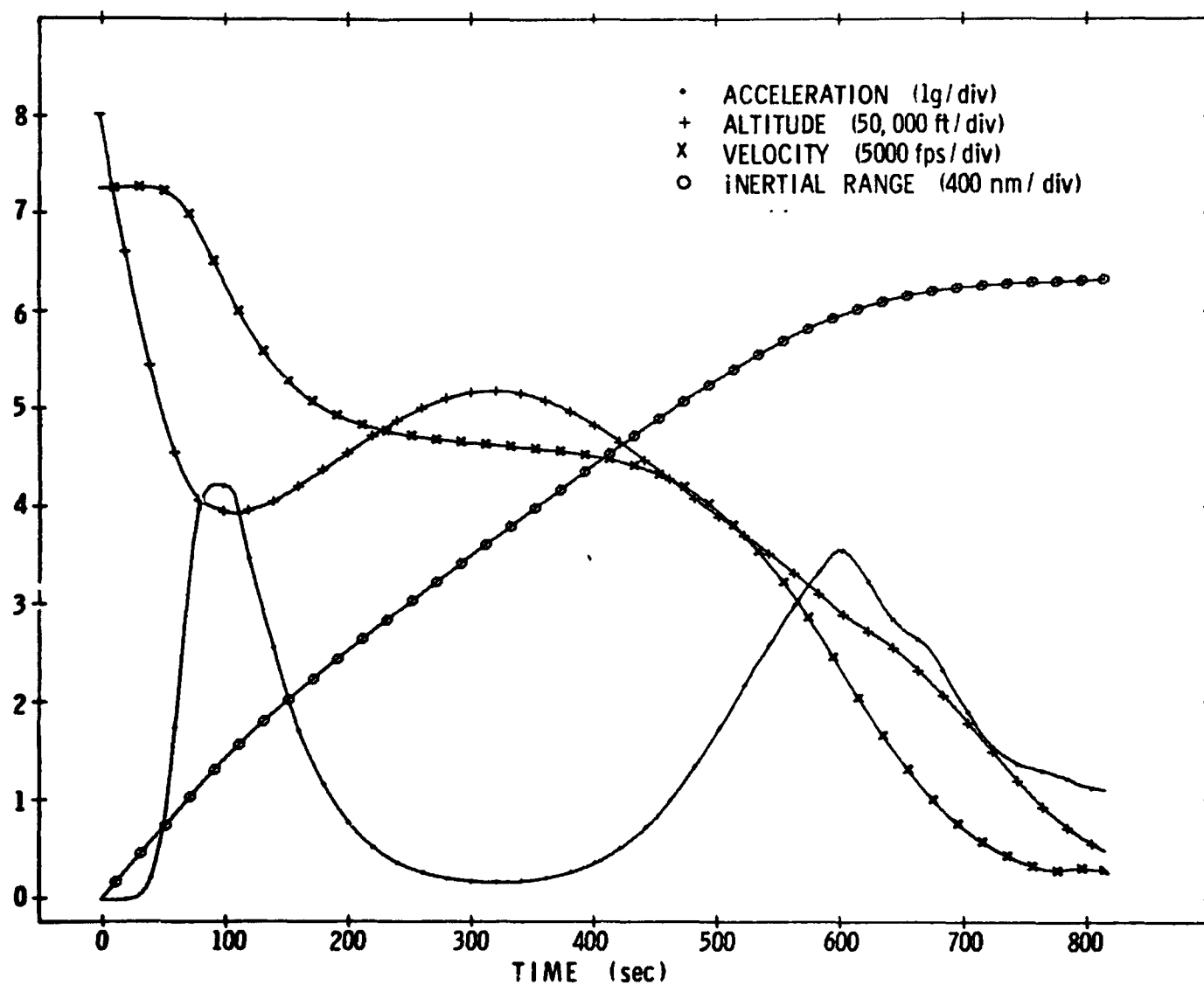


Fig. 5-5a 2350 n.m., -6 Degree Entry

5-13

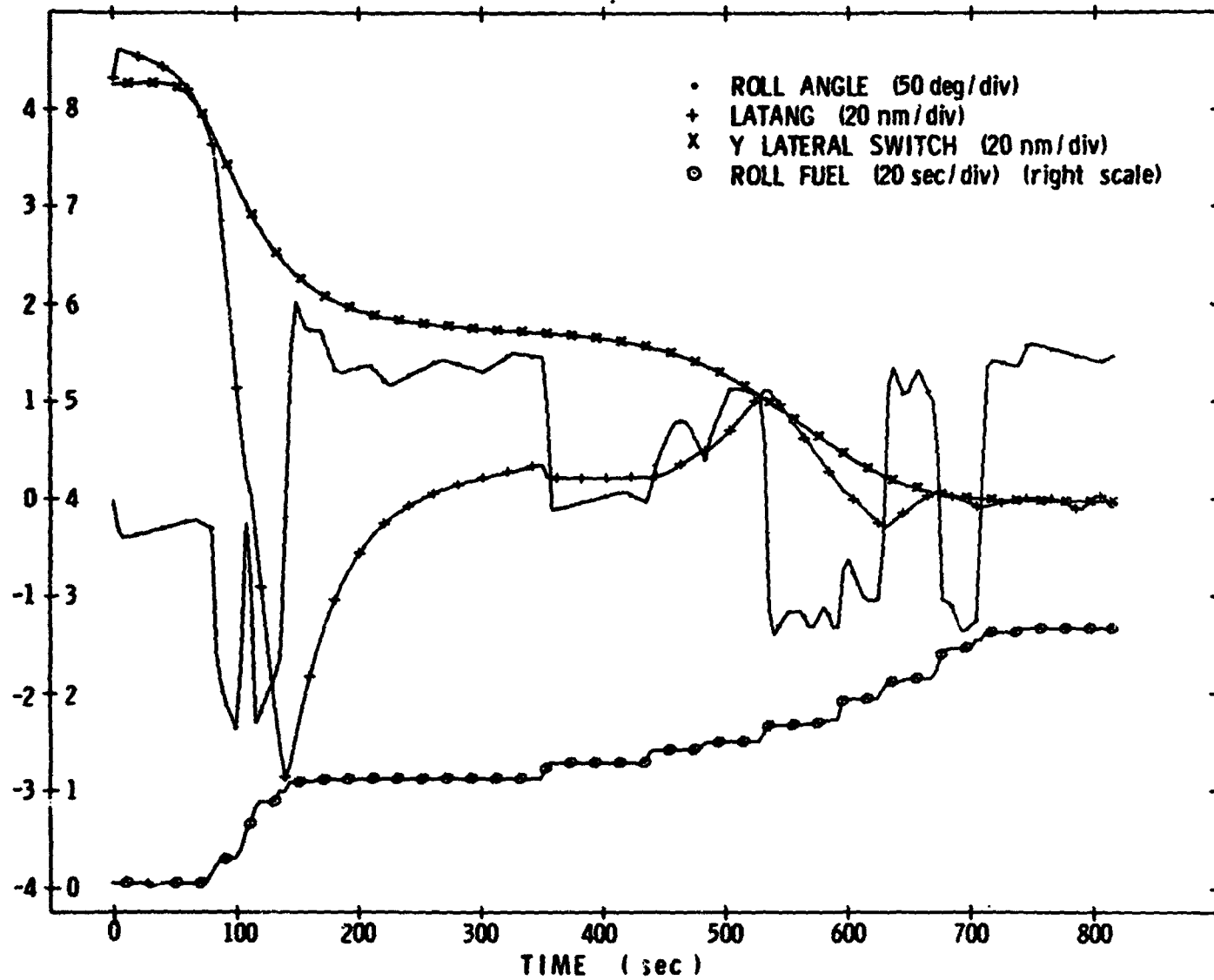


Fig. 5-5b 2350 n.m., -6 Degree Entry

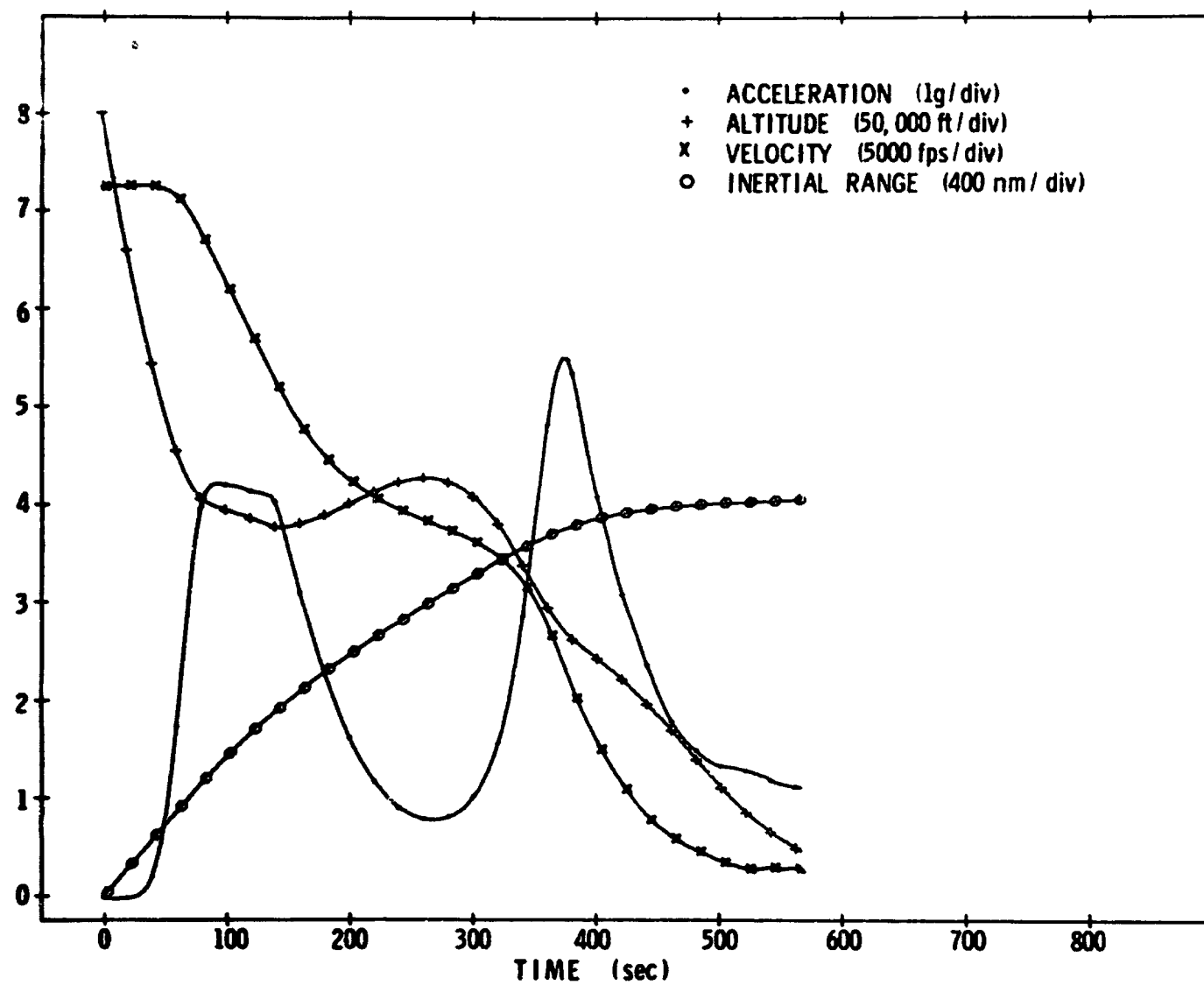


Fig. 5-6a 1500 n.m., -6 Degree Entry

5-15

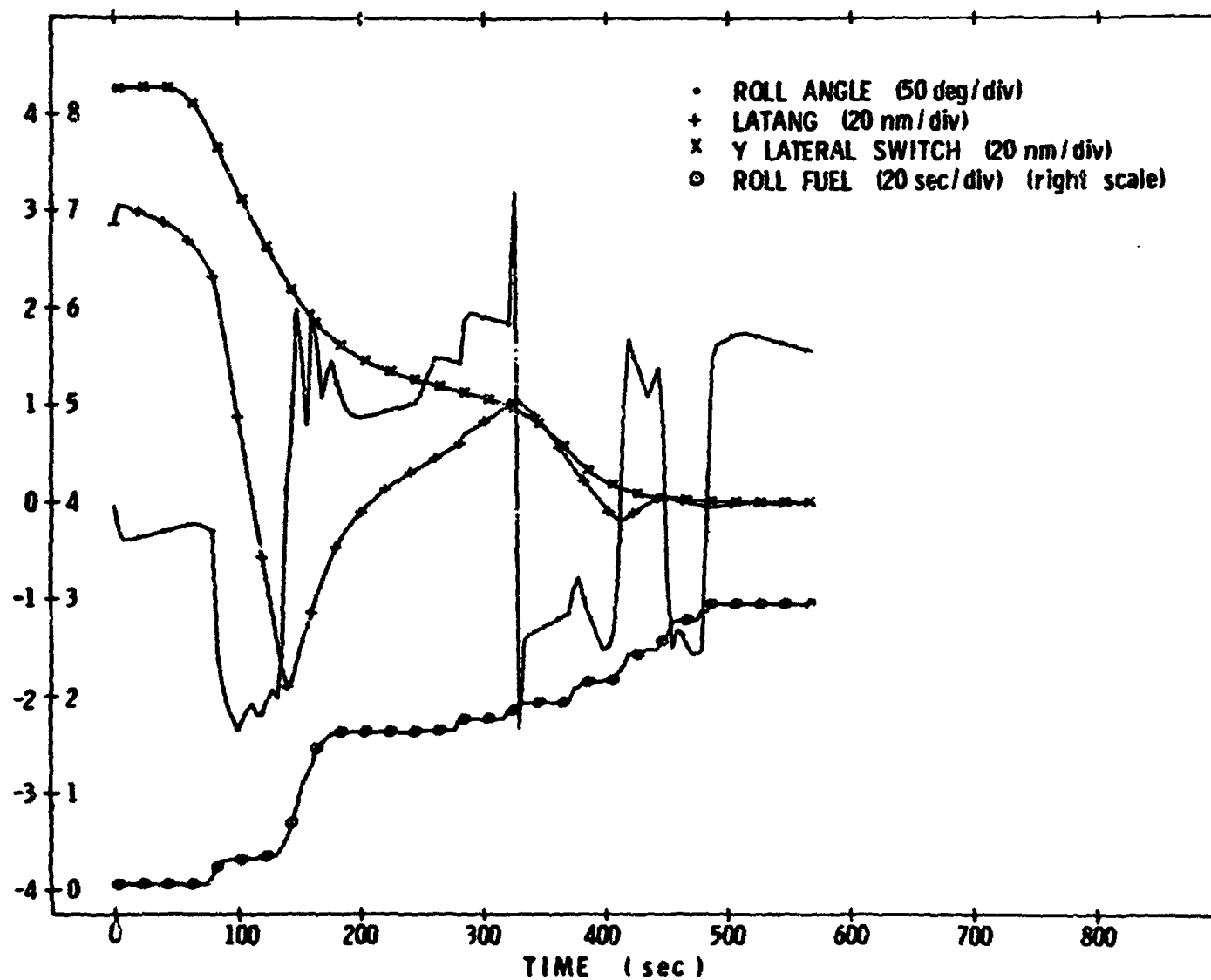


Fig. 5-6b 1500 n.m., -6 Degree Entry

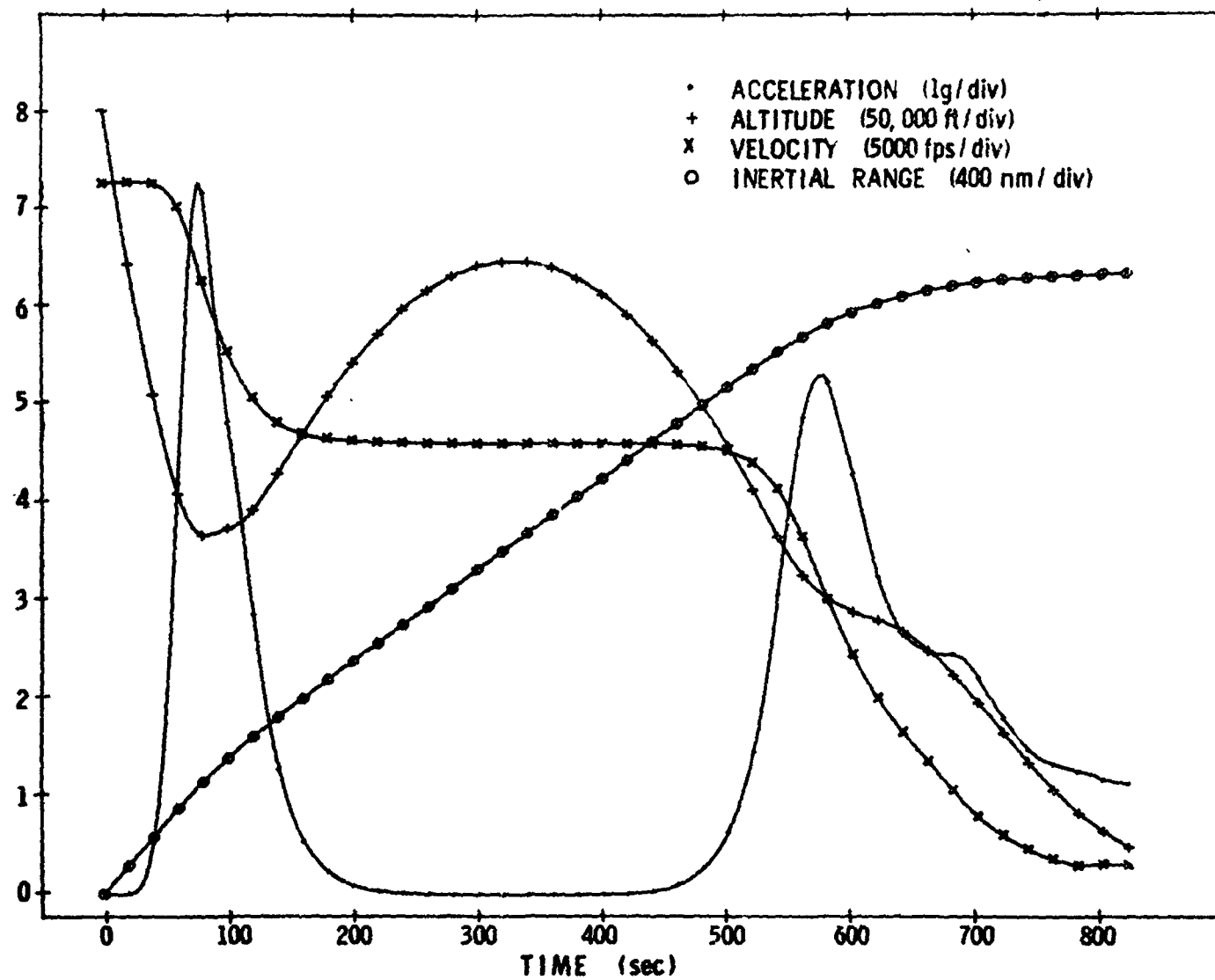


Fig. 5-7a 2350 n.m., -6.7 Degree Entry

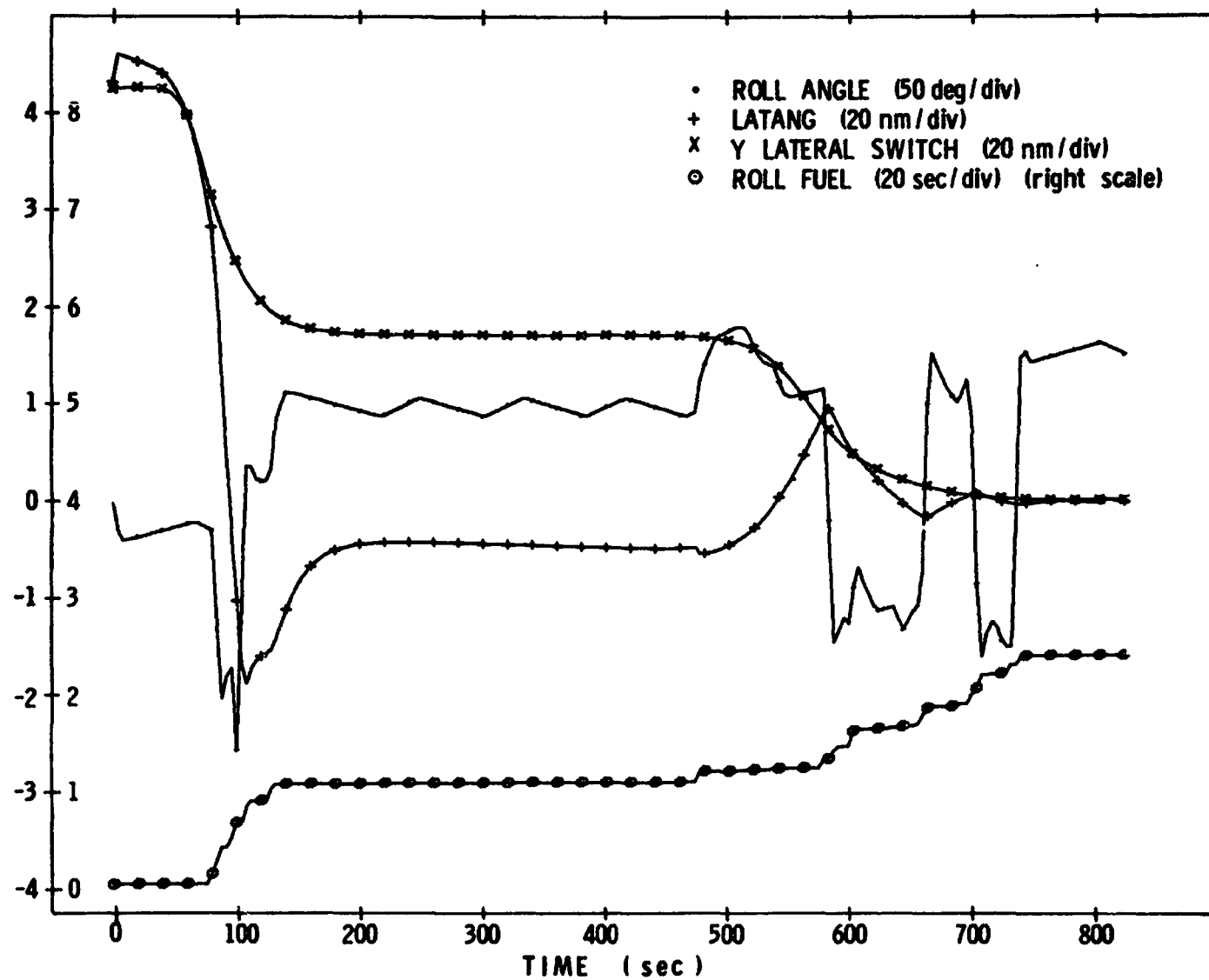


Fig. 5-7b 2350 n.m., -6.7 Degree Entry

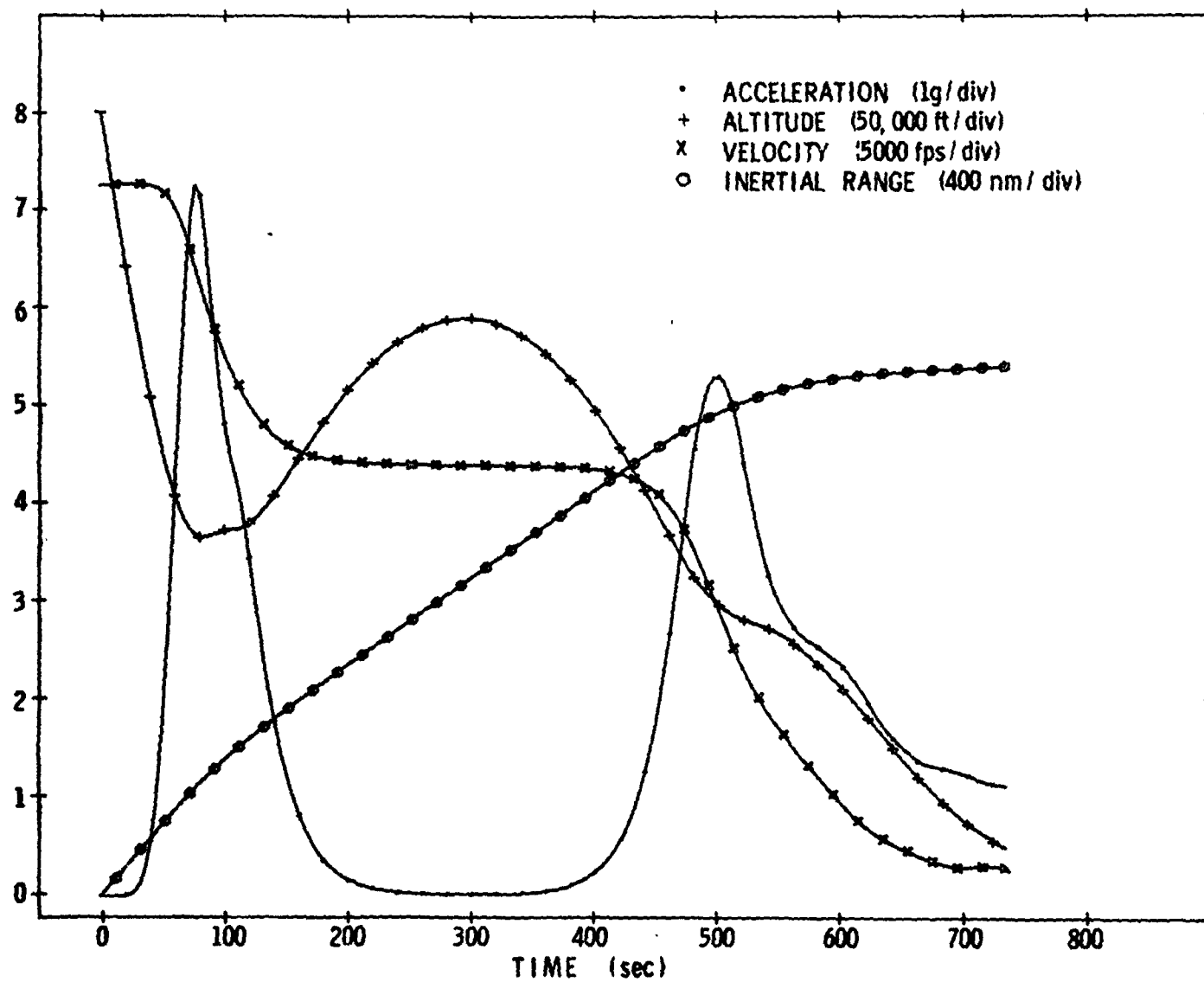


Fig. 5-8a 2000 n.m., -6.7 Degree Entry

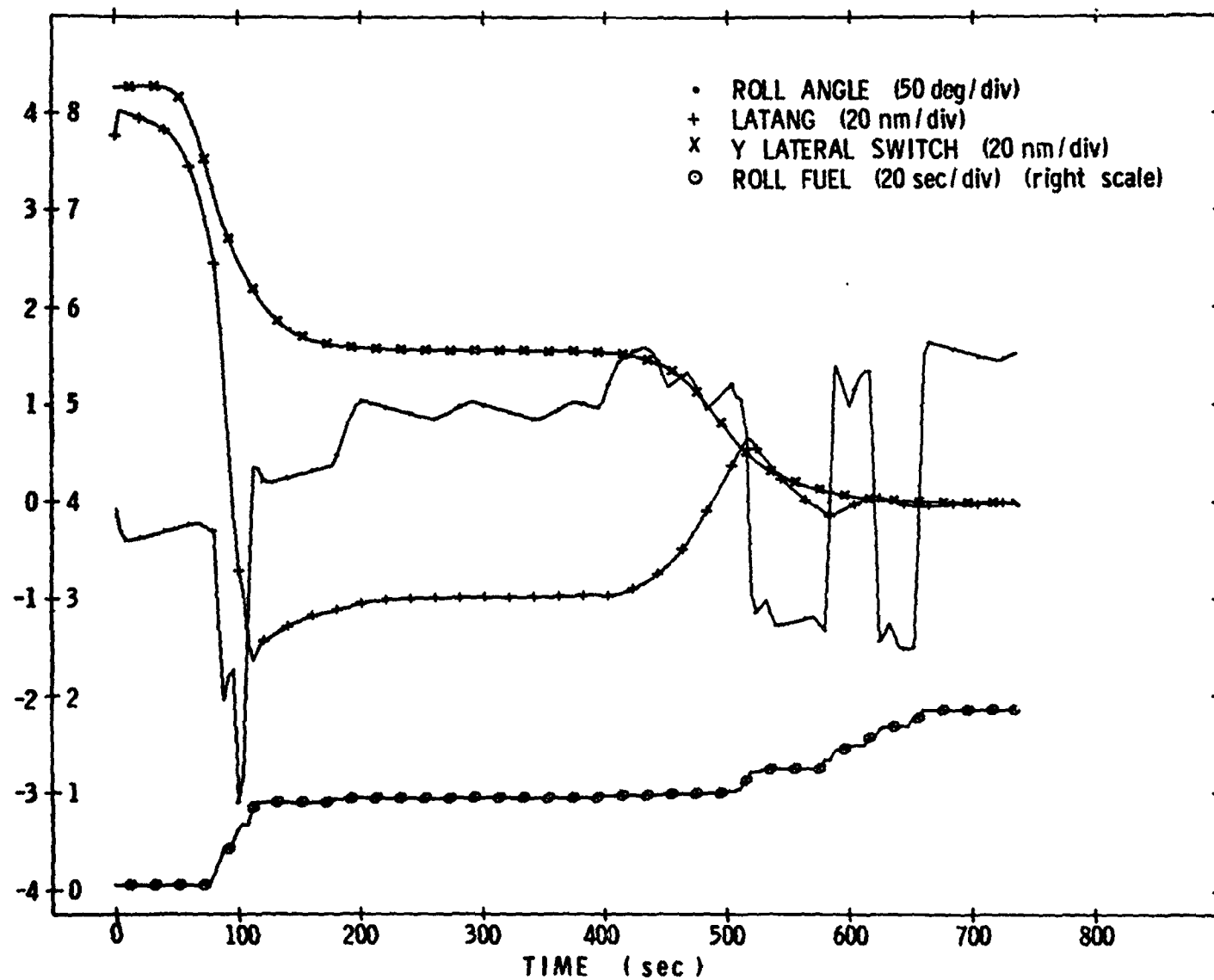


Fig. 5-8b 2000 n.m., -6.7 Degree Entry

5-20

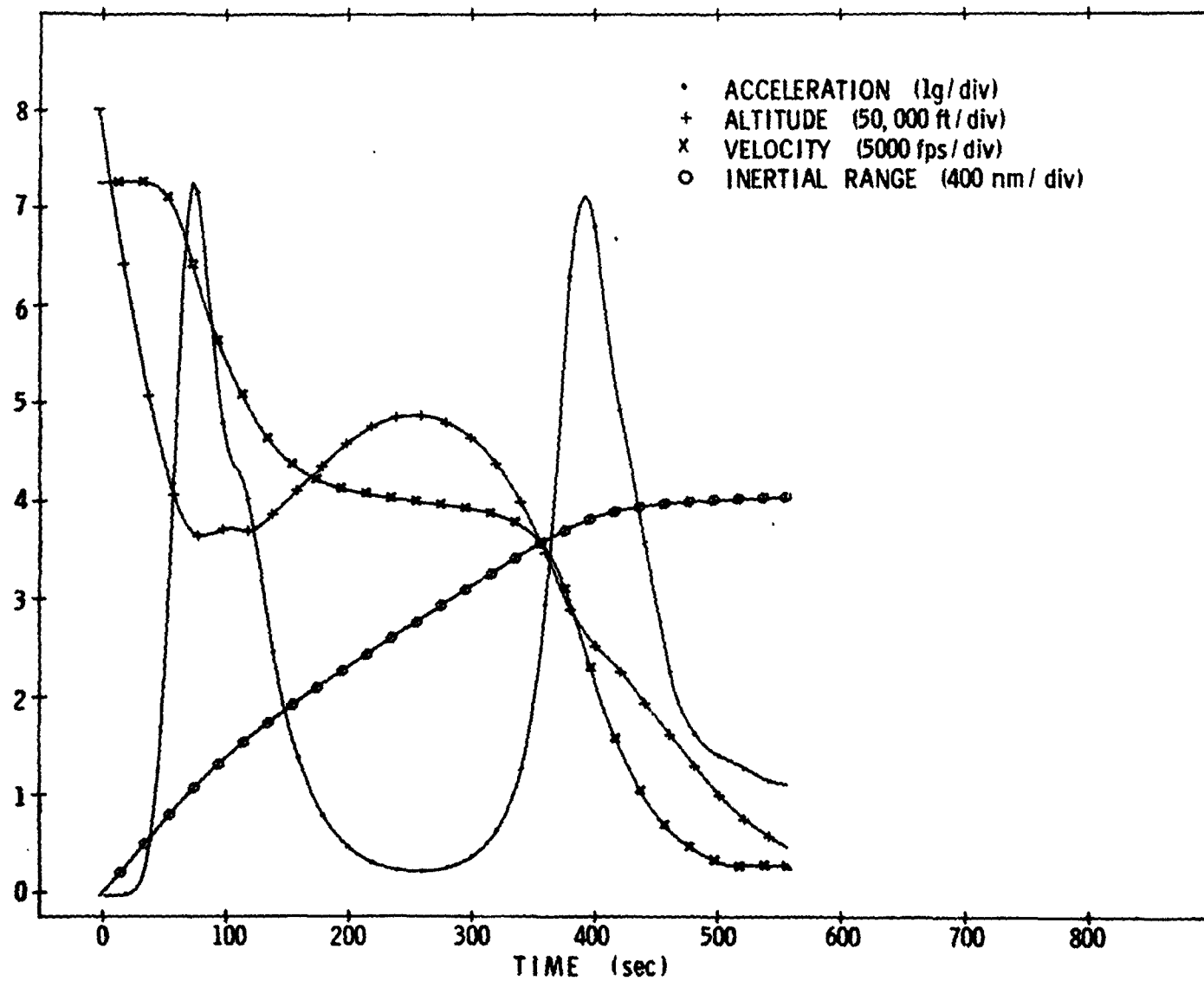


Fig. 5-9a 1500 n.m., -6.7 Degree Entry

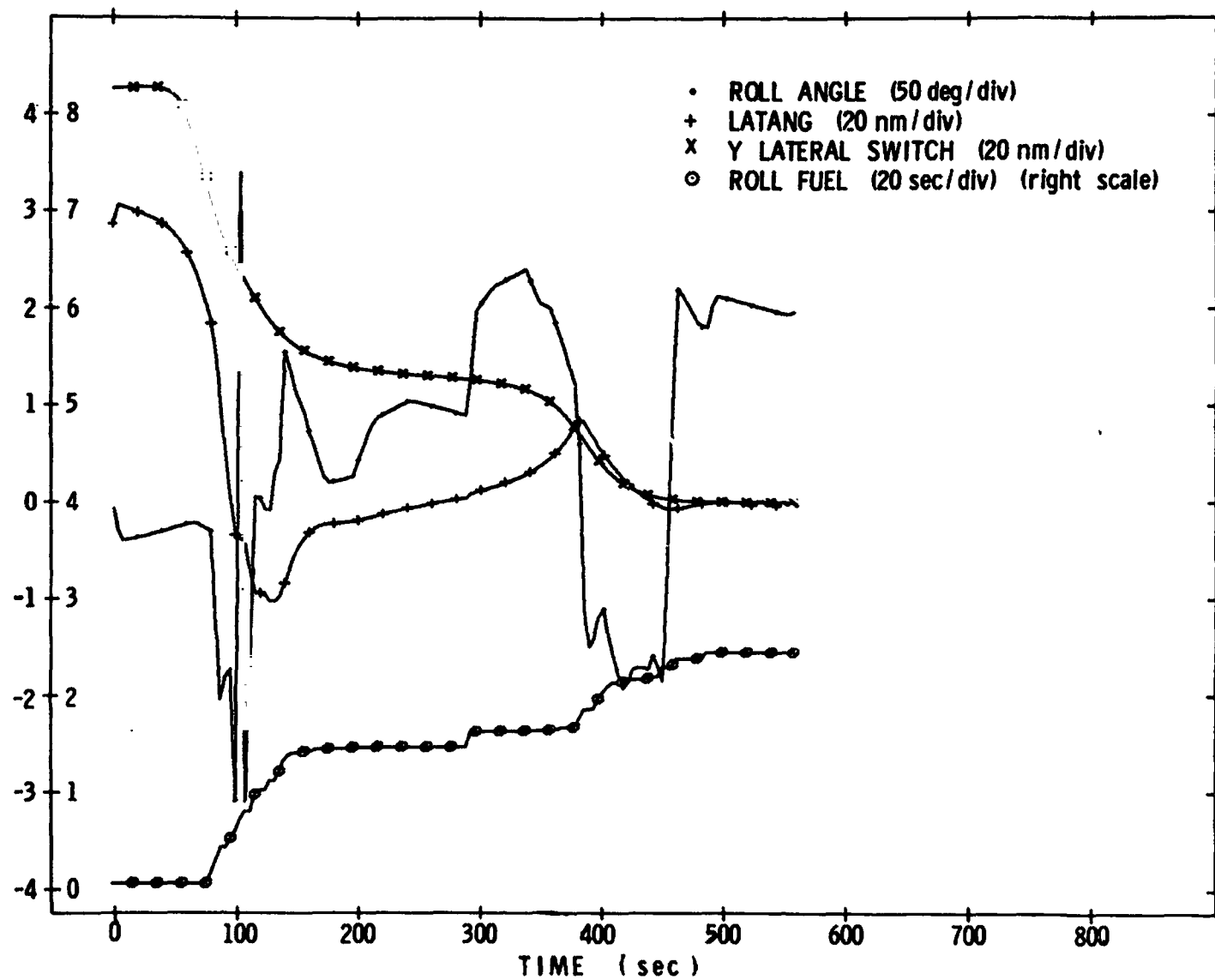


Fig. 5-9b 1500 n.m., -6.7 Degree Entry

MAC RUN		284198		5.2-- L/D = .3		(7/30/65)				
RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SOA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	QGRAD BTU/SQFT
2350	.30	36200	-5.20	200	0	1.14	4.41	71.4	99006	2342
2350	.30	36200	-5.20	0	0	0.15	3.94	74.6	102884	2270
2350	.30	36200	-5.20	-200	0	0.78	4.84	69.9	105125	2207
2000	.30	36200	-5.20	200	0	0.73	6.50	71.1	93223	2370
2000	.30	36200	-5.20	0	0	0.86	5.98	66.1	96411	2297
2000	.30	36200	-5.20	-200	0	0.61	5.78	66.2	98853	2231
1500	.30	36200	-5.20	200	0	0.95	4.80	58.9	82928	2414
1500	.30	36200	-5.20	0	0	0.07	4.24	50.4	84923	2345
1500	.30	36200	-5.20	-200	0	0.68	3.77	46.9	86612	2280

Fig. 5-10 Shallow entry, L/D = .3

MAC RUN 284202

5.2--- L/D = .34

(7/30/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SQA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	GRAD BTU/SQFT
2350	.34	36200	-5.20	200	0	0.94	4.42	64.6	99236	2339
2350	.34	36200	-5.20	0	0	0.22	3.95	57.9	102842	2284
2350	.34	36200	-5.20	-200	0	1.33	5.37	70.2	104334	2218
2000	.34	36200	-5.20	200	0	1.01	6.56	75.0	93595	2368
2000	.34	36200	-5.20	0	0	0.20	6.02	56.1	96278	2311
2000	.34	36200	-5.20	-200	0	1.19	5.93	67.2	98653	2240
1500	.34	36200	-5.20	200	0	1.02	5.22	69.2	82993	2415
1500	.34	36200	-5.20	0	0	1.45	4.10	43.9	84912	2358
1500	.34	36200	-5.20	-200	0	1.33	3.83	52.5	86720	2289

Fig. 5-11 Shallow entry, L/D = .34

MAC RUN 283918

5.2--- L/D = .4

(7/29/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SQA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	GRAD BTU/SQFT
2350	.40	36200	-5.20	200	0	1.04	5.74	86.1	97315	2375
2350	.40	36200	-5.20	0	0	0.08	4.47	78.1	101515	2307
2350	.40	36200	-5.20	-200	0	1.23	6.03	70.7	103887	2238
2000	.40	36200	-5.20	200	0	1.43	7.14	79.4	92813	2401
2000	.40	36200	-5.20	0	0	0.28	6.40	70.3	95647	2333
2000	.40	36200	-5.20	-200	0	2.00	6.25	64.3	98295	2265
1500	.40	36200	-5.20	200	0	0.72	6.78	84.0	82753	2448
1500	.40	36200	-5.20	0	0	0.47	4.66	67.0	84778	2382
1500	.40	36200	-5.20	-200	0	0.66	4.11	55.3	86559	2315

FIG. 5-12 SHALLOW ENTRY, L/D = .4

MAC RUN 284723

6.0 --- L/D = .3

(8/02/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SQA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	QGRAD BTU/SQFT
2350	.30	36200	-6.00	200	0	0.92	4.69	56.6	95543	2621
2350	.30	36200	-6.00	0	0	0.29	4.39	71.6	99411	2568
2350	.30	36200	-6.00	-200	0	0.58	4.34	73.3	101231	2536
2000	.30	36200	-6.00	200	0	0.87	5.29	47.4	90538	2641
2000	.30	36200	-6.00	0	0	0.18	4.92	65.4	93381	2589
2000	.30	36200	-6.00	-200	0	0.59	5.44	56.9	94954	2556
1500	.30	36200	-6.00	200	0	1.33	5.79	59.8	82011	2681
1500	.30	36200	-6.00	0	0	0.32	6.48	63.3	83503	2632
1500	.30	36200	-6.00	-200	0	0.94	5.52	54.0	84511	2606

Fig. 5-13 Mid entry. L/D = .3

MAC RUN 284604

6.0 --- L/D = .34

(8/02/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERVR FPS	SOA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	GRAD BTU/SQFT
2350	.34	36200	-6.00	200	0	0.91	4.68	75.2	95806	2591
2350	.34	36200	-6.00	0	0	1.36	4.22	54.0	100575	2532
2350	.34	36200	-6.00	-200	0	0.53	4.81	67.0	100887	2489
2000	.34	36200	-6.00	200	0	0.88	5.62	65.8	90901	2613
2000	.34	36200	-6.00	0	0	0.72	4.86	58.9	94248	2551
2000	.34	36200	-6.00	-200	0	0.58	5.84	67.7	95539	2510
1500	.34	36200	-6.00	200	0	0.82	6.80	58.3	82373	2654
1500	.34	36200	-6.00	0	0	0.19	5.51	59.2	84041	2598
1500	.34	36200	-6.00	-200	0	1.75	5.39	47.9	34803	2560

Fig. 5-14 Mid entry, L/D = .34

MAC RUN 284726

6.0 --- L/D = .4

(8/02/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERVR FPS	SOA	MISS NM	MAX-G G-5	FUEL SEC.	QCONV BTU/SQFT	GRAD BTU/SQFT
2350	.40	36200	-6.00	200	0	0.82	4.67	68.8	95902	2563
2350	.40	36200	-6.00	0	0	0.28	4.17	69.5	100033	2490
2350	.40	36200	-6.00	-200	0	0.74	5.09	72.4	101920	2436
2000	.40	36200	-6.00	200	0	1.47	6.97	80.6	90111	2587
2000	.40	36200	-6.00	0	0	0.30	5.73	68.8	93987	2513
2000	.40	36200	-6.00	-200	0	0.78	6.22	63.9	96381	2456
1500	.40	36200	-6.00	200	0	1.41	7.08	54.3	82334	2628
1500	.40	36200	-6.00	0	0	0.18	5.95	53.0	84141	2564
1500	.40	36200	-6.00	-200	0	1.53	5.58	61.7	85373	2512

Fig. 5-15 Mid entry, L/D = .4

MAC RUN 283389

6.7 L/D=.3, YULTEST

(7/28/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SOA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	QGRAD BTU/SQFT
2350	.30	36200	-6.70	200	0	0.84	7.63	47.1	80863	3198
2350	.30	36200	-6.70	0	0	0.26	7.63	60.7	83553	3185
2350	.30	36200	-6.70	-200	0	20.12	7.63	111.7	85959	3180
2000	.30	36200	-6.70	200	0	1.68	7.63	39.6	79388	3202
2000	.30	36200	-6.70	0	0	0.87	7.63	40.7	81058	3195
2000	.30	36200	-6.70	-200	0	0.65	7.63	43.2	80413	3187
1500	.30	36200	-6.70	200	0	1.31	7.63	25.6	75704	3214
1500	.30	36200	-6.70	0	0	1.41	7.63	42.1	76358	3204
1500	.30	36200	-6.70	-200	0	0.70	7.63	43.2	77846	3195

Fig. 5-1. Steep entry. L/D = .3

MAC RUN 283301

6.7 L/D=.34 YULTEST

(7/28/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERVR FPS	SOA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	QRAD BTU/SQFT
2350	.34	36200	-6.70	200	20	0.99	7.77	46.5	79499	3220
2350	.34	36200	-6.70	0	0	0.39	7.24	48.2	81262	3125
2350	.34	36200	-6.70	-200	0	0.64	7.24	50.1	86636	3108
2000	.34	36200	-6.70	200	0	0.92	7.24	77.0	81335	3142
2000	.34	36200	-6.70	0	0	0.12	7.24	37.6	80347	3132
2000	.34	36200	-6.70	-200	0	4.20	8.13	43.7	79953	3122
1500	.34	36200	-6.70	200	0	1.10	7.49	48.2	75709	3152
1500	.34	36200	-6.70	0	0	0.55	7.24	49.4	77302	3139
1500	.34	36200	-6.70	-200	0	1.45	7.24	55.0	78428	3131

Fig. 5-17 Steep Entry, L/D = .34

MAC RUN 283224

6.7 L/D=.4. YULTEST

(7/28/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SQA	MISS NM	MAX-G G-5	FUEL SEC.	QCONV BTU/SQFT	GRAD BTU/SQFT
2350	.40	36200	-6.70	200	0	1.30	6.78	66.1	80186	3060
2350	.40	36200	-6.70	0	0	2.15	9.14	49.4	79772	3040
2350	.40	36200	-6.70	-200	0	0.87	6.78	60.4	88314	3009
2000	.40	36200	-6.70	200	0	0.72	7.63	77.6	79550	3060
2000	.40	36200	-6.70	0	0	0.54	8.78	42.0	80256	3045
2000	.40	36200	-6.70	-200	0	0.74	6.78	50.6	84785	3022
1500	.40	36200	-6.70	200	0	1.34	8.99	59.7	76115	3077
1500	.40	36200	-6.70	0	0	4.95	8.68	51.0	77344	3061
1500	.40	36200	-6.70	-200	0	2.22	6.78	73.5	79635	3039

Fig. 5-18 Steep entry. L/D = .4

MAC RUN 283585 6.7 L/D=.3 THICK YULTEST (7/29/65)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SQA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	QRAD BTU/SQFT
2350	.30	36200	-6.70	200	20	0.54	8.16	46.7	78099	3287
2350	.30	36200	-6.70	0	20	0.19	8.16	53.1	80105	3279
2350	.30	36200	-6.70	-200	20	0.52	8.16	41.0	80486	3272
2000	.30	36200	-6.70	200	20	1.67	8.16	49.2	77345	3291
2000	.30	36200	-6.70	0	20	0.22	8.16	53.6	78961	3283
2000	.30	36200	-6.70	-200	20	0.65	8.16	56.9	81327	3278
1500	.30	36200	-6.70	200	20	63.70	8.16	53.1	73729	3303
1500	.30	36200	-6.70	0	20	1.14	8.16	41.5	75499	3294
1500	.30	36200	-6.70	-200	20	21.63	8.16	72.7	75119	3287

Fig. 5-19 Steep entry, thick atmosphere, L/D = .3

MAC RUN 285193

5.2--- L/D = .3. THIN

(8/03/85)

RANGE NM	L/D	VEL. FPS	GAMMA DEG.	ERV FPS	SOA	MISS NM	MAX-G G-S	FUEL SEC.	QCONV BTU/SQFT	QRAD BTU/SQFT
2350	.30	36200	-5.20	200	-20	1.61	4.25	61.1	103887	2094
2350	.30	36200	-5.20	0	-20	0.59	4.64	66.1	105513	2067
2350	.30	36200	-5.20	-200	-20	0.61	5.64	50.5	106979	2033
2000	.30	36200	-5.20	200	-20	0.68	8.09	76.2	97359	2117
2000	.30	36200	-5.20	0	-20	0.23	7.71	65.6	98687	2095
2000	.30	36200	-5.20	-200	-20	0.57	6.20	52.5	99992	2070
1500	.30	36200	-5.20	200	-20	0.24	4.61	49.9	85178	2161
1500	.30	36200	-5.20	0	-20	1.47	4.28	48.4	86275	2139
1500	.30	36200	-5.20	-200	-20	0.53	5.12	46.8	87603	2105

Fig. 5-20 Shallow entry, thin atmosphere, L/D = .3

VI AGC PROGRAM

The detailed reentry program is shown in succeeding pages. Both basic and interpretative programming have been used. These are described in References 3 and 4.

The program speed and size is summarized in fig. 6-1. The program is roughly 1500 words long and the computation time varies from .5 to 1.0 second depending on the program mode.

The program is listed in the form ready for the YUL assembler. The right half of the list (column 41 on the card) contains comments to aid in reading the program.

It is assumed here that prior to entry the vehicle is in the entry attitude and that the SCS, IMU, and CDU are all in the entry mode. Further it is assumed that the mission control program (not described) has put a 2 second call to the "Wait List"* for the PIPUP routine, and the entry calculations have been started in the Initialization Section, STARTENT.

This section starts the attitude control job by assigning a priority of 14 to the job UPTHETA1. The various quantities are initialized in STARTENT, then the program waits until the next cycle to start the normal entry calculations.

Further entries to the main computation are made through the PIPA reading routine, PIPUP. This routine reads the PIPA-s by calling PIPASR by way of ISWCALL. ISWCALL is a routine to call a subroutine in a different switchable bank from the one currently being executed. (It is equivalent to SWCALL except it may be used in the interrupt mode.) The PIPUP routine then perpetuates itself by giving a two second call to the Wait List. It also sets up the INTERPIP routine with a .5 second call to the Wait List. INTERPIP is a routine to read the PIPA-s in a finer time interval to give a more detailed acceleration history. The main computational cycle is then set up by giving a priority of 16 to the program starting at ENTRYTOP.

*Details of the "wait list" and program control are in Ref. 6.

The UPTHETA1 job calls itself by putting a two second call to the Wait List for UPTHETA3, and UPTHETA3 calls UPTHETA with a priority of 14.

The computer variables are listed in fig. 6-2. The maximum value shows the value of the variable if the scaled variable had a value of one. (The real maximum is one bit less than this - 1 part in 2^{28} for double-precision variables.)

The unscaled constants are listed in fig. 6-3. The scaled constants, of course, appear in the AGC program listing.

	TIME SEC	SIZE WORDS
INITIALIZE	.117	57
READ PIPA-S	.001	105
NAVIGATE	.230	147
TARGETING	.270	147
MODE SELECTOR	.001	2
INITIAL ROLL	.015 .053	63
HUNTEST	.301 .350	316
CONSTANT DRAG CONTROL	.067	56
UP-CONTROL	.106 .136	111
BALLISTIC PHASE (INCLUDES ATTITUDE CONTROL)	.371	71
FINAL PHASE	.043	190
G-LIMITER	.009 .037	38
LATERAL LOGIC	.061	82
CONSTANTS	---	131

Fig. 6-1 Program speed and size.

VARIABLE -----	DESCRIPTION -----	MAXIMUM VALUE -----	COMPUTER NAME -----
URTO	INITIAL TARGET VECTOR	2 (UNIT VECTOR)	= RTINIT
UZ	UNIT VECTOR NORTH	2	= (UZ) OR UNITW
V	VELOCITY VECTOR	2 VSAT	= (V)
R	POSITION VECTOR	2 EXP 29 METERS	= RM
VI	INERTIAL VELOCITY	128 M/CENTISEC	= VPIP
RTE	VECTOR EAST AT INITIAL TARGET	2	= RTEAST
UTR	NORMAL TO RTE AND UZ	2	= RTNORM
URT	TARGET VECTOR	2	= (RT)
UNI	UNIT NORMAL TO TRAJECTORY PLANE	2	
DELV	INTEGRATED ACCEL. FROM PIPAS	5.85 16384 CM/S	
G	GRAVITY VECTOR	1/32 M/CS/CS	= GRAVITY
AO	INITIAL DRAG FOR UPCONTRL	805 FPSS	FPSS=FT/SEC/SEC
AHOOKDV	TERM IN GAMMAL CALC. = AHOOK DVL	805/16 VSAT FPS FPS	
ALP	CONST FOR UPCONTRL	1	
ASKEP	KEPLER RANGE	21600 NM	NM = NAUTICAL MILE
ASP1	FINAL PHASE RANGE	21600 NM	
ASPUP	UP-RANGE	21600 NM	
ASP3	GAMMA CORRECTION	21600 NM	
ASPDWN	RANGE DOWN TO PULL-UP	21600 NM	
ASP	PREDICTED RANGE	21600 NM	
COSG	COSINE(GAMMAL)	2	= COSG/2
D	TOTAL ACCELERATION	805 FPSS	
DO	CONTROLLED CONST. DRAG	805 FPSS	
DHOOK	TERM IN GAMMAL COMPUTATION	805 FPSS	
DIFF	THETNM-ASP (RANGE DIFFERENCE)	21600/16 NM	
DIFFOLD	PREVIOUS VALUE OF DIFF	21600/16 NM	
DR	REFERENCE DRAG FOR DOWNCONTROL	805 FPSS	
DREFR	REFERENCE DRAG	805 FPSS	
DVL	VS1-VL	2 VSAT	
E	ECCENTRICITY	4	
F1	DRANGE/D DRAG (FINAL PHASE)	2700/805	
F2	DRANGE/D RDOT (FINAL PHASE)	2700/2VS NM/FPS	
F3	DRANGE/D (L/D)	2700 NM	
FACT1	CONST FOR UPCONTRL	2 VSAT	
FACT2	CONST FOR UPCONTRL	1	
FACTOR	USED IN UPCONTRL	1	
GAMMAL	FLIGHT PATH ANGLE AT VL	1 RADIAN	
GAMMAL1	SIMPLE FORM OF GAMMAL	1 RADIAN	

Fig. 6-2 Computer Variables

VARIABLE	DESCRIPTION	MAXIMUM VALUE	COMPUTER NAME
K1ROLL	INDICATOR FOR ROLL SWITCH		
K2ROLL	INDICATOR FOR ROLL SWITCH		
LATANG	LATERAL RANGE	4 RADIANS	
LEQ	EXCESS C.F. OVER GRAV=(VSQ-V)GS	128.8 FPS	
L/D	DESIRED LIFT TO DRAG RATIO (VERTICAL PLANE)		
PREDANGL	PREDICTED RANGE (FINAL PHASE)	2700 NM	
Q7	MINIMUM DRAG FOR UPCONTROL	805 FPS	
RDOT	ALTITUDE RATE	2 VSAT	
RDOTREF	REFERENCE RDOT FOR UPCONTROL	2 VSAT	
RDTR	REFERENCE RDOT FOR DOWNCONT	2 VSAT	
ROLLC	ROLL COMMAND	8 REVOLUTIONS	
RTOGO	RANGE TO GO (FINAL PHASE)	2700 NM	
SL	SINE OF LATITUDE	1	
T	TIME	16384 SEC	= TENTRY
THETA	DESIRED RANGE (RADIANS)	2 PI RADIANS	= THETAH
THETNM	DESIRED RANGE (NM)	21600 NM	
V	VELOCITY MAGNITUDE	2 VSAT	
V1	INITIAL VELOCITY FOR UPCONTROL	2 VSAT	
VIOLD	PREVIOUS VALUE OF V1	2 VSAT	
VCORR	VELOCITY CORRECTION FOR UPCONTROL	2 VSAT	
VL	EXIT VELOCITY FOR UPCONTROL	2 VSAT	
VREF	REFERENCE VELOCITY FOR UPCONTROL	2 VSAT	
VS1	VSAT OR V1, WHICHEVER IS SMALLER	2 VSAT	
	$\frac{2}{2}$		
VBAR5	$\frac{VL}{VSAT}$	4	
	$\frac{2}{2}$		
VSQ	NORMALISED VEL. SQUARED = $\frac{V^2}{VSAT^2}$	4	= VSQUARE
WT	EARTH RATE TIMES TIME	1 REVOLUTION	= WIE (DTEAROT)
X	INTERMEDIATE VARIABLE IN G-LIMITER		
Y	LATERAL MISS LIMIT	4 RADIANS	

Fig. 6-2a Computer Variables (cont'd)

EXTRA COMPUTER ERASABLE LOCATIONS NOT SHOWN ON FLOW CHARTS

VARIABLE	DESCRIPTION	MAXIMUM VALUE
C/D0	SCALED RECIPROCAL OF D0	
GOTOADDR	ADDRESS SELECTED BY SEQUENCER	
XPIBUF	BUFFER TO STORE X PIPA COUNTS	
YPIBUF	BUFFER TO STORE Y PIPA COUNTS	
ZPIBUF	BUFFER TO STORE Z PIPA COUNTS	
PIPCTR	COUNTS PASSES THRU PIPA READ ROUTINE	
JJ	INDEX IN FINAL PHASE TABLE LOOK-UP	
M1	INDEX IN FINAL PHASE TABLE LOOK-UP	
GRAD	INTERPOLATION FACTOR IN FINAL PHASE	
FX	DRANGE/D L/D = F3	2700 NM
FX + 1	AREF	805 FPSS
FX + 2	RTOGO	2700 NM
FX + 3	RDOTREF	VSAT/4
FX + 4	DRANGE/D RDOT = F2	21600/2VS NM/FPS
FX + 5	DRANGE/D DRAG = F1	2700/805 NM/FPSS
UNITV	UNIT V VECTOR	2
UNITR	UNIT R VECTOR	2
TEM1B	TEMPORARY LOCATION	
SWITCHES		
(6)	GONEPAST	INDICATES OVERSHOOT OF TARGET
(7)	RELVELSW	RELATIVE VELOCITY SWITCH
(8)	EGSW	FINAL PHASE SWITCH
(9)	HUNTIND	INITIAL PASS THRU HUNTEST
(10)	HIND	INDICATES ITERATION IN HUNTEST
(11)	INRLSW	INDICATES INIT ROLL ATTITUDE SET

Fig. 6-2b Computer Variables (cont'd)

CONSTANTS AND GAINS		VALUE	
-----		-----	
C1	FACTOR IN ALP COMPUTATION	1.25	
C16	CONSTD GAIN ON DRAG	.01	
C17	CONSTD GAIN ON RDOT	.001	
C18	BIAS VEL. FOR FINAL PHASE START	500	FPS
C19	MINIMUM CONST DRAG	130	FPSS
C20	MAX DRAG FOR DOWN-LIFT	175	FPSS
CHOOK	FACTOR IN AHOOK COMPUTATION	.25	
CH1	FACTOR IN GAMMAL COMPUTATION	.75	
DCMAX	MAX CONST DRAG	175	FPSS
DT	COMPUTATION CYCLE TIME INTERVAL	2	SEC.
GMAX	MAXIMUM ACCELERATION	322	FPSS (10 G-S)
KA	DRAG TO ROLL UP IF DOWN INITIALLY (=KAT)	64.4	FPSS
K21	OPTIMIZED UPCONTROL GAIN	3.4	
K82	OPTIMIZED UPCONTROL GAIN	.0034	
KDWIN	INCREMENT ON Q7 TO DETECT END OF KEPLER PHASE	.5	FPSS
KLAT	LATERAL SWITCH GAIN	.0125	
KTETA	TIME OF FLIGHT CONSTANT	1000	
K44	GAIN USED IN INITIAL ROLL SECTION	44389312	FPS
LAD	MAX L/D (MIN ACTUAL VEHICLE L/D)	.3	
LATBIAS	LATERAL SWITCH BIAS TERM	.4	NM
L/DCWINR	LAD COS(15 DEG)	.2895	
LEWD	UPCONTROL L/D	.1	
LCD	FINAL PHASE L/D	.18	
Q2	FINAL PHASE RANGE - 23500 Q3	-1002	NM
Q3	FINAL PHASE DRANGE/D V	.07	NM/FPS
Q5	FINAL PHASE DRANGE/ D GAMMA	7050	NM/RAD
Q6	FINAL PHASE INITIAL FLIGHT PATH ANGLE	.0349	RAD
Q7F	MIN DRAG FOR UPCONTROL	6	FPSS
VFINAL	VELOCITY TO START FINAL PHASE ON INITIAL ENTRY	25000	FPS
VLMIN	MINIMUM VL	18000	FPS
VVIN	VELOCITY TO SWITCH TO RELATIVE VEL	VSAT/2	
VRCONTRL	RDOT TO START INTO HUNTEST	700	FPS
VCORLIM	MAX VALUE OF VCORR	1000	FPS
25NM	TOLERANCE TO STOP RANGE ITERATION	25	NM
VQUIT	VELOCITY TO STOP STEERING	1000	FPS
CONVERSION FACTORS AND SCALING CONSTANTS			

ATK	ANGLE IN RAD TO NM	3437.7468	NM/RAD
GS	NOMINAL G VALUE FOR SCALING	32.2	FPSS
HS	ATMOSPHERE SCALE HEIGHT	28500	FT
J	GRAVITY HARMONIC COEFFICIENT	.00162345	
KWE	EQUATORIAL EARTH RATE	1546.70168	FPS
MUE	EARTH GRAVITATIONAL CONSTANT	3.986032232	E 14 CUBIC M/ SEC SEC
RE	EARTH RADIUS	21202900	FT
VSAT	SATELLITE VELOCITY AT RE	25766.1973	FPS
WIE	EARTH RATE	.0000729211505	RAD/SEC

Fig. 6-3 Constants, Gains and Conversion Factors

RE-ENTRY CONTROL

0001 SETLOC 56000

R0002 THE PIPUP SECTION IS A TASK WHICH READS THE PIPAS EVERY .5
R0003 SECONDS. ACCELERATION HISTORY OVER THE LAST TWO SECONDS (FOUR READINGS)
R0004 IS MAINTAINED IN THE XPIBUP, YPIBUP, AND ZPIBUP REGISTERS. EACH PIPA
R0005 READING IS SUMMED INTO THE XPIPSUM ETC. REGISTERS, AND EVERY FOURTH READ
R0006 ING AVERAGE G IS CALLED TO USE THE SUMMED READINGS TO UPDATE POSITION
R0007 AND VELOCITY AND SET THE PIPSUM REGISTERS TO ZERO.

R0008 GOES THRU PIPUP ONLY EVERY 2 SEC. (ELSEWHERE MORE OFTEN.)

0009		CADR	REPIPASR	
0010	REPIFUP	CAF	-1	
0011		TC	PIPUP + 1	REREAD PIPAS IF NECESSARY.
0012		CADR	PIPASR	
0013	PIPUP	CAF	-1	
0014		TC	ISWCALL	GO TO PIPAREAD SUBROUTINE.
0015		CAF	THIRTN	PICK UP AT RED05.13
0016		TC	NEWPHASE	
0017		OCT	5	5.13 RESTART. (NO TIME CALL.)
0018	RED05.13	CAF	DT	
0019		TC	WAITLIST	
0020		CADR	PIPUP	
0021		CS	PIPTIME + 1	
0022		TS	TBASE5	SAVE NEW TIME.
0023		CAF	IPIPDY	
0024		TC	WAITLIST	
0025		CADR	INTERPIP	READ ACCELERATION MORE OFTEN.
0026		CAF	PRI016	
0027		TC	FINDVAC	
0028		CADR	ENTRYTOP	
0029		CAF	TWO	
0030		TS	PIPCTR	
0031		CAF	FOURTN	THIS WILL PICK UP AT ENTRYTOP + 3.
0032		TC	NEWPHASE	
0033		OCT	5	5.14 RESTART.
0034		TC	TASKOVER	

0035 IPIPDY DEC 50

RE-ENTRY CONTROL

P0036			JOB WHICH PROCESSES PIPA READINGS TO UPDATE POSITION AND VFLOCI
0037	ENTRYTOP	XCH	TENTRY
0038		AD	TWO
0039		XCH	TENTRY
			UPDATE ENTRY TIME.
			IN SECS SINCE START OF ENTRY.
0040		CAF	ONE
0041		TS	PIPAGE
0042		CS	DELVX
0043		TS	XPIPBUF + 3
0044		CS	DELVY
0045		TS	YPIPBUF + 3
0046		CS	DELVZ
0047		TS	ZPIPBUF + 3
			SAVE PIP COUNTS.
0050		TC	PHASCHNG
0051		OCT	01705
0052		TC	BANKCALL
0053		CADR	1/PIPA
			5.15 RESTART PICKS UP AT REFAZE4. COMPENSATE THE PIPA DATA
0054	REFAZE4	TC	INTPRET
0055		ITC	0
0056			CALCRVG
A0057			GO TO AVERAGE G INTEGRATION ROUTINES TO USE PIPA READINGS TO UPDATE POSITION AND VELOCITY.
0058		TC	PHASCHNG
0059		OCT	02105
			5.17 RESTART AT REFAZE8.
0060	REFAZE8	TC	INTPRET

RE-ENTRY CONTROL

```

P0061  PROCESS AVERAGE G OUTPUT...SCALE IT AND GET INPUT DATA

0062  SCALEPOP VXSC 0
0063      VPIP
0064      KVSCALE
0065      STORE (V)
                                KVSCALE = (12800/.3048)0(25766.1973 X2)
                                KVSCALE = .81491944
                                V VECTOR

0066      TEST 2
0067      VXV VXSC
0068      VAD
                                (VREL) = (V) + KWE UNITR*UNITW
0069      RELVELSW
0070      GETUNITV
0071      UNITR
0072      UNITW
0073      KWE
0074      (V)
0075      STORE (V)
                                SWITCH NUMBER.
                                NEW V VECTOR IS RELATIVE.

0076  GETUNITV NOLOD 1
0077      UNIT
0078      STORE UNITV
                                HALF MAX. OF COURSE.

0079      TSLT 0
0080      28D
0081      2
0082      STORE VSQUARE
                                RESCALE MAGNITUDE SQUARED.
                                SHIFT COUNT. (2 BECAUSE HALF-LEN SORD
                                VELOCITY SQUARED. (NORMAL SCALING)

0083      DSU 0
0084      VSQUARE
0085      FOURTH
0086      STORE LEQ
                                LEQ = VSQUARE-1
                                4 G-S FULL SCALE

0087      TSLT 0
0088      30D
0089      1
0090      STORE V

0091      DOT 1
0092      TSLT
0093      (V)
0094      UNITR
0095      1
0096      STORE RDOT
                                RDOT = V.UNITR
                                AND SCALE BACK UP. UNITS ARE 1/2.

```

RE-ENTP™ CONTROL

0097		DMOVE	0	SAVE OLD DRAG VALUE.
0098			D	
0099		STORE	COLD	
0100		ABVAL	2	
0101		TSLT	DMP	
0102		BZF		
0103			DELV	KASCALE=5.85 16384/(4 .3048 805 100)
0104			2	2 FOR 2 SEC. 3 FOR 1 SEC. 4 FOR .5 --
0105			KASCALE	= 3. /4 /25
0106			SETMIND	
0107		STORE	D	ACCELERATION (DRAG, ALMOST)
0108	GETUNI	VXV	1	UNI = UNIT(V*R)
0109		UNIT		
0110			(V)	COULD USE UNITV.
0111			UNITR	
0112		STORE	UNI	INERTIAL OR RELATIVE AS IS (V).
R0113	SOME OF THE FOLLOWING TARGETTING MIGHT BE DONE LESS OFTEN THAN ABOVE.			
0114		TEST	1	THIS TEST MIGHT BE COMBINED WITH THE
0115		DMOVE		PREVIOUS ONE IF ALL CALCULATIONS ARE
0116			RELVELSW	DONE EVERY CYCLE.
0117			GETETA	
0118			PIPTIME	
0119		STORE	DTEAROT	

RE-ENTRY CONTROL

0120	UPDATERT	ITC	0	UPDATE PREDICTED TARGET VECTOR RT
0121			EARROT2	
0122		NOLOD	1	
0123		DOT	RTB	SINCE (RT) UNIT VEC, THIS IS 1/4 MAX.
0124			UNI	LATANG = RT*UNI
0125			FRESHPD	
0126		STORE	LATANG	LATANG = MAC LATANGLE/4 (NO 2 PI)
A0127				UNUSUAL SCALING FOR LATANG. (= ASIN L.
0128	GETANGLE	DOT	3	THETA = ARCCOS(RT*UNITR)
0129		DSU	BPL	RT IS UNIT VECTOR
0130		DAD	TSLT	
0131		ACOS		
0132			RT	
0133			UNITR	
0134			NEAR1/4	TO IMPROVE ACCURACY, CALC RANGE BY
0135			TINYTHET	TINYTHET IF HIGH ORDER PART OF
0136			NEAR1/4	ARCCOS ARGUMENT IS ZERO
0137			1	
0138		STORE	THETAH	
0139		EXIT	0	
0140	REFAZE10	TC	PHASCHNG	
0141		OCT	02205	5.18 RESTART AT REFAZE10
0142		TC	INTPRET	

RE-ENTRY CONTROL

P0143 JUMP TO PARTICULAR RE-ENTRY PHASE.

0144 SEQUENCE ITC1 0 BRANCHES TO VARIOUS CONTROL PHASES.
0145 GOTOADDR ADDRESS OF PHASE EQU STORED HERE.

R0146 GOTOADDR CONTAINS THE ADDRESS OF THE ROLL COMMAND EQUATIONS
R0147 APPROPRIATE TO THE CURRENT PHASE OF RE-ENTRY. SEQUENCING IS AS FOLLOWS:

R0148 INITROLL SET HERE INITIALLY. HOLDS INITIAL ROLL ATTITUDE UNTIL KAT EX-
R0149 CEDED. THEN HOLDS NEW ROLL ATTITUDE UNTIL VRTHRESH EXCEEDED.
R0150 THEN BRANCHES TO

R0151 HUNTEST THIS SECTION CHECKS TO SEE IF THE PREDICTED RANGE AT NOMINAL
R0152 L/D FROM PRESENT CONDITIONS IS LESS THAN THE DESIRED RANGE
R0153 IF NOT-- A ROLL COMMAND IS GENERATED BY THE CONSTANT DRAG
R0154 CONTROLLER.
R0155 IF SO-- CONTROL AND GOTOADDR ARE SET TO UPCONTRL
R0156 USUALLY NO ITERATION IS INVOLVED EXCEPT IF THE RANGE DESIRED IS
R0157 TOO LONG ON THE FIRST PASS THRU HUNTEST.

R0158 UPCONTRL CONTROLS ROLL DURING THE SUPER-CIRCULAR PHASE. UPCONTRL IS TERM-
R0159 INATED EITHER (A) WHEN THE DRAG (AS MEASURED BY THE PIPAS)
R0160 FALLS BELOW Q7 OR (B) IF RDOT IS NEGATIVE AND REFERENCE VL
R0161 EXCEEDS V. IN CASE (A), GOTOADDR IS SET TO KEP2 AND IN (B) TO
R0162 PREDICT3. SKIPPING THE KEPLER PHASE OF ENTRY.

R0163 KEP2 GOTOADDR IS SET HERE DURING THE KEPLER PHASE TO MONITOR DRAG.
R0164 SPACECRAFT IS INSTANTANEOUSLY TRIMMED IN PITCH AND YAW TO THE
R0165 COMPUTED RELATIVE VELOCITY VECTOR. THE LAST COMPUTED ROLL
R0166 ANGLE IS MAINTAINED. WHEN THE MEASURED DRAG EXCEEDS Q7+.5,
R0167 GOTOADDR IS SET TO

R0168 PREDICT3 THIS CONTROLS THE FINAL SUB-ORBITAL PHASE. ROLL COMMANDS CEASE
R0169 WHEN V IS LESS THAN VQUI. AN EXIT IS MADE TO TERMALT WHEN
R0170 TERMINAL ALTITUDE IS REACHED.

RE-ENTRY CONTROL

P0171 OUT OF SEQUENCE SUBSECTION TO COMPUTE ETA.

0172 BOOKMARK EQUALS

0173 SETLOC ENDRTHSS

0174 GETETA TEST 1

0175 DMP

NOT USED AT LOW VEL WHERE THETA NEG.

0176 EGSW

BRANCHES IF INTO EQ. GLIDE PHASE.

0177 SUBETA

0178 THETAH

0179 KTETA

= 1000X2PI/(2)E1, 163.84

0180 STORE ETA

DONT REALLY WANT IT, BUT NO PUSH WANTED

0181 GETETA2 NOLOD 1

0182 DAD

0183 PIPTIME

0184 STORE DTEAROT

0185 ITC 0

0186 UPDATERT

0187 SUBETA DSU 1

SWITCH FROM INERTIAL TO RELATIVE
VELOCITY WHEN V LESS THAN .5 VSAT.

0188 BPL SWITCH

0189 V

0190 FOURTH

0191 SUBETA2

0192 RELVELSW

SHOULD CHANGE TO OFF (NON-BRANCH) STATE

0193 SUBETA2 DMP 1

0194 DDV ITC

0195 THETAH

0196 KT

KT = RE(2 PI)/ 2 VS 16384 163.84
/2 VSAT

0197 V

0198 GETETA2

0199 SETMIND DMOVE 0

MAKE D NON-ZERO.

0200 1BITDP

0201 STORE D

0202 ITC 0

0203 GETUNI

0204 TINYTHET NOLOD 3

ENTER WITH X=.249

0205 DSU ABS

GET 1/4 - MPAC

0206 TSLT SQRT

SCALE UP BEFORE SQRT.

0207 DMP

HAS FACTOR FOR UP SCALING.

0208 1BITDP + 1

X = SQRT(2(1-COSX)), IN RADIANS

0209 13D

X/2PI=(1/64PI)(SGRT(((1-COSX)/4)2EXP13)

0210 KACOS

0211 STORE THETAH

0212 RTB 0

OFF TO PRE-SEQUENCER...

0213 REFAZE10

RE-ENTRY CONTROL

PO214 MAINTAINS INITIAL ROLL UNTIL D = KAT, GOES INTO HUNTEST WHEN
RO215 RDOT = VRCONT.

0216 BOOKMRK1 EQUALS
0217 SETLOC BOOKMARK

0218 HUNTCADR CADR HUNTEST

0219 INITROLL TEST 2 IF D=.05 G NEG, GO TO LIMITL/D
0220 DSU BMN IF NOT, SET .05 G SWITCH FOR SCS
0221 EXIT

0222 INRLSW
0223 INITRL1
02231 D
02232 .05G
02233 LIMITL/D

0224 TC RELAYON SEND .05 G SIGNAL TO SCS.
0225 OCT 40100
0226 TC NEWMODE SET MODE TO AFTER .05 G STATE.
0227 OCT 00064
0228 TC INTPRET

022802 DMOVE 0
022804 LAD
022806 STORE L/D

022808 SWITCH 2 IF V-VFINAL NEG, GO TO FINAL PHASE
02281 DSU BPL
022812 RTB
022814 INRLSW
022816 V
022818 VFINAL
02282 UPDWNTST

022822 CAF KEPCADR
022824 TS GOTOADDR
022826 TC INTPRET

022828 ITC 0
02283 LIMITL/D

022832 UPDWNTST DDV 0
022834 RDOT
022836 V RESULT INTO PD

022838 NOLOD 5 IF V-VFINAL+K(RDOT/V)CUBED POS, L/D=-LAD
02284 DSQ DMP
022842 DDV DSU
022844 DAD BOV
022846 BMN LODON
022848 DSU
02285

RE-ENTRY CONTROL

022854		K44	
022856		VFINAL	
022858		V	
02286		LIMITL/D	
022862		LIMITL/D	
022864		LAD	
022866	STORE	L/D	
022868	ITC	0	
02287		LIMITL/D	
022872	INRLSW	EQUALS	LATSW
0229	INITRL1	DSU	2
0230		BPL	LODON
0231		DMOVE	
0232		KAT	
0233		D	
0234		VRTHRES	
0236		LAD	
0237	STORE	L/D	
0238	VRTHRES	DAD	1
0239		BMN	EXIT
0240			RDOT
0241			VRCONT
0242			LIMITL/D
A0243			
0244	CAF		HUNTCADR
0245	TS		GOTOADDR

IF KAT-D POS, GO TO OUT WITH COMMAND
IF NEG, L/D = LAD

WHEN D GREATER THAN KAT, L/D = LAD

IF RDOT + VRCONT NEG, GO TO STEER
IF POS, SET SELECTOR TO HUNTEST.

DO LATERAL CONTROL IF NEEDED. SPACER.

AND FALL THRU INTO HUNTES1.

RE-ENTRY CONTROL

P0246 ... HUNTEST SECTION... CHECKS TO SEE WHEN PREDICTED RANGE = DESIRED ONE

0247	PREHUNT	TC	INTPRET,	
0248	HUNTEST	DMOVE	0	IF RDOT POS, TEM1B = LAD
0249			I AD	
0250		STORE	TEM1B	
0251		BMN	1	
0252		LODON	DMOVE	
0253			RDOT	
0254			AOCALC	
0255			LEWD	
0256		STORE	TEM1B	
0257	AOCALC	DDV	1	$V1 = V + RDOT/TEM1B$
0258		DAD		
0259			RDOT	
0260			TEM1B	
0261			V	
0262		STORE	V1	
0263		DSQ	3	$AO = (V1/V) SQ(DO + RDOT SQ/(TEM1B^2 C1 HS))$
0264		DDV	DDV	
0265		DAD	DMP	
0266		DMP	DDV	
02661			RDOT	
02662			TEM1B	
02663			2C1HS	
02664			D	
02665			V1	
02666			V1	
02667			VSQUARE	
02668		STORE	AO	
0267	TESTHSW	TEST	1	IF HUNTSW1 ON (BRANCH), GO TO HUNTEST1
0268		DMOVE	SWITCH	HUNTSW1 = HUNTIND
0269			HUNTSW1	
0270			HUNTEST1	
0271			AO	
0272			HUNTSW1	DO = AO
0273		STORE	DO	
0274		DSU	1	IF C19-D POS, DO = C19
0275		BMN	DAD	
0276			C19	
0277			DO	
0278			MAXTST1	
0279			DO	
0280		STORE	DO	
02801	MAXTST1	DSU	1	IF DO-DOMAX POS, DO = DOMAX
02802		BPL	DAD	
02803			DOMAX	
02804			DO	
028045			HUNTEST2	

RL-ENTRY CONTROL

02805		DO	
02806	STORE	DO	
0281	HUNTEST2	DDV	0
0282		C001	
0283		DO	
0284	STORE	C/DO	
0285	DMOVE	0	ZERO DIFFOLD THE FIRST TIME THRU.
0286		3ZEROS	
0287	STORE	DIFFOLD	
0288	DAD	0	$V1OLD = V1 + C18 \quad (500FPS)$
0289		V1	MAKES OLD V CORR -500 AND NEW +500 ..
0290		C18	INITIAL VALUE ON V CORR = -100 FPS SO
0291	STORE	V1OLD	(INITIAL VALUES IF NEEDED ON 1ST PASS)
0292	DMOVE	0	$Q7 = Q7F$
0293		Q7F	
0294	STORE	Q7	
0295	HUNTEST1	DMP	2
0296		DDV	RTB
0297		DDV	
0298		A0	
0299		2HSD/LWD	
0300		V1	
0301		FRESHPD	
0302		V1	
0303	STORE	ALP	$ALP = A0 \quad 2HSD/LWD / V1 \quad V1$
0304	NOLOD	1	
0305	BDSU	BDDV	
0306		NEARONE	$FACT1 = V1 / (1 - ALP)$
0307		V1	
0308	STORE	FACT1	
0309	DSU	1	
0310	DMP	DDV	$FACT2 = ALP(ALP - 1) / A0$
0311		ALP	
0312		NEARONE	
0313		ALP	
0314		A0	
0315	STORE	FACT2	
0316	DMP	2	$VL = FACT1(1 - SQRT(ALP + Q7 \quad FACT2))$
0317	DAD	SQRT	
0318	BDSU	DMP	
0319		Q7	
0320		FACT2	
0321		ALP	
0322		NEARONE	
0323		FACT1	
0324	STORE	VL	

PE-ENTRY CONTROL

0325	NOLOD	2	GAMMAL = LEWD(VI-VL)/VI
0326	BDSU	DMP	
0327	DDV		
0328		V1	
0329		LEWD	
0330		VL	
0331	STORE	GAMMAL1	GAMMAL1 USED IN UPCTRL
0332	DSU	1	IF VL-VMIN NEG. GO TO SHORT
0333	BMN		
0334		VL	
0335		VMIN	
0336		PREFINAL	PREFINAL = SHORT
0337	DSQ	0	VRARS = VL VL
0338		VL	
0339	STORE	VBARS	
0340	DSU	1	IF VSA1 - VL NEG. GO TO CONSTD.
0341	BMN		
0342		HALVE	VSA1 = .5
0343		VL	
0344		BECONSTD	GOTOADDR MAY BE SIDETRACKED.
0345	STORE	DVL	DVL = VSA1 - VL
0346	DMOVE	0	
0347		HALVE	VS = VSA1
0348	STORE	VS	
0349	NOLOD	2	
0350	DSU	BMN	IF V1 GREATER THAN VSA1, GO ON.
0351	BDSU		
0352		V1	
0353		GETDHOOK	
0354		DVL	DVL = DVL - (VSA1-V1) = V1 - VL
0355	STORE	DVL	
0356	DMOVE	0	
0357		V1	
0358	STORE	VS	VS = V1
0359	GLTDHOOK	TSRT 3	DHOOK = ((1-VS/FACT1).SQ - ALP)/FACT2
0360		DDV BDSU	
0361		TSRT DSU	
0362		DDV DDV	
0363		VS VS	
0364		1 1	
0365		FACT1 FACT1	
03655		HALVE HALVE	
0366		1 1	
0367		ALP ALP	
0368		FACT2 FACT2	
0369	STORE	DHOOK	
0370	TSRT	1	RESCALE BY 32.
0371	DDV	DSU	

RE-ENTRY CONTROL

0372		DHOOK
0373		5
0374		Q7
0375		CHOOK
0376	STORE	AHOOKDV

0377	NOLOD	4
0378	DAD	DMP
0379	DMP	DMP
0380	DDV	DDV
0381	BDSU	BMN
0382		1/8TH
0383		CH1
0384		DVL
0385		DVL
0386		DHOOK
0387		VBAR5
0388		GAMMAL1
0389		NEGAMA
0390	STORE	GAMMAL

GAMMAL = GAMMAL1-CH1 DVL5Q(1+AHOOK DVL
/DHOOK VBAR5

FIND CONDITIONS FOR GAMMAL = 0.

R-ENTRY CONTROL

```

P0391      ... PREDICT RANGES FOR EACH PHASE OF TRAJECTORY...

0392  RANGER  DSQ   1
0393          TSRT  BLSU
0394          GAMMAL
0395          2
0396          HALVE
0397          STORE COSG/2

0398          DSU   3
0399          DMP   DMP
0400          DMP   TSLT
0401          DAD   SQRT
0402          VBARS
0403          HALVE
0404          VBARS
0405          COSG/2
0406          COSG/2
0407          2
0408          C1/16

0409          DMP   2
0410          DMP   DDV
0411          ASIN  TSLT
0412          VBARS
0413          COSG/2
0414          GAMMAL
0415          -
0416          1

0417          DMP   1
0418          DAD   DAD
0419          VL
0420          Q3
0421          Q2

0422          DSQ   3
0423          DMP   DCV
0424          DDV   RTB
0425          DMP   DDV
0426          V1
0427          Q7
0428          VBARS
0429          A0
0430          LOG
0431          C12
0432          GAMMAL1

0433          DMP   1
0434          DMP   DDV
0435          KC3
0436          RDOT
0437          V
0438          A0

```

COSG = 1-GAMMAL SQ/2 • TRUNCATED SERIES
 $E = \sqrt{(1 + VBARS - 2)VBARS \text{ COSG} \text{ COSG}}$
 MULT BY 4
 E (E/4 REALLY) INTO PD.
 ASKEP/2 = ARCSIN(VBARS COSG SING/E)
 E FROM PD.
 ASKEP INTO PD.
 $ASP1 = Q2 + C3(VL - Q4) = Q2' + Q3 \text{ VL}$
 ASP1 + ASKEP INTO PD.
 $ASPUP = -C12 \text{ LOG}(V1 \text{ V1 } Q7 / VBARS \text{ D}) / \text{GAMMAL1}$
 ASPUP UNTO PD
 $ASPDWN = KC3 \text{ RDOT } V / A0$
 ASPDWN INTO PD.

KL-ENTRY CONTROL

0439		DSU	2	ASP3 = Q5 (Q6-GAMMAL)
0440		DMP	DAD	
0441		DAD	DAD	
0442			Q6	
0443			GAMMAL	ASP = ASP1+ASKEP+ASPUP+ASP3
0444			Q5	ASP INTO PD
0445		NOLOD	1	
0446		BDSU	TSRT	
0447			THETAH	
0448			4	DIFF = (ASP-THETA)/16
0449		STORE	DIFF	END OF TEST
0450		NOLOD	4	
0451		ABS	DSU	IF ABS((THETAH-ASP) - 25NM NEG, GOTOUPSY
0452		BMN	TEST	IF HIND SET, GO TO GET LV THE REPEATWAY
0453		LODON	BMN	IF DIFF NEG, GO TO CONSTD
0454		LODON	DSU	VCCRR = V1 - V1OLD
0455			25NM	
0456			GOTOUPSY	
0457			HIND	
0458			GETVCOR	
0459			DIFF	
0460			DCONSTD	SETTING UP DIFFOLD ON THE WAY
0461			V1	
0462			V1OLD	VCORR = V1 - V1OLD
0463		STORE	VCORR	
0464	GETVCOR	DSU	1	
0465		DDV	BDDV	VCORR = VCORR(DIFF/(DIFFOLD-DIFF))
0466			DIFFOLD	
0467			DIFF	
0468			VCORR	
0469			DIFF	
0470		STORE	VCORR	
0471		EXIT	0	
0472		TC	PHASCHNG	HAVE GROUP 3 PICK UP AT PREHUNT.
0473		OCT	02003	3.16 RESTART.
0474		CAF	ADENEXT	SIDETRACK NEXT PASS UNTIL THIS ONE DONE.
0475		TS	GOTOADDR	ONLY AFTER RESTART IS LEFT AFTER DETOUR.
0476		TC	INTPRET	
0477		NOLOD	2	
0478		BDSU	BPL	IS VCORR - 1000 POS.
0479		DAD		VCORR = 1000
0480			VCOR'.IM	
0481			CHKVL	
0482			VCORR	LEAVING VCORLIM IN MPAC
0483		STORE	VCORR	

RE-ENTRY CONTROL				
0484	CHK VL	DAD	2	
0485		DSU	RMN	IF VL + VCORR - VSAT POS. VCORR=VCORR/
0486		LODCH	TSRT	
0487			VCORR	
0488			VL	
0489			HALVE	
0490			GETNUV1	
0491			VCORR	
0492			1	
0493		STORE	VCORR	
0494	GETNUV1	DAD	0	
0495			V1	
0496			VCORR	
0497		STORE	V1	
0498		DMOVE	0	SAVE OLD VALUE OF ASP
0499			DIFF	
0500		STORE	DIFFOLD	
0501		TEST	1	SET ND AND GO TO HUNTEST1
0502		SWITCH	ITC	
0503			HIND	
0504			HUNTEST1	
0505			HIND	
0506			HUNTEST1	
0507	NEGAMA	NOLOD	1	ENTER WITH GAMMAL IN MPAC
0508		DMP	DMP	FIND GAMMAL VL / 3
0509			VL	
0510			1/3RD	.. AND PUSH DOWN PARTIAL RESULT..
0511		DAD	3	
0512		DMP	DMP	DEL VL = GAMMAL VL/3)/(LEWD/3 - DVL(2/3
0513		DDV	DDV	+ AHOOKDV)(CH1 GS/DHOOK VL))
0514		BDSU	BDDV	
0515			AHOOKDV	
0516			1/12TH	
0517			DVL	
0518			CH1	
0519			DHOOK	
0520			VL	
0521			LEWD/3	OUT OF AND BACK INTO PD.
0522		DAD	0	
0523			VL	
0524		STORE	VL	VL = VL + DEL VL
0525		NOLOD	3	VL IS IN MPAC
0526		DDV	BDSU	Q7 = ((1-VL/FACT1)SQ - ALP)/ FACT2
0527		DSG	DSU	
0528		DDV		
0529			FACT1	

PE-ENTRY CONTROL

0530			NEARONE	
0531			ALP	
0532			FACT2	
0533		STORE	QT	
05332		DSQ	0	GET NEW VBARS.
05334			VL	
05336		STORE	VBARS	
0534		DMOVE	0	
0535			3ZEROS	
0536		STORE	GAMMAL	GAMMAL = 0
0537		ITC	0	
0538			RANGER	
0539	UPCADR	CADR	UPCONTRL	
0540	GOTOUPSY	EXIT	0	BACK TO BASIC.
0541	HUNTDUMP	CAF	UPCADR	RESET GOTOADDR
0542		TS	GOTOADDR	
0543		TC	NEWMODE	CHANGE MODE TO SIGNAL END OF HUNT-TEST.
0544		OCT	00065	
0545		CS	ONE	MAKE GROUP 3 INACTIVE WHEN DONE WITH
0546		TC	NEWPHASE	THE ITERATIONS.
0547		OCT	3	GROUP 3.
0548		TC	INTPRET	... AND GO INTO UPCONTROL...

RE-ENTRY CONTROL

P0549 THIS SECTION IS THE UPCONTROL FOR THE SUPERELLIPTICAL PHASE

0550	UPCNTRL	DSU	3	IF V-V1 POS, GO TO DOWNCONTROL
0551		BPL	LODON	IF D-Q7 NEG, GO TO KEP
0552		DSU	PMN	
0553		LODON	BMN	IF RDOT NEG, GO TO VLTFST
0554			V	VLTEST TESTS FOR START OF FINAL PHASE
0555			V1	
0556			DOWNCNTRL	
0557			D	
0558			Q7	
0559			KEP	SET CONSTS, ETC FOR BALLISTIC PHASE.
0560			RDOT	
0561			VLTEST	
0562	CONT1	DSU	1	
0563		BPL		
0564			D	IF D=A0 NEG, L/D=LAD, GO TO 310
0565			A0	
0566			GOPOSLAD	
0567		DMP	2	VREF=FACT1(1-SQRT(FACT2 D + ALP))
0568		DAD	SQRT	
0569		BDSU	DMP	
0570			D	
0571			FACT2	
0572			ALP	
0573			NEARONE	
0574			FACT1	
0575		STORE	VREF	
0576		NOLOD	1	RDOTREF = LEWD(V1-VREF)
0577		BDSU	DMP	
0578			V1	
0579			LEWD	
0580		STORE	RDOTREF	
0581		DSU	1	IF VSAT - VREF NEG, GO TO CONTINU2
0582		BMN	NOLOD	NOLOD TO PUSH DOWN (HALVE-VREF)
0583			VS	
0584			VREF	NO RDHOOK UNTIL VREF LESS THAN VSAT.
0585			CONTINU2	PUSHING DOWN IF NO BRANCH.
0586		NOLOD	5	RDHOOK=CH1(AHOOKDVL/DVL(DV+1))DV DV
0587		DMP	DDV	/DHOOK VREF
0588		DAD	DMP	WHERE DV = VS - VREF
0589		DMP	DMP	
0590		DDV	DDV	
0591		BDSU		
0592			AHOOKDV	
0593			DVL	
0594			1/8TH	
0595			CH1	
0596			0	ABOVE SHOULD HAVE PUSHED INTO LOC 0.
0597			-	
0598			DHOOK	

FI-ENTRY CONTROL

0599			VREF	
0600			RDOTREF	
0601		STORE	RDOTREF	RDOTREF = RDOTREF - RDHOOK
0602	CONTINU2	DSU	0	
0603			A0	FACTOR = (D-Q7)/(A0-Q7)
0604			Q7	PARTIAL RESULT IN PD
0605		DSU	1	
0606		DDV		
0607			D	
0608			Q7	FACTOR INTO PD
0610		DSU	3	L/D = LEWD
0611		DMP	DDV	-((PDOT-RDOTREF)F1/KB1+V-VREF)F1/KB2
0612		DAD	DSU	
0613		DMP	DDV	
0614			RDOT	
0615			RDOTREF	
0616			0	
0617			KB1	
0618			V	
0619			VREF	
0620			-	KB2 IS NEGATIVE
0621			KB2	DELTA L/D INT PD
0622		BOV	3	NON-LINEAR CIRCUIT FOR REDUCING HIGH
0623		ABS	DSU	GAINS HERE
0624		BMN	DMP	
0625		DAD	SIGN	
0626			GOMAXL/D	
0627			0	
0628			POINT1	
0629			NEXT1	
06291			POINT1	
06292			POINT1	
06293	NEXT1	DAD	1	
06294		BOV		
06295			LEWD	
06296			-	
06297			GOMAXL/D	
06298		STORE	L/D	
062991	NEGTESTS	NOLOD	3	IF L/D NEG, AND D-C20 POS, L/D = 0
062992		BPL	LODON	
062993		DSU	BMN	
062994		DMP		
0630			LIMITL/D	
0631			D	
0632			C20	
0633			LIMITL/D	
0635			3ZEROS	L/D = 0 (NO NEG LIFT)
0636		STORE	L/D	
0637		ITC	0	
0638			LIMITL/D	

RE-ENTRY CONTROL

P0639		CONSTANT DRAG CONTROLLER		
0640	BCONSTD	DMOVE	0	
0641			DIFF	SAVE OLD VALUE OF DIFF FOR NEXT PASS.
0642		STORE	DIFFOLD	
0643		DMOVE	0	V1OLD = V1
0644			V1	
0645		STORE	V1OLD	
0646	By CONSTD	AXT+1	1	RESETS GOTOADDR TO GO TO HUNTEST
0647		SXA+1		
0648			HUNTEST	
0649			GOTOADDR	
0650	CONSTD	DMP	0	
0651			LEQ	
0652			C/D0	C/D0 LEQ INTO PD
0653		DMP	2	
0654		DDV	DAD	
0655		DMP	DAD	
0656			2HS	RDOTREF = - 2 HS D0/V
0657			D0	
0658			V	
0659			RDOT	
0660			K2D	C/D0 LEQ + K2D(RD01-RDOTREF) INTO PD
0661		DMOVE	0	
0662			D0	D0 INTO PD
0663	CONSTD1	DSU	2	
0664		DMP	DAD	
0665		TSLT	BOV	
0666			D	
0667			-	
0668			K1D	
0669			-	
0670			8D	
0671			GOMAXL/D	
0672		STORE	L/D	
0673		ITC	0	
0674			NEGTESTS	
0675	DOWNCNTL	DSU	2	RDTR = LAD(V1-V)
0676		DMP	DAD	
0677		DMP	DAD	
0678			V	
0679			V1	
0680			LAD	
0681			RDOT	
0682			K2D	
0683			LAD/256	LAD + K2D(RDOT-RDTR) INTO PD
0684		DSU	1	

RE-ENTRY CONTROL

0685		DSQ	DDV	
0686			V1	
0687			V	
0688			2C1HSLAD	(V1-V)SQ/(2 C1 HS/LAD) INTO PD
0689		DSQ	?	DPRE = ((V/V1)SQ AD) = PD
0690		DDV	BDDV	
0691		DSU		
0692			V1	
0693			V SQUARE	
0694			A0	
0695		ITC	0	
06951			CONSTD1	
0696	KEP	EXIT	0	
0697		CAF	KEPCADR	SET GOTOADDR TO KEPLER PHASE.
0698		TS	GOTOADDR	
0699		TC	NEWMODE	SET MODE TO KEPLER PHASE.
0700		OCT	00066	
0701		TC	INTPRET	
0702	KEP2	DAD	1	IF Q7+KDMIN = D NEG, GO TO FINAL PHASE
0703		DSU	BMN	
0704			Q7	MIN DRAG = Q7 + .5 FT/SEC/SEC
0705			KDMIN	
0706			D	
0707			PREFINAL	FALL THRU IF POS.
0708	ENDEXIT	EXIT	0	GOTOADDR IS SET HERE DURING VLHUNT.
0709		TC	OVERNOUT	
0710	KEPCADR	CADR	KEP2	
0711	P3CADR	CADR	PREDICT3	
0712	VLTEST	DSU	1	IF V-VL-C18 NEG,EGSW=1,SELECTOR=PREDIC
0713		DSU	BPL	GO TO PREDICT3
0714			V	
0715			VL	
0716			C18	
0717			CONT1	
0718	PREFINAL	SWITCH	1	
0719		EXIT		
0720			EGSW	
0721		CAF	P3CADR	
0722		TS	GOTOADDR	SET TO PREDICT3 PHASE.
0723		TC	NEWMODE	
0724		OCT	00067	
0725		TC	INTPRET	... AND FALL INTO PREDICT3...

RE-ENTRY CONTROL

00726 SUBORBITAL CONTROL (REFERENCE TRAJECTORY BY TABLE LOOK-UP.)

0727	PREDICT3	DSU	4	
0728		BMN	LODON	IF V - VQUIT NEG, STOP STEERING
0729		TEST		
0730		VXV	DOT	IF (RT)*UNITR*UNI NEG, SET GONEPAST
0731		BMN	EXIT	
0732			V	
0733			VQUIT	
0734			STEER	
0735			GONEPAST	
0736			GONEGLAD	
0737			RT	
0738			UNITR	
0739			UNI	(MIGHT SAVE THIS FROM EARLIER..)
0740			SETGPAST	
0741		CS	NEG14	
0742	BACK	TS	JJ	
0743		CS	V	
0744		INDEX	JJ	
0745		AD	VREFER	VREF - V, HIGHEST VREF AT END OF TABLE.
0746		CCS	A	IF VREF-V POS LOOP BACK
0747		CCS	JJ	DECREMENT JJ • JJ CANNOT BE ZERO
0748		TC	BACK	
0749		AD	ONE	
0750		TS	TEM1B	V-VREF IN TEM1B (MUST BE POSITIVE NUM)
0751		INDEX	JJ	
0752		CS	VREFER	
0753		INDEX	JJ	
0754		AD	VREFER + 1	$V(K+1) - V(K)$ (POS NUM)
0755		XCH	TEM1B	
0756		EXTEND		
0757		DV	TEM1B	
0758		TS	GRAD	$GRAD = (V-VREF)/(VK+1 - VK)$ (POS NUM)
0759		CAF	FIVE	
0760	HACK2	TS	M1	
0761		CAF	DEC15	
0762		AD	JJ	
0763		TS	JJ	
0764		INDEX	A	
0765		CS	VREFER	
0766		INDEX	JJ	
0767		AD	VREFER + 1	$X(K+1) - X(K)$
0768		EXTEND		
0769		MP	GRAD	
0770		INDEX	JJ	
0771		AD	VREFER	
0772		INDEX	M1	
0773		TS	FX	$FX = AK + GRAD (AK+1 - AK)$
0774		CCS	M1	

PI-ENTRY CONTROL

0775	TC	BACK2	
0776	CAF	ZERO	ZERO FX + 1
0777	XCH	FX + 1	DREFR
0778	AD	D	
0779	EXTEND		
0780	MP	FX + 5	F1
0781	TS	TEM1B	TEM1B= F1(D-DREF)
0782	CS	RDOT	FORM RDOTREF - RDOT
0783	DOUBLE		
0784	DOUBLE		SCALE UP BY 6 FOR THIS PHASE.
0785	DOUBLE		
0786	AD	FX + 3	RDOTREF
0787	EXTEND		
0788	MP	FX + 4	F2
0789	AD	TEM1B	ADD F2(DADV1-DADVR)
0790	AD	FX + 2	RTOGO
0791	XCH	PREDANG	NO OVERFLOW SKIP PLEASE.
0792	TC	INTPRET	
0793	SMOVE	4	
0794	TSRT	BDSU	THETAH - PRED ANGLE
0795	DDV	TSLT	
0796	BOV	DAD	$L/D = LOD + (THET-PA)/Y$
0797	BOV		
0798		PREDANG	
0799		3	
0800		THETAH	
0801		FX	$X = DRANGE/D \quad L/D = Y$
0802		5	
0803		GOMAXL/D	
0804		LOD	
0805		GOMAXL/D	
0806	STORE	L/D	
0807	ITC	0	
0808		GLIMITER	
0809	GOPOS LAD	DMOVE	0
0810		LAD	
0811	STORE	L/D	
0812	ITC	0	
0813		LIMITL/D	
0814	SETGPAST	SWITCH	0
0815		GONEPAST	SHOULD BE BY TARGET IF HERE.
0816	GONEGLAD	COMP	0
0817		LAD	$L/D = - LAD$
0818	STORE	L/D	
0819	ITC	0	
0820		GLIMITER	

RE-ENTRY CONTROL

0821	COMAXL/D	RTB	1	
0822		DMP		L/D = LAD SIG(MPAC)
0823			SIGNMPAC	
0824			LAD	
0825		STORE	L/D	AND FALLS INTO LIMITL/D SECTION.
0826	GLIMTIER	DSU	2	IF GMAX/2-D POS. GO TO LIMITL/D
0827		DAD		IF GMAX-D NEG. GO TO GOPOSLAD
0828		DMP		
0829		BMN	GMAX/2	
0830			D	
0831			LIMITL/D	
0832			GMAX/2	
0833			GOPOSLAD	
0834			ZHS	ZHS(GMAX-D) INTO PD
0835		DMP	1	
0836		DAD	DMP	
0837			LEG	
0838			1/GMAX	
0839			LAD	ZHS(GMAX-D) (LEQ/GMAX+LAD) INTO PD
0840		DDV	3	
0841		DAD	SQRT	XLIM = SQRT(PD+(2HSCMAX/V)SQ)
0842		DAD	BMN	IF RDOT+XLIM NEG. L/D=LAD
0843		ROUND		L/D = (RDOT+XLIM+KGLIM1 LEQ)/(KGLIM2 D
0845			VSQUARE	
0846			-	
0848			GOPOSLAD	

RE-ENTRY CONTROL

PO859 COMES HERE TO COMPUTE ROLL COMMAND, CHECK LATERAL ERRORS, AND STEER

0860	LIMITL/D	TEST	1	NO LATERAL CONTROL IF PAST TARGET
0861		DMP	DAD	$Y = KLAT \text{ VSQUARE} + LATBIAS$
0862			GONEPAST	
0863			L355	
0864			VSQUARE	
0865			KLAT	
0866			LATBIAS	
0867		STORE	Y	
0868	L350	ABS	4	IF $ABS(L/D) - L/DCMINR$ NEG, GO TO L353
0869		DSU	BMN	
0870		LODON	SIGN	IF K2ROLL LATANG NEG, GO TO L357
0871		BMN	LODON	
0872		TSRT		$Y = Y/2$
0873			L/D	
0874			L/DCMINR	
0875			L353	
0876			LATANG	
0877			K2ROLL	
0878			L357	
0879			Y	
0880			1	
0881		STORE	Y	
0882	L353	SIGN	2	IF LATANG SIGN(K2ROLL)-Y POS, SWITCH
0883		DSU	BMN	
0884		RTB		
0885			LATANG	
0886			K2ROLL	
0887			Y	
0888			L355	
0891			BL361	
0892	L355	DDV	2	$ROLLC = ACOS((L/D)/LAD)$
0893		TSRT	ACOS	
0894		SIGN		$ROLLC = ROLLC \text{ SIGN}(K2ROLL)$
0895			L/D	
0896			LAD	
0897			1	
0898			K2ROLL	
0899		STORE	ROLLC	

RE-ENTRY CONTROL

0900	STEEFR	EXIT	0	
0904	STEEFR2	CS	ROLLC	SCALE ROLL OUTPUT FOR 16 SPEED.
0905		EXTEND		
0906		MP	NEG1/8	ROLL = ROLLC/8 + K1ROLL
0907		AD	K1ROLL	
0908		TS	MPAC	AFRAID TO STORE POSS BAD NUM IN THETAD
0909		TC	+4	SKIPS ON OVERFLOW
0910		INDEX	A	
0911		CAF	LIMITS	ALLOW OVERFLOW (GO TO NEGMAX FROM POSMX)
0912		AD	MPAC	
0913		INHINT		
0914		TS	THETAD	THETAD = X CDU = ROLL
0915		CS	BIT3	
0916		MASK	TMMARKER	
0917		AD	BIT3	SET BIT 3 IN TMMARKER WHEN THETAD COMP
0918		TS	TMMARKER	
0919	OVERNOUT	TC	PHASCHNG	RECYCLE GROUP 5 TO PIPUP WAIT STATE.
0920		OCT	0 405	5.12 RESTART. (PIPUP SYNCED WITH 2 SEC)
0921		TC	ENDOFJOB	
0922	BL361	CS	K2ROLL	K2ROLL = - K2ROLL
0923		TS	.2ROLL	
0924		CCS	L/D	IF L/D POS, EXIT
0925		TC	RE-ENTER	SO IT WONT STORE IN PUSH LIST.
0926		TC	RE-ENTER	
0927		TC	+2	
0928		TC	RE-ENTER	
0929		CCS	K2ROLL	K1ROLL = K1ROLL + K3ROLL SIGN(K2ROLL)
0930		CAF	K3ROLL	K3ROLL = - .125
0931		TC	+2	
0932		CS	K3ROLL	
0933		AD	K1ROLL	
0934		TS	K1ROLL	
0935		TC	RE-ENTER	SKIPS THIS ON OVERFLOW.
0936		INDEX	A	POSMAX + 1 = NEGMAX ETC.
0937		CAF	LIMITS	NO LIMIT ON NUMBER OF ROLL REVS DURING
0938		AD	K1ROLL	ENTRY. (ROUTINE IS GENERAL.)
0939		TS	K1ROLL	STILL DOESNT WORRY ABOUT 25COMP, THO.
0940		TC	RE-ENTER	
0941	L357	SIGN	0	
0942			L/DCMINR	L/D = L/DCMINR SIGN(L/D)
0943			L/D	
0944		STORE	L/D	
0945		ITC	0	
0946			L355	
0947	FNDSTR	EQUALS		

RE-ENTRY CONTROL

```

P0951      ROUTINE TO PREDICT AND SET PITCH ANGLE FOR 2ND ENTRY CONDITIONS.

09515      SETLOC PFS25/1      IN BANK 25 TO MAKE ROOM IN BANK 27
0952      UPTHETA3 CAF      PRI014
0953      TC      FINDVAC
0954      CADR      UPTHETA1

0955      TC      TASKOVER

0956      UPTHETA1 TC      INTERPRET      STARTS OFF IN BASIC

0957      UPTHETA ITC      0      FIND DESIRED SPACECRAFT ORIENTATION.
0958      GETUNB

0959      ITC      0      GET OGC, IGC, MGC, GIMBAL COMMANDS
0960      CALCGTA

0961      EXIT      0

0962      CS      IGC
0963      COM
0964      DOUBLE
0965      TS      THETAD + 1      COMMAND PITCH ANGLE
0966      CS      MGC
0967      COM
0968      DOUBLE
0969      TS      THETAD + 2      CHANGE FORM INTERP SCALING TO CDU.
                                COMMAND YAW ANGLE

0970      INHINT
0971      CAF      PITCHDT      CALL UP ATTITUDE CONTROL LOOP PITCHDT
0972      TC      WAITLIST      SECONDS AFTER FINISHING THIS TIME.
0973      CADR      UPTHETA3

0974      UPNOVER TC      ENDOFJOB

09745      PITCHDT DEC      200
09747      IPIPD1 DEC      50

```

RE-ENTRY CONTROL

P0975 PIPAS ARE READ (BUT NOT CLEARED) AT A HIGHER RATE HERE.

0976	INTERPIP	CS	PIPAX
0977		INDEX	PIPCTR
0978		TS	XPIPBUF
0979		CS	PIPAY
0980		INDEX	PIPCTR
0981		TS	YPIPBUF
0982		CS	PIPAZ
0983		INDEX	PIPCTR
0984		TS	ZPIPBUF
0985		CCS	PIPCTR
0986		TC	+4
0987		CAF	TWO
0988		TS	PIPCTR
0989		TC	TASKOVER
0990		TS	PIPCTR
0991		CAF	IPIPD1
0992		TC	WAITLIST
0993		CADR	INTERPIP
0994		TC	TASKOVER

0996 ENDUPTHT EQUALS

RE-ENTRY CONTROL

P1000 DETERMINE TIME TO OPEN CHUTE HERE IF NEEDED

10015 SETLOC ENDSTR

1002 DT DEC 200

MAIN LOOP DT.

1003 DT C15 DEC 15

1004 F3ROLL DEC -.125

1005 ADENDEXT CADR ENDEXIT

R1006 DEFINED BY EQUALS

1007 HIND EQUALS HIND2SW

HUNT INDICATOR SWITCH

1008 ASP EQUALS 0

1009 Y EQUALS 20D

TEMP

1010 GAMMAL1 EQUALS 22D

RE-ENTRY CONTROL

P1011 TABLE USED FOR SUP-ORBITAL REFERENCE TRAJECTORY CONTROL.

1012	VREFER	DEC	0	REFERENCE VELOCITY SCALED V/51552.3946
1013		DEC	.006539	15 POINTS ARE STORED AS THE INDEPENDENT
1014		DEC	.020958	VARIABLE AND THEN SIX 15 POINT FUNC-
1015		DEC	.040809	TIONS OF V ARE STORED CONSECUTIVELY
1016		DEC	.076107	
1017		DEC	.122156	
1018		DEC	.165546	
1019		DEC	.196012	
1020		DEC	.271945	
1021		DEC	.309533	
1022		DEC	.356222	
1023		DEC	.404192	
1024		DEC	.448067	
1025		DEC	.456023	
1026		DEC	.67918	HIGH VELOCITY OR SAFETY
1027		DEC	-.008035	DRANGE/DA SCALED DRDA/(2700/805)
1028		DEC	-.008035	
1029		DEC	-.010820	
1030		DEC	-.016550	
1031		DEC	-.026935	
1032		DEC	-.042039	
1033		DEC	-.058974	
1034		DEC	-.070721	
1035		DEC	-.098538	
1036		DEC	-.107482	
1037		DEC	-.147762	
1038		DEC	-.193289	
1039		DEC	-.602557	
1040		DEC	-.99999	
1041		DEC	-.99999	
1042		DEC	0	-DRANGE/DRDOT
1043		DEC	0	SCALED((2VS/8 2700) DR/DRDOT)
1044		DEC	-.0494520	B-3
1045		DEC	-.0683663	B-3
1046		DEC	-.1343468	B-3
1047		DEC	-.2759846	B-3
1048		DEC	-.4731437	B-3
1049		DEC	-.6472087	B-3
1050		DEC	-1.171693	B-3
1051		DEC	-1.466382	B-3
1052		DEC	-1.905171	B-3
1053		DEC	-2.547990	B-3
1054		DEC	-4.151220	B-3
1055		DEC	-5.813617	B-3
1056		DEC	-5.813617	B-3
1057		DEC	-.00642065	B3 RDOTREF SCALED (8 RDT/2VS)
1058		DEC	-.00642065	B3
1059		DEC	-.0134426	B3

RE-ENTRY CONTROL

1060	DEC	-.013947	H3
1061	DEC	-.013462	H3
1062	DEC	-.011813	H3
1063	DEC	-.0095631	H3
1064	DEC	-.00808946	H3
1065	DEC	-.006828	H3
1066	DEC	-.00806946	H3
1067	DEC	-.0109791	H3
1068	DEC	-.0151496	H3
1069	DEC	-.0179817	H3
1070	DEC	-.0159061	H3
1071	DEC	-.0159061	H3

1072	DEC	0	RANGE TO GO SCALED RTGO/2700
1073	DEC	0	
1074	DEC	.00100	2.7 NM
1075	DEC	.0032963	8.9
1076	DEC	.0081852	22.1
1077	DEC	.017148	
1078	DEC	.027926	
1079	DEC	.037	
1080	DEC	.063296	
1081	DEC	.077889	
1082	DEC	.098815	
1083	DEC	.127519	
1084	DEC	.186963	
1085	DEC	.238148	
1086	DEC	.238148	

1087	DEC	-.042360	-AREF SCALED ARFF/805
1088	DEC	-.042360	
1089	DEC	-.052919	
1090	DEC	-.074534	
1091	DEC	-.101242	
1092	DEC	-.116646	
1093	DEC	-.122360	
1094	DEC	-.127081	
1095	DEC	-.147453	
1096	DEC	-.155528	
1097	DEC	-.149565	
1098	DEC	-.118509	
1099	DEC	-.034907	
1100	DEC	-.007950	
1101	DEC	-.007950	

1102	DEC	.000371	DRANGE/D L/D SCALED Y/2700
1103	DEC	.000371	
1104	DEC	.004770	
1105	DEC	.008081	
1106	DEC	.016030	
1107	DEC	.035815	
1108	DEC	.069422	
1109	DEC	.104519	
1110	DEC	.122	
1111	DEC	.172407	

RE-ENTRY CONTROL

1112	DEC	.252852
1113	DEC	.363148
1114	DEC	.512963
1115	DEC	.558519
1116	DEC	.558519

END OF STORED REFERENCE

1117 ENDREENS EQUALS

RE-ENTRY CONTROL

P1118 CONTINUATION OF RE-ENTRY SECTION IN 2ND BANK. (CONSTANTS AND M923=8

1119 SETLOC BOOKMRK1

1120 NEARONE 2DEC .999999999
 1121 1/3RD 2DEC .333333333 ONE THIRD
 1122 1/12TH 2DEC .083333333 ONE TWELFTH

R1123 VSAT = 25766.1973 FT/SEC.

R1124 RE = 21,202,900 FEET

1125 LEWD 2DEC .1
 1126 LEWD/3 2DEC .033333333 LEWD/3 (LEWD = .1)
 1127 FOURTH 2DEC .25
 1128 3ZEROS 2DEC 0
 1129 1BITDP 2OCT 00000 00001 DOUBLE PREC 1 BIT
 1130 DEC 0
 1131 NEAR1/4 2OCT 07777 00000 1/4 LESS 1 BIT IN UPPER PART.
 1132 C18 2DEC .0097026346 500/2VS
 1133 KDMIN 2DEC .00062111801 .5/805
 1134 C1/16 2DEC .0625 1/16
 1135 2HSD/LWD 2DEC .16278661 2(1.0) 28500 805/ .1 (2VS) SQ
 1136 Q2 2DEC -.046388889 -1002/21600 = (643/21600-Q2(23500/2VS))
 1137 Q3 2DEC .167003132 .07 2VS/21600
 1138 Q5 2DEC .326388889 .3 23500/21600
 1139 Q6 2DEC .034893617 820/23500
 1140 Q7F 2DFC .0074534161 6/805 (VALUE OF Q7 IN FIXED MEM.)
 1141 VMIN 2DEC .34929485 18000/2VS
 1142 C12 2DEC .00684572901 32 28500/(21102900 2 PI)
 1143 G5 2DEC -.16
 1144 KB1 2DEC .29411765 1/3.4
 1145 KB2 2DEC -.0057074322 -1/(.0034 2 VS)
 1146 C19 2DFC .16149068 130/805
 1147 VCORLIM 2DEC .019405269 1000/2VS
 1148 VQUIT EQUALS VCORLIM BOTH ARE 1000 FT/SEC

1149 KAFIX 2DEC .08 64.4/805 (2 G-S)
 1150 C20 2DEC .21739130 (175 FPS) LIFT UP IF ABOVE C20
 11505 DOMAX EQUALS C20

1151 25NM 2DEC .0011574074 B-4 25/(21600 16) (25 NAUT MILES)
 1152 K1D 2DEC .0314453125 .01 805/256
 11525 K2D 2DEC -.201298418 -.001 2VS/256
 1153 KVS SCALE 2DEC .81491944 12800/(2 VS .3048)
 1154 KASCALE 2DEC .97657358 5.85 16384/(4 .3048 100 805)
 1155 KTETA 2DEC* .383495203 [2 B-14* 1000 2PI/16384(163.84)
 1156 KI 2DEC* .157788327 [2 B-14* RE(2PI)/2VS(16384)163.84
 1157 .05G 2DEC .002 .05/25
 1158 LAD 2DEC .3
 1159 LAD/256 2DEC .001171875 .3/256
 1160 KLAT 2DEC .0125
 1161 LATBIAS 2DEC .00003 APPRX .5 NM/ 4(21600/2 PI)
 1162 KWE 2DEC .120056652
 1163 KACOS 2DEC .004973592 1/32(2PI)

RE-ENTRY CONTROL

1164	LAD/KC1	2DEC	.375	LAD/KC1 = .3/.8
1165	OKC2	2DEC	.0074051405	2HS LAD(32.2)25/KC2(2VS)SQ (KC2=.7)
1166	CHOOK	2DEC	1 8-5	.25/8
1167	1/8TH	2DEC	.125	
1168	CH1	2DEC	.24	8 CH1/ 25 (CH1 = .75)
1169	KC3	2DEC	-.082540747	KC3 (2VS)SQ /2PI 25 32.2 LAD R
1170	LOD	2DEC	.18	
1171	VRCONT	2DEC	.0135836886	700/2 VSAT
1172	HALVE	2DEC	.5	
1173	NEG1/8	EQUALS	K3ROLL	ONLY A SINGLE PRECISION NUMBER.
1174	L/DCMINR	2DEC	.2895	LAD COS(15 DEG)
1175	CO01	2DEC	-.000625	-(4/25) / 256 (LEQ/DO CONST)
1178	GMAX/2	2DEC	.2	5/25
1179	1/GMAX	2DEC	.4	
1180	2HS	2DEC	.0172786611	2 28500 25 32.2/(4 VS VS)
1181	2HSGMXSQ	2DEC	.000047768341	((2 28500 322/(4VS VS))SQ
1182	KWIEM	2DEC	.147323336	RESULT IN METERS OVER 12800
1183	COS(13)	2DEC	.9763	REAL COS OF 12.5 DEG. NOT 1/2 COSINE.
1184	-SIN(13)	2DEC	-.21644	REAL SIN OF 12.5 DEG. NO FACTOR OF 1/2
11841	2C1HS	2DEC	.0215983264	2 1.25 28500 805/(2 VS)SQ
11842	2C1HSLAD	2DEC	.071994421	2 1.25 28500 805/(.3 4 VS VS)
11843	POINT1	2DEC	.1	
11844	K44	2DEC	.00116091912	2 VS/(236 57.3 57.3 57.3)
11845	VFINAL	2DEC	.48513173	25000/2 VS
11846	KAT	2DEC	.08	2 G-S (2/25)
R1185	... END OF RE-ENTRY CONSTANTS...			

RE-ENTRY CONTROL

R1186 CLOSED SUBROUTINE TO COMPUTE DESIRED NAV BASE ORIENTATION
R1187 NEEDED DURING ENTRY PHASE.

R1188 ENTER WITH VN, UNITR, UNITW, AND ROLLC
R1189 COMPUTES UXNB, UYNB, AND UZNB. (NAV BASE UNIT VECTORS)

1190	GETUNB	RTB	3	RESET PUSH COUNTER.
1191		VXV	VXSC	GET VELOCITY OF ATMOSPHERE
1192		VAD	UNIT	GET UVA., RELATIVE VELOCITY
1193		VXSC		RESOLVE BY COS OF 13 DEG.
1194			FRESHPD	
1195			UNITR	
1196			UNITW	NEG OF REAL VEL.
1197			KWIEM	EARTH RATE CONST IN METERS X 4.
1198			VN	
1199			COS(13)	UVA COS(13) INTO PD.
1200		NOLOD	1	
1201		VXV	UNIT	UYA = UNIT(VA*RN)
1202			UNITR	
1203		STORE	16D	UYA INTO LOC 16 OF VAC AREA.
1204		COS	1	COS (ROLLC)
1205		VXSC		GET UYA COS(ROLLC). PUSH INTO LOC 6.
1206			ROLLC	
1207			16D	AND PUSH.
1208		SIN	0	
1209			ROLLC	SIN (ROLLC) INTO PD AT LOC 12
1210		VXV	2	UNA = UNIT(UYA*UVA)
1211		UNIT	VXSC	UNB = UYA COS(ROLL) + UNA SIN(ROLL)
1212		VAD	UNIT	UNIT COULD BE REPLACED BY VSLT 1.
1213			16D	UYA STORED AT LOC 16
1214			0	UVA FIRST ITEM INTO PUSH LIST
1215		STORE	UYNB	1 SCAL AND 1 VEC FROM PD.
1216		NOLOD	2	
1217		VXV	UNIT	UN = UNIT (UYNB*UVA)
1218		VXSC	VSU	UXNB = -UN SIN(13) - UVA COS(13)
1219			0	
1220			-SIN(13)	PULLS UVA COS(13) FROM PD.
1221		STORE	UXNB	
1222		NOLOD	1	
1223		VXV	VSLT	UZNB = UXNB*UYNB
1224			UYNB	
1225			1	
1226		STORE	UZNB	
1227		ITCQ	0	AND RETURN.

RE-ENTRY CONTROL

P1228	SUBROUTINE TO READ PIPA COUNTERS, TRYING TO BE VERY CAREFUL SO THAT			
R1229	IT WILL BE RESTARTABLE.			
R1230	(ARRIVE IN INTERRUPTED STATE OR INHIBITED AFTER RESTART.)			
R1231	(EXIT IS THRU ISWRETRN)			
1232	PIPASR	CS	ZERO	PUT THESE INTO THE IMPOSSIBLE STATE
1233		TS	TEMX	FOR THEIR INITIAL VALUES.
1234		TS	TEMY	
1235		TS	TEMZ	
1236		CAF	ZERO	
1237		TS	DELVX + 1	
1238		TS	DELVY + 1	PIP COUNTERS MAY NOT HAVE POS ZERO IN
1239		TS	DELVZ + 1	
1240		TS	PIPAGE	ZERO THIS TO INDICATE IN PIPA READING.
1241	REPIP1	TC	READTIME + 1	PROBABLY NOT NEEDED SINCE NOT MUCH
1242		CS	RUPTSTOR + 1	CHANCE OF TIME1 OVERFLOWING NOW. (PUT
1243		TS	PIPTIME + 1	JUST POSSIBLE IF MANY RESTARTS.
1244		CS	RUPTSTOR	
1245		TS	PIPTIME	
1246		CS	PIPAX	
1247		TS	TEMXY	
1248		XCH	TEMX	PUT NEGZERO INTO PIPACTRS AS READ.
1249		XCH	PIPAX	
1250	REPIP1B	TS	DELVX	
1251		TS	DELVX + 1	DOUBLE SAVE.
1252	REPIP2	CS	PIPAY	
1253		TS	TEMXY	
1254		XCH	TEMY	
1255		XCH	PIPAY	
1256	REPIP2B	TS	DELVY	
1257		TS	DELVY + 1	
1258	REPIP3	CS	PIPAZ	REPEAT PROCESS FOR 2 PIPA.
1259		TS	TEMXY	SAVE NEG OF PIPA READ
1260		XCH	TEMZ	SAVE HERE AS PICK UP NEGZERO
1261		XCH	PIPAZ	RESETTING PIPA AS READ OUT)
1262	REPIP3B	TS	DELVZ	AND STORE IN Z.
1263		TS	DELVZ + 1	SHOWS THAT IT REALLY MADE IT.
1264	REPIP4	CS	ZERO	LEAVE THESE AT NEGZERO
1265		TS	DELVX + 1	
1266		TS	DELVY + 1	
1267		TS	DELVZ + 1	
1268		CS	BIT1	
1269		MASK	TMMARKER	
1270		AD	BIT1	SET BIT 1 IN TM MARKER.
1271		TS	TMMARKER	
1272		TC	ISWRETRN	AND EXIT. SHOULD HAVE COME THRU ICALL

RE-ENTRY CONTROL

P1273 ROUTINE TO RESTART IF READING PIPA COUNTERS.

1274	REPIPASR	CCS	PIPAGE	WAS I READING PIPS.
1275		TC	PIPASR	NO.. PIPAGE = PLUS CONST.
1276		CCS	DELVZ + 1	PIPAGF = 0 (I WAS READING PIPS.)
1277		TC	REPIP4	Z WAS READ OK.
1278		TC	+3	Z NOT DONE, CHECK Y.
1279		TC	REPIP4	
1280		TC	REPIP4	
1281		CCS	DELVY + 1	HAS IT CHANGED FROM ITS +ZERO INIT VALU
1282		TC	+3	YES, Y DONE. TRY TO REDO Z.
1283		TC	CHKDELVX	NO, GO LOOK AT X.
1284		TC	+1	YES.
1285		CCS	TEMZ	DOES TEMZ STILL = -0.
1286		TC	+4	NO TRY TO RESTORE
1287		TC	+3	
1288		TC	+2	
1289		TC	REPIP3	YES, GO BACK AND READ Z AGAIN.
1290		CS	TEMXY	MUCH MORE LOGIC COULD BE INCORPORATED
1291		TC	REPIP3B	TO CHECK PIPA CTR FOR SIZE.
1292	CHKDELVX	CCS	DELVX + 1	HAS THIS CHANGED.
1293		TC	+3	YES
1294		TC	CHKTEMX	NO.
1295		TC	+1	YES
1296		CCS	TEMY	
1297		TC	+4	
1298		TC	+3	
1299		TC	+2	
1300		TC	REPIP2	
1301		CS	TEMXY	
1302		TC	REPIP2B	
1303	CHKTEMX	CCS	TEMX	HAS THIS CHANGED.
1304		TC	+4	YES
1305		TC	+3	YES
1306		TC	+2	YES
1307		TC	REPIP1	NO
1308		CS	TEMXY	
1309		TC	REPIP1B	

RE-ENTRY CONTROL

P1310 ENTRY INITIALIZATION ROUTINE.
R1311 -----

1312	STARTENT	TC	PHASCHNG	KEEP UPTHETA RUNNING IN CASE OF RESTART.
1313		OCT	03204	4.26 RESTART.
1314		TC	PHASCHNG	PICK UP CURRENT STRING AT NEWMODE63.
1315		OCT	02305	5.19 RESTART. RESYNCING PIPUP ALSO.
1316		INHINT		
1317		CAF	PRI014	ESTABLISH UPTHETA FOR 1ST TIME.
1318		TC	FINDVAC	
1319		CADR	UPHETA1	START UPTHETA JOB.
1320		RELINT		
1321	NUMODE63	TC	NEWMODE	
1322		OCT	00063	ENTRY PHASE = MODE 63
1323		CAF	INITCADR	
1324		TS	GOTOADDR	
1325		CAF	EARGCADR	
1326		TS	CALCG	
1327		CAF	ZERO	
1328		TS	TENTRY	
1329		CAF	NUDELTAT	
1330		TS	DELTAT	
1331		CAF	NU/PIPADT	
1332		TS	1/PIPADT	
1333		CS	ENTMASK	INITIALIZE SWITCHES(BITS 6-11 IN STATE)
1334		MASK	STATE	6=GONEPAST, 7= RELVELSW, 8= EGSW.
1335		AD	ENTRYSW	9=HUNTSW1, 10=HIND, 11=INRLSW.
1336		TS	STATE	ALL BUT RELVELSW SET TO NON-BRANCH (1)
1340		TC	INTPRET	
1341		RTB	2	SET CDUX AGAIN JUST IN CASE.
1342		VXV	DOT	
1343		COMP	RTB	
1344			CDUXFIX	
1345			VN	
1346			UNITR	
1347			RTINIT	THIS GIVES LATANG.
1348			SIGNMPAC	GETS SIGN OF MPAC
1349		STORE	K2ROLL	K2ROLL = - SIGN(LATANG)
1350		DOT	1	
1351		TSLT	ACOS	
1352			UNITR	
1353			RTINIT	
1354			1	
1355		STORE	THETAH	
1356		VMOVE	0	
1357			RT	
1358		STORE	RTINIT	

RE-ENTRY CONTROL

1359	COMP	0
1360		DTEAROT
1361	STORE	DTEAROT
1362	ITC	0
1363		EARROT1
1364	RTB	0
1365		OVERNOUT

EXIT SETTING RESTART BITS TO 5.12 FOR EN

1366	INITCADR	CADR	INITROLL
1367	EARGCADR	CADR	CALCGEAR
1368	NUDELTAT	DEC	200 B5
1369	NU/PIPDY	DEC	200 B6
1370	ENTMASK	OCT	01760
1371	ENTRYSW	OCT	01360
1372	ENDD202S	EQUALS	

AVERAGE G INTEGRATOR

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R0001 ROUTINE CALCRVG INTEGRATES THE EQUATIONS OF MOTION BY AVERAGING THE
R0002 GRAVITATIONAL ACCELERATION OVER A TIME INTERVAL, DELTAT, AND INCLUDING
R00025 THE VELOCITY INCREMENT AS MEASURED BY THE PIPAS.
R0003 FOR THE EARTH-CENTERED GRAVITATIONAL FIELD THE PERTURBATION DUE TO
R0004 OBLATENESS IS COMPUTED TO THE SECOND HARMONIC COEFFICIENT J.
R0005 ROUTINE NORMALISE MUST BE CALLED PRIOR TO THE FIRST ENTRY INTO
R0006 CALCRVG. IT REQUIRES RN SCALED TO 2(+29)M IT LEAVES RN NORMALISED, SO
R0007 THAT THE SCALED MAGNITUDE OF THE VECTOR CONTAINS ONE LEADING ZERO, BY
R0008 SHIFTING THE VECTOR LEFT N BINARY PLACES.
R0008 ROUTINE CALCRVG REQUIRES
R0009 1) THRUST ACCELERATION INCREMENTS IN DELV SCALED SAME AS PIPAX,Y,Z
R0010 2) VN SCALED AT 2(+7) M/CS
R0011 3) ADDRESS OF CALCGLUN OR CALCGEAR IN CALCG
R0012 4) DELTAT SCALED AT 2(+9) CS
R0013 5) PUSH-DOWN COUNTER SET TO ZERO
R0014 IT LEAVES UPDATED RN, SCALED AT 2(29-N) M, VN, AND GRAVITY SCALED AT
R0015 2(-5) M/CS/CS
0021 SETLOC ENDINFSS

0022 NORMLISE ABVAL 3 COUNT NUMBER OF LEADING ZEROS IN
0023 TSLC INCR,1 ABVAL (RN) AND STORE -N(=2-M) IN NSHIFT
0024 SXA,1 INCR,1 RN MUST BE SCALED AT 2(+29)M
0025 SXA,1 ITA
0026 RN
0027 X1
0028 2
0029 NSHIFT SAVE C(X1)=-N
0030 14D
0031 XSHIFT SAVE C(X1) =14-N
0032 S2

0033 VMOVE 1
0034 VSLT*
0035 RN
0036 14D,1
0037 STORE RN RN SCALED AT 2(29-N)METRES

0038 ITC 0
0039 CALCGRAV

0040 ITCI 0
0041 S2

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AVERAGE G INTEGRATOR				
0042	CALCRVG	VXSC	0	
0043			DELV	
0044			KPIP	DV TO PD SCALED AT 2(+4)M/CS
0045		VXSC	1	
0046		LXA+1	BVSU	
0047			GRAVITY	
0048			DELTAT	
0049			XSHIFT	
0050			0	(DV-(OLD GDT))/2 TO PD SCALED 2(+3)M/CS
0051		NOLOD	3	
0052		VSRT	VAD	
0053		VXSC	VSLT*	
0054		VAD	ITA	
0055			4	
0056			VN	
0057			DELTAT	
0058			1+1	
0059			RN	
0060			S2	
0061		STORE	RN1	SCALED AT 2(29-N) METERS
0062		ITC	0	
0063			CALCGRV	
0064		NOLOD	3	
0065		VXSC	BVSU	
0066		VAD	VSRT	
0067		VAD		
0068			DELTAT	
0069			-	(DV-(OLD GDT))/2
0070			-	DV/2
0071			4	
0072			VN	
0073		STORE	VN1	SCALED AT 2(+7) MET/CS
R00731 IN AVERAGE G, UP THE PHASE BITS BY 2 OF ACTIVE PROG BEFORE COPY CYCLE.				
00732		EXIT	0	
007322		INDEX	FIXLOC	
007324		CS	S2	SAVE NEG RETURN ADDRESS IN NON-VAC AREA.
007326		TS	AVGRETRN	SAVE NEG OF RETURN ADDRESS.
00733		TC	BANKCALL	
007335		CADR	INCPHAS2	
00734	REFAZE6	INHINT		
007343		CAF	ELEVEND	
007347		TS	MPAC	USE MPAC FOR LOOP COUNTER.
00735		INDEX	MPAC	
007353		CS	RN1	RN1 AND VN1 MUST BE IN ORDER.
007357		COM		LEAVE RN1 ALONE IN CASE OF RESTARTS.
00736		INDEX	MPAC	SELECT THE RIGHT TERM.

AVERAGE G INTEGRATOR

007363	TS	RN	...	AND GO THRU COPY CYCLE.
007367	CCS	MPAC		ARE WE DONE..
00737	TC	REFAZE6 + 2		NO, NOT YET.
007373	CS	BIT2		YES, MPAC ≠ 0.
007377	MASK	TMMARKER		
00738	AD	BIT2		SET BIT 2 TO ONE IN TMMARKER.
007382	TS	TMMARKER		
A007385				WHAT ABOUT GRAVITY FOR RESTART..
007387	RELINT			
00739	CS	AVGRETRN		NEG OF ADDRESS WAS STORED.
0074	TC	BANKJUMP		
0075	ELEVEND	DEC	11	11D (ELEVEN DECIMAL, OF COURSE.)
0076	CALCGRAV	NOLOD	1	
0077		UNIT		
0078		STORE	UNITR	
00782		DMOVE	0	
00784			30D	
00786		STORE	RMAG	SCALED AT 2(30-N)M
0079		TSLT	0	
0080			28D	
0081			3	
0082		STORE	RMAGSQ	SCALED AT 2(57-2N)M(+2)
0083		ITA	1	
0084		XAD+1	ITC1	
0085			27D	
0086			NSHIFT	
0087			CALCG	
0088	CALCGEAR	DOT	0	
0089			UNITR	
0090			UNITW	
0091		STORE	25D	
0092		NOLOD	2	
0093		DSQ	DMP	
0094		TSLT	BDSU	
0095			DP(5/8)	
0096			4	
0097			DP2(-3)	
0098		DDV	1	
0099		TSLT*		
0100			J(RE)SQ	SCALED AT 2(+40) M(+2)
0101			RMAGSQ	

AVERAGE G INTEGRATOR

0102			0.1		
0103		STORE	23D	J(RI/PH) SQ SCALED AT 2(-3)	
0104		NOLOD	2		
0105		DMP	VXSC		
0106		VAD			
0107			-		
0108			UNITR		
0109			UNITR		
0110		DMP	1		
0111		VXSC	VAD		
0112			23D		
0113			25D		
0114			UNITW		
0115		DMOVE	1		
0116		ITC			
0117			MUEARTH		
0118			MU/RSQ		
0119	CALCGLUN	VMOVE	0		
0120			UNITR		
0121		DMOVE	1		
0122		INCR,1			
0123			MUMOOT.		
0124			6		
0125	MU/RSQ	NOLOD	2		
0126		DDV	TSLT*		
0127		VXSC			
0128			RMAGSQ	C(X1)=14-2N (EARTH)	
0129			5.1	=20-2N (MOON)	
0130		STORE	GRAVITY	SCALED AT 2(-5) M/CS/CS	
0131		ITCI	0		
0132			27D		
0133	KPIP	2DEC	0.59904		
0134	DP2(-3)	2DEC	0.125		
0135	DP(5/8)	2DEC	0.625		
0136	MUEARTH	2DEC	0.009063188	1.98603223E+34	2(-42)M(+3)/CS(+2)
0137	MU	2DEC	0.00713443	5.97277800E+24	2(+36)M(+3)/CS(+2)
0138	JRKE15	2DEC	0.00006663		2(-40)M(+3)
0139					

POWERED FLIGHT SUBROUTINES

P1240 THIS CODING APPEARS IN THE POWERED FLIGHT SECTION.

R12405 THIS ROUTINE RESOLVES THE VECTOR IN RTINIT THROUGH AN ANGULAR ROTAT-
R1241 ION WIE(DTEAROT) SCALED AT ONE REVOLUTION ABOUT THE UNIT POLAR AXIS
R1242 UNITW. IT REQUIRES DTEAROT SCALED AT 2(+28)CS. IT LEAVES THE RESOLVED
R1243 VECTOR IN RT WITH EASTERLY AND NORMAL COMPONENTS IN RTEAST AND RTNORM
R1244 RESPECTIVELY. AT THE SAME SCALING. FOR CONTINUOUS UPDATING ONLY ONE
R1245 ENTRY AT EARROT1 IS REQUIRED. WITH SUBSEQUENT ENTRIES AT EARROT2.

1248	EARROT1	VXV	1	
1249		VSLT		
1250			UNITW	
1251			RTINIT	
1252			2	
1253		STORE	RTEAST	
1254		NOLOD	1	
1255		VXV	VSLT	
1256			UNITW	
1257			1	
1258		STORE	RTNORM	
1259	EARROT2	STZ	1	BRANCH TO OVERADAY UNTIL DTEAROT
1260		DDV	BOV	LESS THAN ONE SIDEREAL DAY
1261			OVFIND	
1262			DTEAROT	
12622			1/WIE	TIME FOR ONE SIDEREAL REVOLUTION
12624			OVERADAY	
12626		STORE	30D	
1263		NOLOD	2	
1264		COS	DSU	
1265		VXSC		
1266			DP2(-1)	DP2(-1)= DOUBLE PREC. .5
1267			RTNORM	
1268		SIN	2	
1269		VXSC	VAD	
1270		VAD		
1271			30D	
1272			RTEAST	
1273			RTINIT	
1274		STORE	RT	
1275		ITCQ	0	
12751	OVERADAY	SIGN	1	
12752		BDSU		
12753			1/WIE	
12754			DTEAROT	
12755			DTEAROT	
12756		STORE	DTEAROT	
12757		BPL	-1	GO BACK WITHOUT DISTURBING UPRET.

POWERED FLIGHT SUBROUTINES

127575			1/WIE	ANY POSITIVE CONSTANT WILL DO.
12758			FARROT?	
1276	WIE	2DEC	0.190148570	EARTH RATE SCALED AT 2(-14) REV/SEC
12765	1/WIE	2DEC	0.032098670	8.61642098 E4 SECS SCALED AT 2(+26) CS
1277	ENDPFLSS EQUALS			

APPENDIX A

DERIVATION OF THE UP-CONTROL REFERENCE, $V = f(D)$

Start with the equations of motion of a point mass assuming small flight path angle

$$dV/dT = -D \quad (D \text{ and } L \text{ are accelerations}) \quad (A-1)$$

$$d\dot{R}/dT = V^2/R - G + L \quad (A-2)$$

$$dH/dT = \dot{R} \quad (A-3)$$

If the centripetal and gravity accelerations are neglected, $V^2/R - G = 0$, we can write dividing (A-2) by (A-1)

$$d\dot{R}/dV = -L/D$$

which can be integrated starting at $V = V_1, \dot{R} = 0$

$$\dot{R} = L/D (V_1 - V) \quad (A-4)$$

Now we can solve for H as a function of V by combining (A-1), (A-3), and (A-4) to eliminate time

$$dH/dV = -L/D (V_1 - V)/D \quad (A-5)$$

Relate drag to velocity by

$$D = 1/2 \rho V^2 (SCD/m) \quad (A-6)$$

and ρ to H by assuming an exponential variation of density with altitude

$$\rho = \rho_1 e^{-\beta(H-H_1)} \quad (A-7)$$

Substitute (A-6) and (A-7) into (A-5) to get

$$dH/dV = -L/D (V_1 - V)(1/2 \rho_1 e^{-\beta(H-H_1)} V^2 SCD/m) \quad (A-8)$$

Equation (A-8) integrates directly to

$$(SCD/m)/(\beta L/D)(-1/2 \rho_1 e^{-\beta(H-H_1)} + 1/2 \rho_1) = -LN(V_1/V) + V_1/V - 1$$

or

$$(SCD/m)/(\beta L/D)(-1/2 \rho + 1/2 \rho_1) = -LN(V_1/V) + V_1/V - 1 \quad (A-9)$$

The log function can be expanded in a series

$$LN(1 + w) = w - w^2/2 + \dots$$

so

$$LN(V_1/V) + V_1/V - 1 = (V_1/V - 1)^2/2$$

Put the result back into (A-9)

$$(SCD/m)/(\beta L/D)(-1/2 \rho + 1/2 \rho_1) = 1/2 ((V_1 - V)/V)^2 \quad (A-10)$$

To solve for V in terms of D , regroup Eq. (A-10) into a quadratic in V.

$$V^2 (2 D_1/(\beta V_1^2) - L/D) + 2 L/D V_1 V - 2 D/\beta - L/D V_1^2 = 0$$

Rewrite this equation

$$X^2 L/D(\alpha - 1) + 2 L/D X - L/D(\beta D/D_1 + 1) = 0$$

where

$$X = V/V_1$$

$$\alpha = 2 D_1/(\beta V_1^2 L/D)$$

Solve this equation with the quadratic formula noting that the positive sign on the square root is appropriate

$$X = -1/(\alpha - 1) + \sqrt{(1/(\alpha - 1))^2 + \alpha (D/D1 + 1)/(\alpha - 1)}$$

This can be simplified to

$$X = (1/(1 - \alpha))(1 - \sqrt{(\alpha - 1)\alpha D/D1 + \alpha}) \quad (A-11)$$

Finally, summarize by rewriting the result in the form used in the AGC

$$V = F1 (1 - \sqrt{F2 D + \alpha}) \quad (A-12)$$

where

$$\alpha = 2 D1 / (\beta V1^2 L/D)$$

$$F1 = V1/(1 - \alpha)$$

$$F2 = \alpha (\alpha - 1)/D1$$

APPENDIX B

HOOK ON ALTITUDE RATE

This derivation is to allow for the previously neglected gravity and centripetal accelerations in the reference path for the up-control phase. When the L/D slipped to its present value, this refinement was necessary since the neglected acceleration became a larger part of the total acceleration.

Start again with the basic equations for a point mass, this time including the gravity and centripetal accelerations.

$$dV/dT = -K_1 e^{-\beta H} V^2 \quad (B-1)$$

$$dR/dT = K_2 e^{-\beta H} V^2 + (V^2/VS^2 - 1) G \quad (B-2)$$

$$dH/dT = \dot{R} \quad (B-3)$$

Divide (B-2) by (B-1) to eliminate time

$$\dot{R}/dV = -K_2/K_1 + (G/(K_1 e^{-\beta H}))(1/V^2 - 1/VS^2) \quad (B-4)$$

Note that $K_2/K_1 = L/D$. This time (B-3) and (B-4) are a non-linear set and cannot be integrated directly as was the case in Appendix A.

The key approximation needed to integrate this set of equations is to assume at straight line variation of the density ratio $e^{\beta H}$ with velocity.

$$e^{\beta H} = 1 + AH(VS - V)$$

The constant AH is yet to be determined. This approximation yields for Eq. (B-4).

$$\dot{R}/dV = -L/D + G/K_1 (1 + AH(VS - V)) (1/V^2 - 1/VS^2) \quad (B-5)$$

This readily integrated from VS to V

$$\begin{aligned} \dot{R} = \dot{R}_0 + L/D(VS - V) + G/K1 \{ (1 + AH VS)(-1/V + 1/VS) - AH \ln(V/VS) \} \\ + G/K1 \{ (1 + AH VS)(1/VS - V/VS^2) + AH V^2/(2VS^2) - AH/2 \} \quad (B-6) \end{aligned}$$

We can simplify (B-6) by making a series approximation for the logarithm

$$\ln(V/VS) = (V - VS)/VS - .5 ((V - VS)/VS)^2$$

This substitution gives after some algebra

$$\dot{R} = \dot{R}_0 + L/D(VS-V) + (G/(DHOOK \ V))(-(VS-V)^2 - AH(VS-V)^3) \quad (B-8)$$

where

$$DHOOK = \text{drag at VS}$$

Note that

$$\dot{R}_0 + L/D(VS - V) = LEWD(V1 - V)$$

Now return to determining AH.

The drag is assumed to vary parabolically with velocity (as calculated in Appendix A), with no gravity correction. This yields an exit velocity, VL, at the exit drag, Q7. A straight line is drawn between the acceleration at VS (DHOOK) and the acceleration at VL (Q7). The desired slope of the density variation is then

$$AH = ((DHOOK - Q7)/Q7)/(VS - VL)$$

This assumes that the velocity is constant over this time period, a small approximation compared to some of the others.

The square and cube terms of (VS-V) in Eq. (B-8) give the general shape of $\dot{R}$ versus velocity shown in fig. B-1. Of some importance is V^2 , the

velocity at which $\dot{R}$ becomes zero. This signifies a peak altitude for the up-control phase and that the exit acceleration, Q7, cannot be reached, because the gravity acceleration is too great. To allow for this effect the following is done. If $\dot{R}$ is negative on the particular computation cycle, the derivative $d\dot{R}/dV$ is approximated at V_L by

$$d\dot{R}/dV = (-3 A_H DVL^2 - 2 DVL) G/(DHOOK V_L) + LEWD \quad (B-9)$$

where

$$DVL = VS - V_L$$

Then V_2 is calculated using this derivative

$$V_2 = V_L + \dot{R}_L/(d\dot{R}/dV) \quad (B-10)$$

This V_2 is set equal to the exit velocity V_L , and a new exit acceleration is calculated by using the usual parabolic relation

$$Q7 = ((1 - V_L/F1)^2 - \alpha)/F2$$

Remember

$$\alpha = 2 A_0 HS/(LEWD V_1^2)$$

$$F1 = V1/(1 - \alpha)$$

$$F2 = \alpha(\alpha - 1)/A_0$$

This $Q7$ is used for reference trajectory calculation in future computation cycles.

This rather simple scheme for calculating V_2 works because the exit altitude rate is only slightly different from zero the first time it becomes negative. Thus only one pass through this Newtonian type iteration is required.

B-4

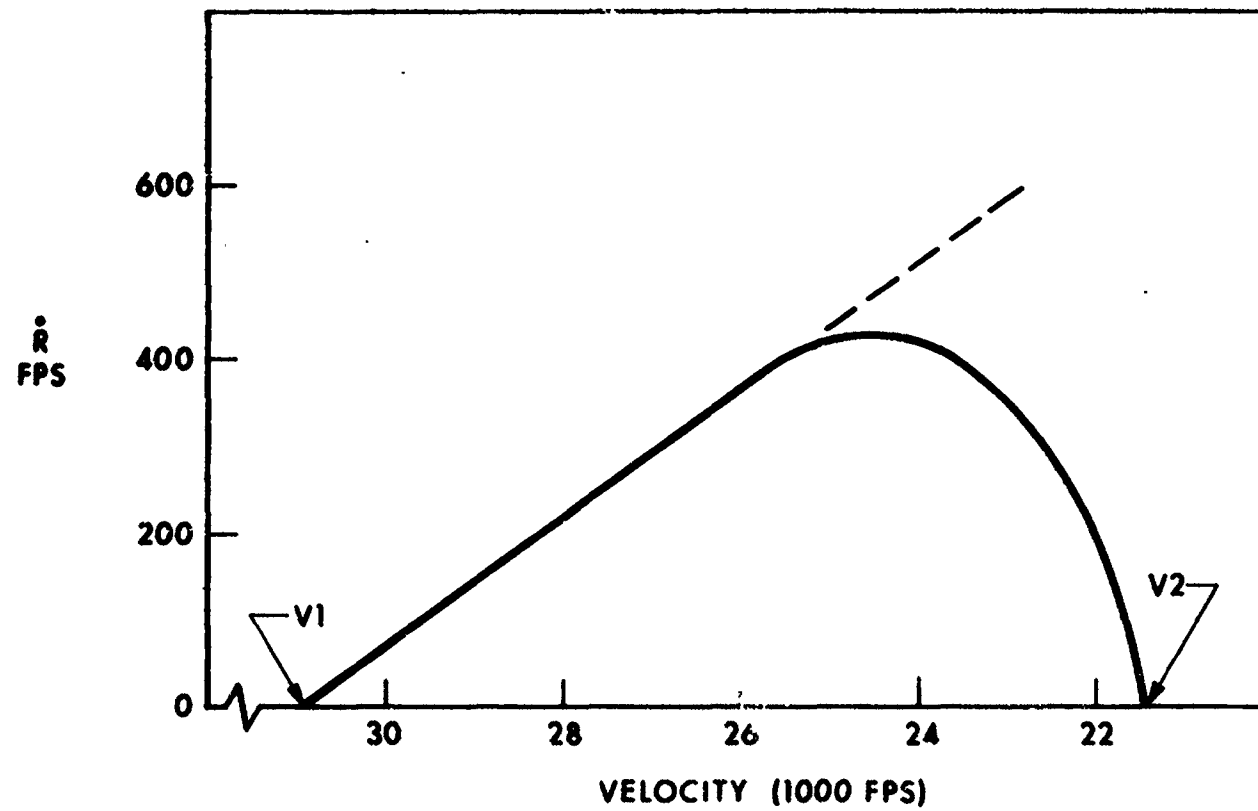


Fig. B-1. "Hook" on Altitude Rate

APPENDIX C

THE FINAL PHASE REFERENCE

The final phase reference is generated by these equations

$$\begin{aligned}\dot{X} &= V \text{ COSG} \\ \dot{V} &= -Q \text{ SCD} - G \text{ SING} \\ \dot{\gamma} &= -V/(RE+H) - G/V \text{ COSG} + Q \text{ SCL}/V \\ \dot{H} &= V \text{ SING}\end{aligned}$$

where

$$\begin{aligned}\text{SING} &= \sin\gamma, \text{ COSG} = \cos\gamma \\ \text{SCD} &= G/(W/CDA), \text{ SCL} = \text{LOD SCD} \\ Q &= 1/2 \rho V^2\end{aligned}$$

These equations represent flight over a spherical non-rotating earth. The atmospheric density, ρ , is defined by the 59 ARDC standard atmosphere, a is the rate of change of density with altitude, DRDZ , and the scale height, $\text{HS} = -\text{DRDZ}/\rho$.

The adjoint to the set of linearized perturbation equations of the above set are then solved. This set is

$$\begin{aligned}\dot{L}_2 &= -\text{COSGL}_1 + (2 Q \text{ SCD}/V) L_2 \\ &\quad + ((-1/RE - G/V^2) \text{ COSG} - Q \text{ SCL}/V^2) L_3 - \text{SING} L_4 \\ \dot{L}_3 &= V \text{ SING} L_1 + G \text{ COSG} L_2 + (V/RE - G/V) \text{ SING} L_3 \\ &\quad - V \text{ COSG} L_4 \\ \dot{L}_4 &= 1/2 V^2 \text{ SCD DRDZ} L_2 - 1/2 V \text{ SCL DRDZ} L_3 \\ \dot{L}_5 &= -Q L_3 \text{ SCD}/(V 6080)\end{aligned}$$

These are solved with time running backwards, and with V, γ, H , and X generated from the first set. The appropriate boundary conditions are $L1(T) = 1, L2(T) = 0, L3(T) = 0, L4(T) = 1/(\tan(\gamma(T))), L5(T) = 0$.

These equations generate the required derivatives which may be identified

$$\begin{aligned}dX/dV &= L2, & \text{ft/fps} \\dX/d\dot{R} &= L3/V, & \text{ft/fps} \\dX/dH &= L4, & \text{ft} \\dX/d(L/D) &= L5, & \text{n.m.}\end{aligned}$$

If we assume the change in drag is due to a change in altitude we may write

$$dX/dD = -HS L4/D, \quad \text{ft/fps}$$

This technique is well established and may be found in Reference 3 among others.

APPENDIX D

ERROR CHARACTERISTICS

Initial Condition Deviations and Uncertainties

It is important to give a detailed discussion of the initial condition deviations and uncertainties since these pose the most significant design problem for the entry steering. The uncertainties, lack of knowledge of our position are by far more important than are the deviations, differences from our planned position; both will be discussed here.

The most important uncertainty is our lack of knowledge of altitude rate. This uncertainty has two components corresponding to the estimated inertial velocity vector and the estimated direction toward the center of the earth. These two components are highly correlated. Shown in fig. D-1 is a typical situation. We are at position 2, corresponding to perigee, while we think we are at position 1 before perigee. At parabolic speeds the range angle, THETA , is twice the flight path angle, γ . Our indicated inertial velocity is off by $+\gamma$, while the indicated direction of down is off by $\text{THETA} = -2\gamma$. The net result is that the error in flight path angle is $-\gamma$. In other words, a positive R uncertainty becomes a negative $\dot{R}$ uncertainty when the correlated range uncertainty is included. Further, positive altitude rate uncertainties, which tend to cause the vehicle fall short, are accompanied by negative range uncertainties which also tend to cause the vehicle to fall short.

All this correlation is possible because of the following observation. The perigee has a fixed angle in space. The reason for this is not known, but it is suspected that the small velocity corrections made near the end of the Midcourse phase cannot change this angle by an appreciable amount, but can only change the altitude at perigee. Moreover, the equations of the Midcourse section allow for this fact, so that the calculated perigee direction is also fixed. This being true, the entry angle deviation is equal to the range uncertainty at the time of the last velocity correction. Of course, the range uncertainty can be improved with further observations. Summarizing then, the entry angle deviation is equal to the flight path uncertainties if no observations have improved that uncertainty.

Error Propagation

Fortunately, the altitude rate uncertainty decreases with time. This can be seen by considering the following equation for altitude rate,

$$\dot{R} = \bar{V} \cdot \bar{U}_R$$

Perturbing this equation, we can write for the error in altitude rate,

$$\delta \dot{R} = \delta \bar{V} \cdot \bar{U}_R + \bar{V} \cdot \delta \bar{U}_R$$

We have shown previously, for parabolic entry velocities that if $\dot{R} = 1$, then

$$\delta \bar{V} \cdot \bar{U}_R = -1 \text{ and } \bar{V} \cdot \delta \bar{U}_R = 2$$

During the critical time of entry, $\delta \bar{V}$ and $\delta \bar{U}_R$ are almost constant, varying with the Schuler period. Also $\bar{V}$ is almost parallel to $\delta \bar{U}_R$. So we may write

$$\delta \dot{R} / \dot{R}_0 = 2 V / V_0 - 1$$

where $\dot{R}_0$ and V_0 are the initial values. Figure D-2 dramatizes this relation. Shown is the actual altitude rate uncertainty history for a typical entry plotted next to this formula. Of course, the variation in $\delta \bar{V}$ and $\delta \bar{U}_R$ will introduce further variations in $\delta \dot{R}$, as will the instrument and platform errors. All of which are not included here. But all of these effects are secondary over the critical up-control phase. More important is the assumed correlation between the two contributors to $\delta \dot{R}$. The correlation of

$$\bar{V} \cdot \delta \bar{U}_R / \delta \bar{V} \cdot \bar{U}_R = -2$$

is quite good at parabolic velocities, but must be redetermined for other velocities. The point of all this is that should we be able to determine the altitude rate error by independent means, we would be able to determine the correlated range error and thereby reduce our position uncertainty.

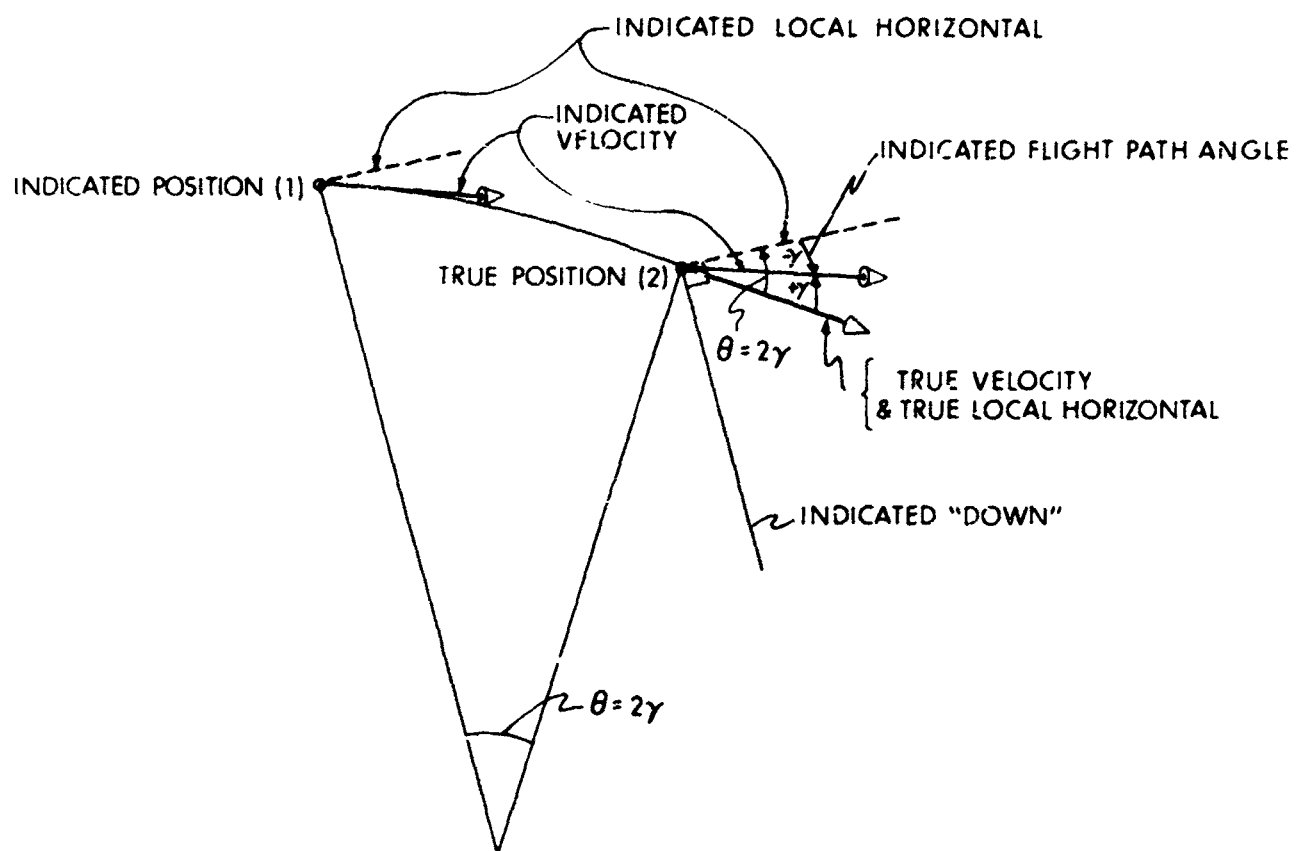


Fig. D-1. Correlation of Range and Velocity

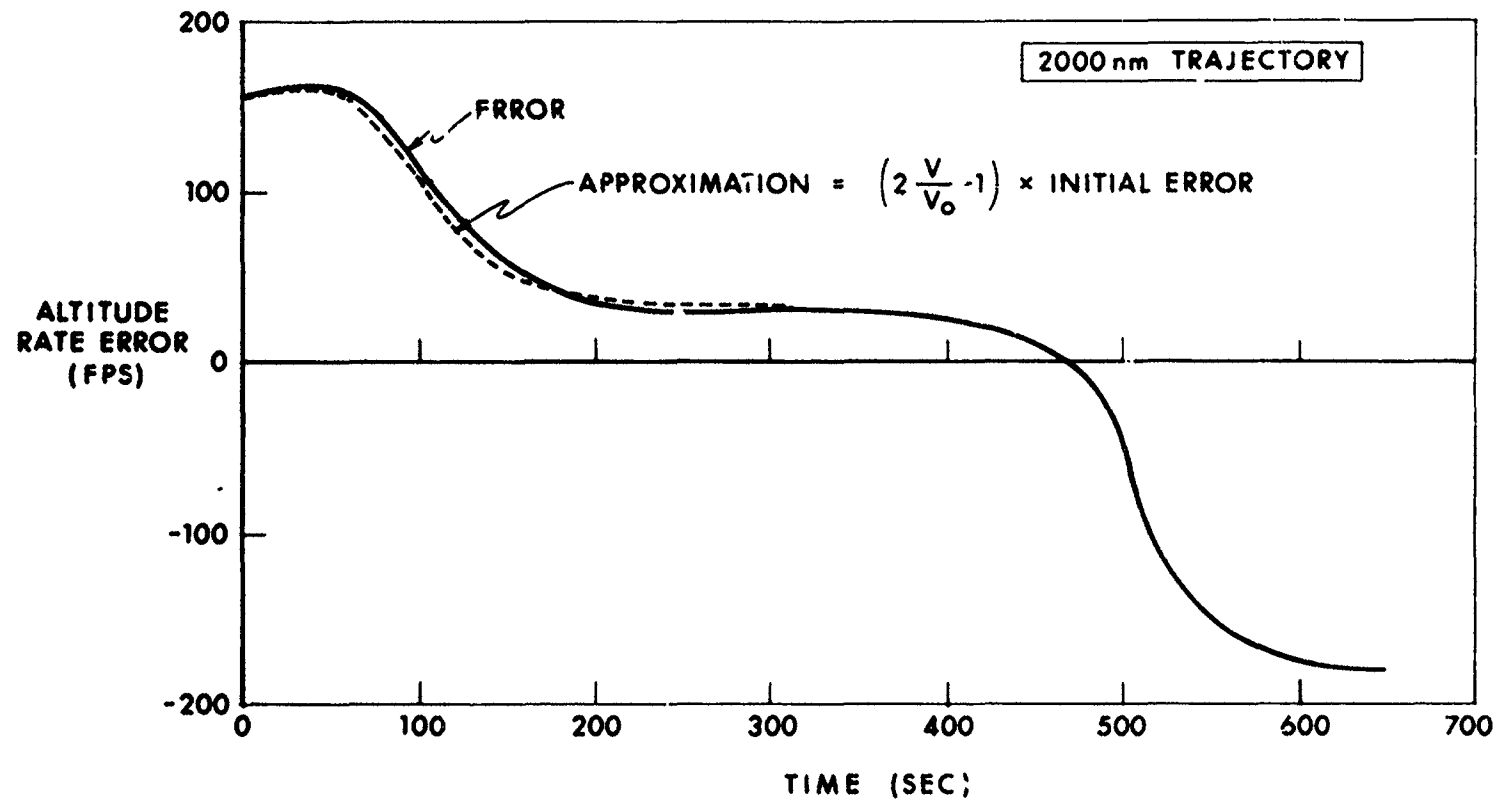


Fig. D-2. Propagation of Altitude Rate Error During Entry

APPENDIX E

ALTITUDE RATE CALCULATION

The equation of interest is that for drag acceleration.

$$D = 1/2 \rho V^2 SCD/m$$

If assume an exponential atmosphere, $\rho = \rho_0 e^{-H/HS}$, we can write for the rate of change of altitude.

$$\dot{H} = HS(2 \dot{V}/V - \dot{D}/D)$$

Use the $\dot{H}$ notation to distinguish it from the measured $\dot{R}$. Since we measure only differences in drag and velocity we write the equivalent difference equation,

$$\dot{H}_{i-3/2} = 2 HS/DT (2(V_{i-1} - V_{i-2})/(V_{i-1} + V_{i-2}) - (D_{i-1} - D_{i-2})/(D_{i-1} + D_{i-2}))$$

The subscript i refers to present time, i.e. multiply the subscript by the time increment to get the time of the sample. We "smooth" the drag acceleration by averaging the last three points,

$$\hat{D}_{i-1} = (D_i + D_{i-1} + D_{i-2})/3$$

This corresponds to a least square fit through the last three points. Substituting the "smoothed" values for the D's we get

$$\begin{aligned} \dot{H}_{i-3/2} = & 2 HS/DT (2(V_{i-1} - V_{i-2})/(V_{i-1} + V_{i-2}) \\ & - (D_i - D_{i-3})/(D_i + 2 D_{i-1} + 2 D_{i-2} + D_{i-3})) \end{aligned}$$

We seek the time at which $\dot{H} = 0$, at which time we will set the indicated $\dot{R}$ to zero. We do this by looking for a change in the sign of $\dot{H}$. When this occurs, we make a correction to $\dot{R}$ by

$$\dot{R} = \dot{R} + \dot{R}CORR$$

where

$$\dot{R}CORR = -(X \dot{R}_{i-2} + (1 - X) \dot{R}_{i-1})$$

$$X = \dot{H}_{i-3/2} / (\dot{H}_{i-3/2} - \dot{H}_{i-5/2}) + .5$$

The error in this calculation is due mainly to a random error in the drag due to vehicle oscillations. This was shown to be about 1 fpss in Section II. The worst case will arise when one sample is +1 and the next sample is -1. In this case, the error in $\dot{H}$ is

$$2 \dot{H} S^2 / (DT^2 D)$$

If $DT = 2$ seconds, a large DT is desirable, and $D = 150$ fpss, the error in $\dot{H}$ is 56 fps.

The results of the previous section show that this corresponds to a range error of 10 n.m. The rms error of course is less than this worst case and is 5 n.m..

This correction is not incorporated into the logic at this time. This is because of the uncertainty in the estimation of the drag noise. The early flights should improve this uncertainty.

APPENDIX F

CHARACTERISTICS OF THE CONSTANT DRAG CONTROLLER

The same assumptions as in Appendix E lead to this equation for the rate of change of drag.

$$\begin{aligned}\dot{D} &= -\beta D \dot{R} - 2 D^2/V \\ &= 0, \text{ for constant drag}\end{aligned}$$

The second derivative is

$$\begin{aligned}\ddot{D} &= -\beta D \ddot{R} - \beta \dot{R} \dot{D} - (4 D/V) \dot{D} - D^2/V^2 \ddot{V} \\ &= 0, \text{ for constant drag.}\end{aligned}$$

Let $\delta D = D - D_0$, where D_0 is the constant drag value and

$$\delta \dot{R} = \dot{R} - 2 H S D/V$$

then

$$\delta \ddot{D} = -\beta D \delta \ddot{R} - \beta \dot{R} \delta \dot{D} + (4D/V) \delta \dot{D} - D^2/V^2 \delta \ddot{D} - \beta D^2 \delta(L/D)$$

This can be simplified by neglecting $-D^2/V^2 \delta \ddot{D}$ and recognizing

$$\begin{aligned}\delta \ddot{R} &= L/D \delta \ddot{D} \\ \text{and } L/D &= -(V^2/R - G)/D \\ \text{and } \beta \dot{R} &= -2 D/V \\ \text{and } \delta(L/D) &= C16 \delta D - C17 \delta \dot{R} \\ \text{and } \delta \dot{R} &= -\delta \dot{D}/(\beta D)\end{aligned}$$

The final result is

$$\ddot{D} + (2D/V + C17 D) \delta \dot{D} + (C16 D^2 - \beta(V^2/R - G)) \delta D = 0$$

AI PENDIX G

RANGE CALCULATIONS FOR THE UP-CONTROL SECTION

ASPDWN

To calculate the range from the start of up-control to pull-out ($R = 0$) assume constant velocity and constant acceleration over this short period. The range is then the product of velocity and time, where time is $-R/(LAD A0)$.

$$\begin{aligned} \text{ASPDWN} &= -R V / (LAD A0), \quad \text{ft} \\ &= -R V \text{ ATK} / (A0 LAD RE), \text{ n.m.} \end{aligned}$$

ASPUP

To calculate the range from pull-out to exit, assume constant $\dot{R} = \dot{R}_L$, the exit value with no velocity correction, and constant velocity V_L . The range is the product of velocity and time. In this case the time is the change of altitude divided by $\dot{R}$. The change in altitude is calculated assuming an exponential change of density with altitude

$$H = H_S \text{ LN}(\rho_1 / \rho_L)$$

where

$$\begin{aligned} \rho_1 &= \text{initial density} = K A0 / V_1^2 \\ \rho_L &= \text{final density} = K Q7 / V_L^2 \end{aligned}$$

Summarizing

$$\begin{aligned} \text{ASPUP} &= (H_S V_L / R_L) \text{ LN}(A0 V_L^2 / (Q7 V_1^2)), \quad \text{ft} \\ &= (H_S \text{ ATK GAMMAL1} / RE) \text{ LN}(A0 V_L^2 / (Q7 V_1^2)), \text{ n.m.} \end{aligned}$$

ASKEP

The kepler range is a straight-forward application of conic sections. The derivation is included here for completeness.

From the polar form of the ellipse we can write

$$\cos f = (1 - l/R)/E$$

where

f = true anomaly

l/R = semilatus rectum/ R

$$= \bar{V}^2 \cos^2 \gamma$$

E = eccentricity

$$= 1 - 2 \bar{V}^2 \cos^2 \gamma + \bar{V}^4 \cos^2 \gamma$$

= flight path angle

$\bar{V}$ = normalized velocity

$$= V/VSAT$$

The ballistic range is $2f$.

It is more convenient to solve for the sine of the true anomaly which is in view of the above relations

$$\sin f = \bar{V}^2 \cos \gamma \sin \gamma / E$$

Since the flight path angle is small, these approximations are made

$$\cos \gamma = \text{COSG} = 1 - \text{GAMMAL}^2/2$$

$$\sin \gamma = \text{GAMMAL}$$

We have then the final result

$$\text{ASKEP} = 2 \text{ ATK } \sin^{-1}(\text{VBARS COSG GAMMAL}/E), \text{ n.m.}$$

where

$$\text{VBARS} = \text{VL}^2/\text{VSAT}^2$$

ASP1

The final phase range is a linear correction to the reference range at the start of the final phase reference trajectory.

$$ASP1 = Q2 + Q3 VL$$

ASP3

The flight path angle correction to the final phase range uses the initial values of the reference trajectory altitude rate and rate of change of range with altitude rate

$$ASP3 = Q5(Q6 - GAMMAL)$$

APPENDIX H

LIMIT ALTITUDE RATE FOR G-LIMITER

If the vehicle is at the limit altitude rate, R_1 , full positive lift will just cause the g-level to become tangent to the maximum g-level. This limit altitude rate is derived as follows.

Start with the equation for rate of change of altitude rate,

$$d\dot{R}/dT = V^2/R - G + 1/2 \rho V^2 SCL/m$$

Eliminate time by using $dH/dT = R$

$$\dot{R} d\dot{R} = (LEQ + L) dH$$

where

$$LEQ = V^2/R - G$$

$$L = 1/2 \rho V^2 SCL/m e^{-H/HS}$$

Integrate from point 1 (present conditions) to point 2 (at maximum g) assuming constant velocity

$$\dot{R}_2^2 - \dot{R}_1^2 = 2 LEQ (H_2 - H_1) - 2 HS (L_2 - L_1)$$

but $\dot{R}_2^2 = (2 HS GMAX/V)^2$

and $H_2 - H_1 = HS \ln(L_1/L_2) = HS \ln(D/GMAX)$

and $L = L/D \quad D = LAD/D$

So we can write

$$\dot{R}_1^2 = (2 HS GMAX/V)^2 - 2 HS LEQ \ln(D/GMAX) + 2 HS LAD (GMAX - D)$$

Represent the log function by a truncated series

$$\begin{aligned}\ln(D/G_{\max}) &= \ln(1 + (D - G_{\max})/G_{\max}) \\ &= (D - G_{\max})/G_{\max}\end{aligned}$$

So we can write

$$\dot{R}_1^2 = (2 HS G_{\max}/V)^2 + 2 HS LAD(G_{\max} - D) + 2 HS LEQ(G_{\max} - D)/G_{\max}$$

Finally we take the negative square root

$$\dot{R}_1 = -\text{SQRT}(\dot{R}_1^2)$$

APPENDIX I

NOMENCLATURE

$\vec{A}$	Vector with 3 components
$\vec{B}$	Vector cross product of $\vec{A}$ and $\vec{B}$
$\vec{A} \cdot \vec{B}$	Vector dot product of $\vec{A}$ and $\vec{B}$
SQRT	Square root
ABVAL	Absolute value of vector only
=	Is replaced by. e. $A = B + C$ means quantity labeled A is replaced by the sum of B and C
$\dot{A}$	Time derivative of A
δ	Variation
ARCCOS	Arccosine function
LOG	Logarithm to Naperian base
SGN	Signum function = +1 for pos arg, = 0 for 0 arg. = -1 for neg arg.

APPENDIX J

Between the time this report was prepared and it was ready for publication, certain improvements were made in the steering logic. These changes are minor but lead to a significant improvement in performance in some of the more difficult parts of the design envelope. In view of this, they are included here rather than adopted into the main body of the report so that the description and results in the report may be consistent.

The first change, shown in revised diagram of HUNTEST, allows for a change in the reference L/D for the Up-control phase, LEWD. If the drag is greater than D2, LEWD = LEWD2. Otherwise LEWD = LEWD1.
(LEWD2 = .2, LEWD1 = .1, D2 = 175 fpss)

The second change shown in the same diagram fixes the constant drag value, D0, at one value (130 fpss) for all entry angles.

The third change uses the weighted average of GAMMAL and GAMMAL1 rather than GAMMAL1 in the calculation of ASPUP.

$$\text{GAMMAL1} = (1 - Q19) \text{GAMMAL} + Q19 \text{GAMMAL1} \dots (Q19 = .2)$$

The revised diagram for the Up-control section shows the next change. In this phase Q7MIN is now used in calculating FACTOR. This is done so that the gains in the Up-control phase will not decrease to zero as the drag approaches Q7. (Q7MIN = 35 fpss) Also, A1 is used instead of A0 in calculating FACTOR. A1 is calculated to be either A0 or D in the HUNTEST section depending on the sign of R. This last calculation is made so that FACTOR will be near one at the start of the Up-control phase so that the full effect of the gains will be had.

Finally, K44 is decreased from 236 to 153 so that down-lift will be held for all entries shallower than mid-entry. This factor has considerable latitude, since there is a large band of entry angles for which the initial lift may be either down or up.

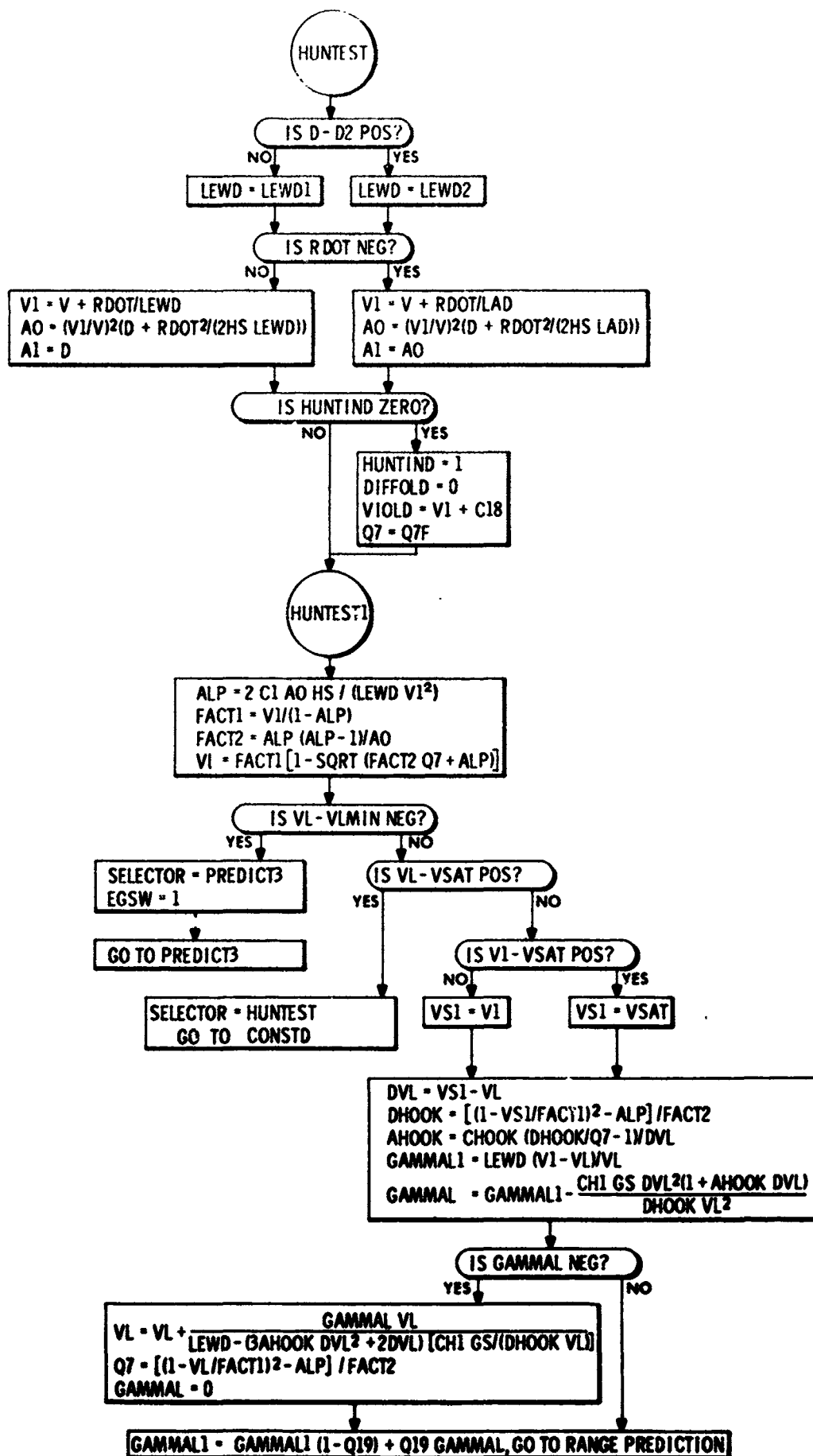


Fig. J-1 Hunttest Section (revised)

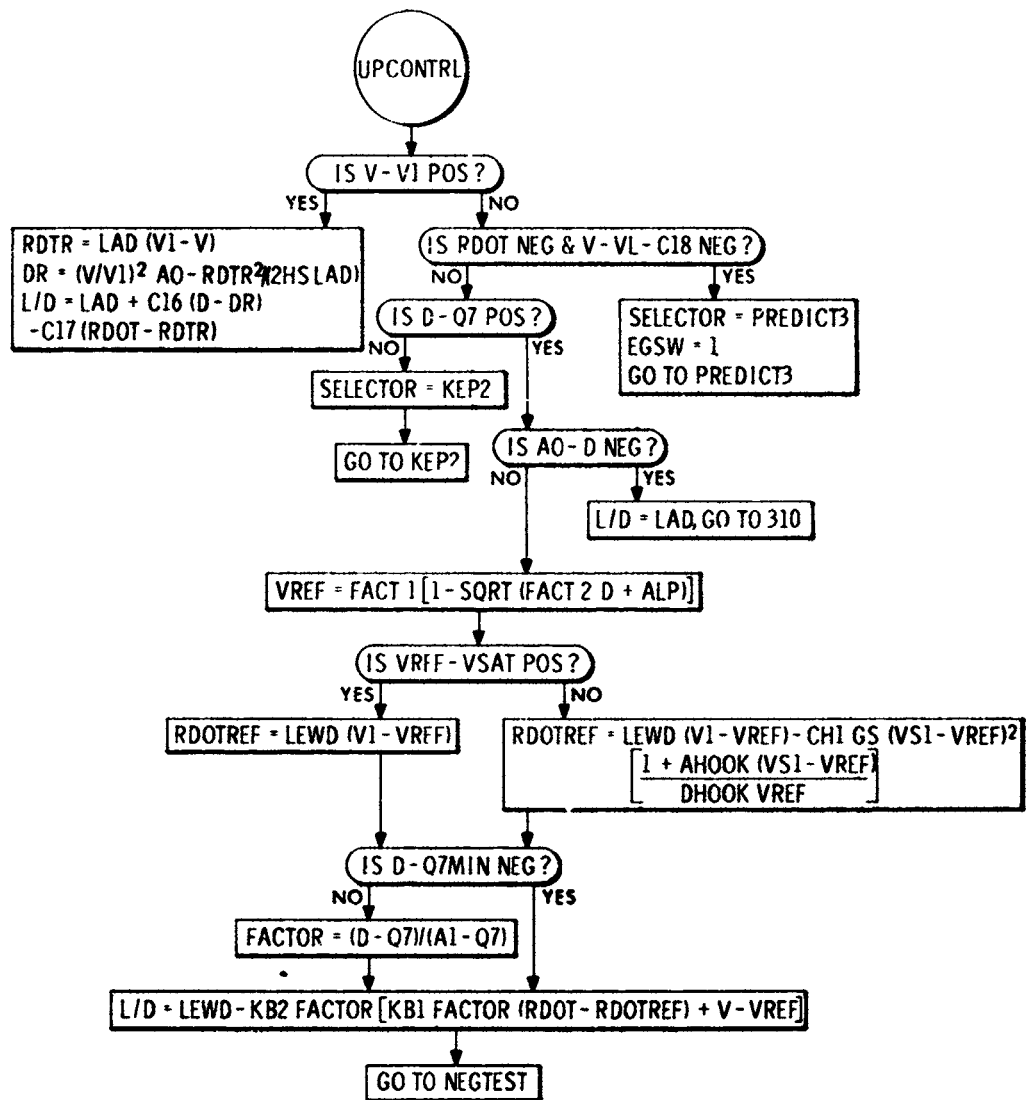


Fig. J-2 Up-control Section (revised)

APPENDIX K
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