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Phase II - FINAL REPORT

Research on Computational and Control Requirements for Human Control of Space Vehicle Boosters

Part I - THEORY and RESULTS

November 1966

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PHASE II FINAL REPORT

RESEARCH ON COMPUTATIONAL AND DISPLAY REQUIREMENTS FOR HUMAN CONTROL OF SPACE VEHICLE BOOSTERS

Part I: Theory and Results

Advanced Studies Office
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George C. Marshall Space Flight Center
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FOREWORD

This is the final report on the second phase of a study of man-computer boost guidance techniques. The research was sponsored by the Advanced Systems Office Astrionics Laboratory, Marshall Space Flight Center under Contract No. NAS 8-20023. The research was performed by the Systems and Research Division of Honeywell Inc. at facilities in Minneapolis, Minnesota. Mr. J. F. Pavlick of MSFC was the contract monitor for the study. Mr. R. C. Kiene was the program manager. Project personnel were D. E. Soland, principal investigator, Dr. J. D. Gilchrist, and R. Livingston. The report covers work extending from 22 June 1966 to 22 October 1966. The report was prepared by Dr. J. D. Gilchrist and R. Livingston.

The report is in two parts. Part I includes the theory, results of computer experiments, and conclusions. Part II provides descriptions, listings, and flow diagrams of computer programs developed during the study.

SYMBOLS

a = Speed of sound

c^* = Exhaust velocity

C_D = Drag coefficient

C_{D_o} = Drag coefficient at zero angle of attack

C_L = Lift coefficient

C_{L_α} = Derivative lift coefficient

D = Aerodynamic drag force

g = Acceleration of gravity

g_o = Acceleration of gravity at sea level

h = Altitude above sea level

L = Aerodynamic lift force

m = Instantaneous vehicle mass

M = V/a = Mach number

q = Dynamic pressure

R = Range

r = Radial distance from earth's center

p_i = Optimization (auxiliary) variables

V_x, V_z = Velocity component in predictive model

x = Steering angle in predictive model

χ = Position component in predictive model

z = Position component (altitude) in predictive model

ABBREVIATIONS

CRT	Cathode Ray Tube
NGS	Nominal Guidance System
PI	Performance Index
PMGS	Predictive Model Guidance System
PWLI	Pilot Work Load Index
ROT	Reusable Orbital Transport

r_o = Mean radius of the earth

S = Vehicle reference surface area

T = Thrust

t = Time

t_f = Final time

t_s = Time of staging

V = Vehicle velocity relative to the earth

V_w = Horizontal wind velocity in plane of trajectory

α = Angle of attack

β = Mass flow rate

β_1, β_2 = Maximum flow rate (subscript refers to stage)

γ = Flight path angle relative to the local horizontal

θ = Vehicle attitude

λ = Characteristic height of the atmosphere

ρ = Atmospheric density

ρ_o = Reference density (assumed equal to density at sea level)

A, B = Optimization parameter

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SECTION 1
INTRODUCTION

1.1 GENERAL STATEMENT OF THE PROBLEM

The ultimate goal of this study is to develop the minimum computational and display requirements which will allow full utilization of the capabilities of a human pilot to guide and control a launch vehicle during the entire mission. Present implementation of automatic guidance schemes involve complex equations or complex iteration procedures to arrive at guidance commands which generate optimal trajectories. Generally, the result is that only the nominal trajectory is programmed in the vehicle computer.

Deviations from the nominal trajectory can occur due to sensor or processing electronics failures, data noise, and mechanical failures. Redundant components, adaptive guidance schemes, and adaptive self-optimizing control systems are some of the measures used in automatic guidance and control systems to ensure fulfillment of mission objectives with corresponding penalties in system weight, cost, and complexity.

The possibility of manned launch vehicles with significant aerodynamic capabilities opens the question of the desirable division of navigation, guidance and control functions between the flight crew and automatic systems. A vital part of the answer depends on the information which defines the degree to which automatic equipment can be simplified by the inclusion of man in the guidance and control loop and still accomplish these functions in a near-optimal manner.

1.2 BACKGROUND

This report covers a four-month extension to a study whose ultimate goal is to define the minimum computational and display requirements for near-optimal guidance and control of an aerodynamic launch vehicle by a human pilot. The previous phase[1] was concerned with the determination of the boost-phase fuel-optimal guidance function. In that phase, various trajectory optimization methods were studied with particular emphasis placed on the simplification of these methods with the use of man in the iterative computation loop. The results of that phase indicated that the optimization method based on results from the calculus of variations or equivalently, from Pontryagin's Maximum Principle, could be used in a manual optimal guidance scheme. A preliminary system was defined stating proposed displays, computing method and man's role in the proposed system. This proposed system is called the Manual Predictive Model Guidance Scheme. The objective of this present phase of study was to provide analyses and simulation to further determine the applicability and capability of manual determination of an optimum flight path for a launch vehicle.

1.3 STUDY VEHICLE

For the purpose of the study, the vehicle is assumed to have two stages, take off horizontally, and develop considerable aerodynamic lift in the first stage. The takeoff weight is approximately 1.5 million pounds, and the initial velocity is nominally 650 ft/sec. The mission profile consists of a planar boost to circular orbit at an altitude of 100 nautical miles, with no restriction on the distance down-range at orbit injection. Variations of lift and drag coefficients with Mach number are included in addition to an acceleration limit of 3 g's. The vehicle parameters are characteristic of those of a Reusable Orbital Transport (ROT)[7].

1.4 THE PREDICTIVE MODEL GUIDANCE SCHEME

The guidance scheme proposed in the previous phase of the study is considered a significant addition to the methods of optimal manual guidance. To evaluate this Manual Predictive Model Guidance Scheme, a second more conventional manual scheme, the Manual Nominal Guidance Scheme, was simulated for the study vehicle. To place this study in proper perspective, some of the basic differences between the proposed manual scheme and past automatic schemes such as considered for the Saturn-V vehicle are shown in Table 1-1. To summarize, the onboard computer for the automatic guidance system is replaced by a pilot-display-computer system. The computer requirements of the manual scheme are lower than the automatic scheme; however, a display system has been added which is not required in a completely automatic system.

Table 1-1. Comparison of an Automatic with the Predictive Model Guidance Scheme

Characteristics	Automatic Guidance Scheme (e.g. Saturn-V - polynomial guidance mode)	Manual Guidance Scheme (e.g. Predictive Model Guidance scheme)
Preflight Computation Requirements	High	None
Onboard Computation Requirements	High	Moderate
Mission Flexibility	Low (limited by computer storage)	Moderate (limited by vehicle considerations; e.g. fuel)
Propellant Economy	Fuel optimal	Fuel-optimal
Display Requirements	None	Moderate
Piloting Requirements	None	One pilot

Table 1-1 shows only one of the two manual guidance schemes studied during this phase. The two manual optimal guidance schemes considered and simulated during this study are the Nominal Guidance Scheme (NGS) and the Predictive Model Guidance Scheme (PMGS). Figure 1-1 shows the man-computer-

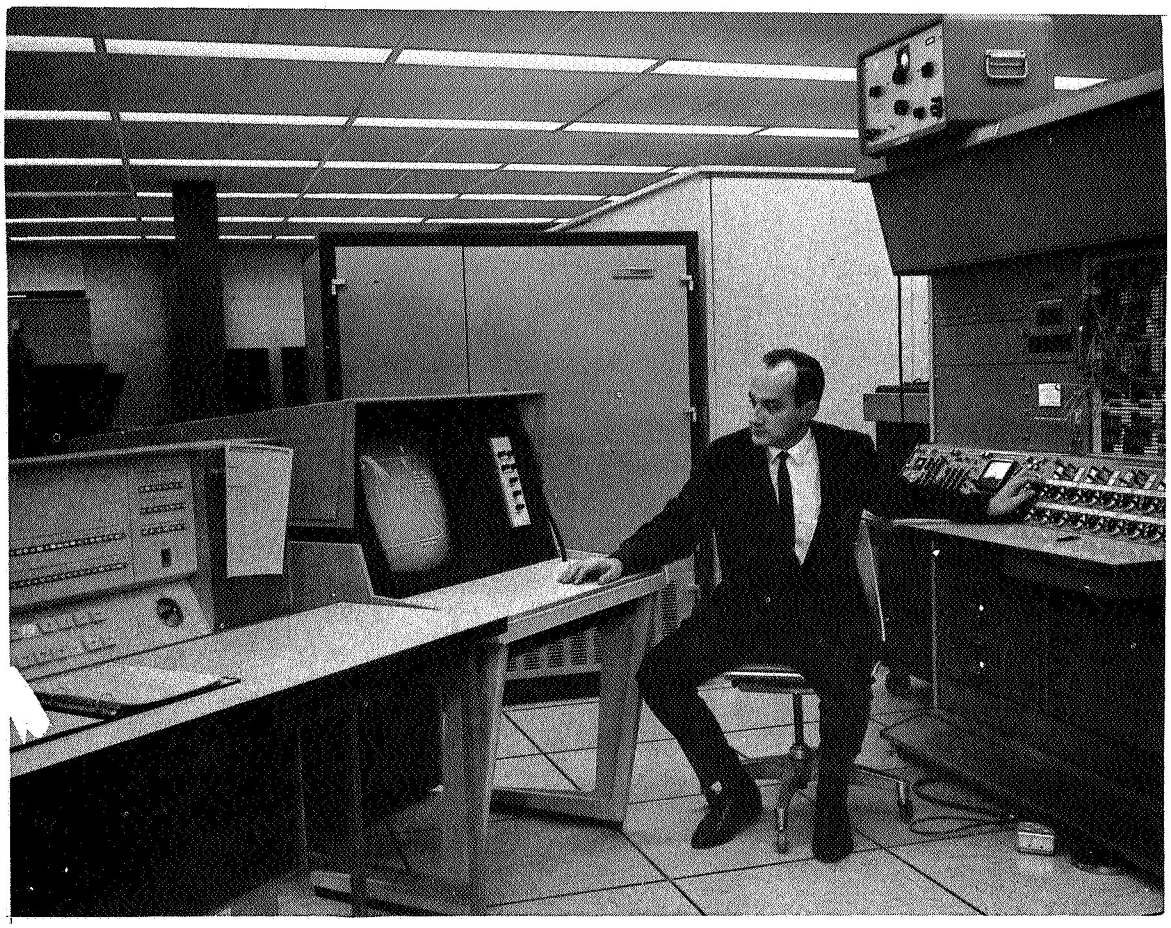


Figure 1-1. Man-Computer Display Simulation System

display system used in the simulation. It is felt that the PMGS is a significant contribution to the field of manual guidance since it incorporates the following features:

- It minimizes the fuel required.
- The accuracy in the desired terminal conditions is approximately an order of magnitude improved over that obtainable with a more conventional manual guidance scheme (for example, the NGS).
- The work load imposed on the pilot is low compared with conventional manual boost guidance schemes.
- The display requirements in the man-computer guidance loop are low.
- The onboard computational requirements are low in comparison to an automatic scheme such as the polynomial guidance mode considered for the Saturn-V.
- Flexibility of the mission objectives is maintained with the PMGS; thus it would be of a distinct advantage in performing abortive maneuvers.
- The PMGS is based on results from two diverse fields: research in optimal control theory and studies on the capability of a human pilot to perform the guidance function. These two areas of endeavor should also provide for some significant advances in the study of manual optimal attitude control.

The nominal guidance scheme, although certainly not new in concept[2, 3], was studied for purposes of comparison with the PMGS.

1.5 OBJECTIVES

The objectives of the present phase of the study were to:

(1) Define a manual optimal closed-loop guidance scheme for the study vehicle. This scheme was the Predictive Model Guidance Scheme proposed in the previous phase of the study.

(2) Determine the pilot's role in the manual scheme and the displays which are required for efficient implementation of the manual scheme.

(3) Define a conventional manual guidance scheme for the study vehicle. This conventional scheme consisted of the pilot manually controlling the vehicle attitude so that the vehicle follows a nominal trajectory. This conventional manual guidance scheme, called the Nominal Guidance Scheme, is used as a basis for comparing the Predictive Model Guidance Scheme.

(4) Determine an optimum display format for the Nominal Guidance System along with a satisfactory control for the pilot. Determine the effect of using a display of the predicted vehicle state.

(5) Compare the two manual guidance schemes on the basis of:

  (a) The accuracy of the desired terminal conditions

  (b) Pilot work load

  (c) Degree of mission flexibility afforded by each scheme

  (d) Fuel requirements

  (e) Display requirements

  (f) Computational requirements

(6) Define a manual guidance scheme for both stages of the boost phase which have the following general characteristics:

(a) Small error in desired terminal conditions

(b) Low pilot work load

(c) Minimum fuel required

(d) Mission flexibility maintained

(e) Minimum computation and display requirements

A real-time man-computer-display simulation of the guidance schemes was required in this study to fulfill the study objectives. A hybrid computing facility was used; the simulation of the vehicle dynamics was performed on the digital computer due to the nonlinearity of the equations and the large range of the variables. Manual control of the vehicle simulation was achieved with the analog computer. The display was used for the operator to evaluate his performance.

SECTION 2
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Present guidance techniques for manned booster vehicles require extensive precomputation and onboard computer storage of reference trajectories or equivalent steering commands in order to allow the vehicle to follow a near-optimal trajectory in the possible event of large disturbances. Prior manual guidance studies have used a pilot in a command tracking task about a nominal reference trajectory to greatly simplify the onboard computer requirements. Such methods, however, lack the flexibility of the automatic approach in coping with unexpected events such as engine failures which may make it impossible or, at least, undesirable to follow the reference trajectory. The addition of an onboard capability for trajectory synthesis and display of predicted trajectories would combine some of the best features of both approaches. Consequently, the present study has been concerned with comparative evaluation for onboard application of near-optimal trajectory prediction techniques. The ultimate goals of the program are the minimum computational and display requirements which will fully utilize the capabilities of a man to guide and control a launch vehicle for the entire mission.

The vehicle used for the model in this investigation is a Reusable Orbital Transport (ROT), a two-stage launch vehicle with appreciable aerodynamic lift capability in the first stage. The mission phase under study involves a horizontal takeoff and boost to a 100 nautical-mile orbit. An acceleration maximum of 3 g's was an additional constraint to be satisfied.

Two manual optimal schemes, the Predictive Model Guidance Scheme and the Nominal Guidance Scheme, were defined for the ROT vehicle and were successfully simulated on a real-time basis with a pilot actively engaged in the guidance function.

The Predictive Model Guidance Scheme was successfully utilized for a second-stage guidance scheme only. It was only simulated for second stage for the following reasons.

(1) The sensitivity of the desired terminal conditions to the optimization parameters increases as the required flight time increases. This sensitivity is not considered an insurmountable problem.

(2) The fast-time model required in the first stage to account for the aerodynamic effects is more complex than for the vacuum phase. The effectiveness of the predictive model scheme decreases as the fast-time solution rate decreases. Also, this solution rate must necessarily decrease as the fast-time predictive model complexity increases.

(3) In the previous study phase[(1)], it was determined that the fuel-optimal path in the atmosphere consists of a "basic" path, uniquely defined in the altitude-velocity plane, with thrust as a parameter. This path is independent of initial conditions, the remaining portion of the trajectory being a transition path to put the vehicle on this path after takeoff or after some disturbance. In view of this, an optimal nominal trajectory is close to an optimal trajectory for other initial conditions since all optimal trajectories have a portion of this "basic" path in common.

(4) In summary, sensitivity and predictive model complexity are degrading characteristics of the predictive model scheme during the first stage. A nominal guidance scheme, however, is particularly well suited to the atmospheric phase due to the "basic" path feature and the reduced computation requirements.

As the result of a successful simulation of the Predictive Model Guidance Scheme for second-stage guidance, the following conclusions were reached; these conclusions are pertinent to the design of such a system:

(1) A human operator is effective in the manual scheme with a fast-time solution rate of one per second.

(2) A meter-type display of the predicted terminal errors in altitude and flight-path angle during the terminal phase of boost is a definite requirement to obtain the desired accuracy in the terminal conditions.

(3) A two-dimensional display of the predicted trajectory in the altitude-velocity plane is useful to the pilot for the iterative task of "shaping" or synthesizing the predicted trajectory. After the trajectory has the proper shape, the meter display is required to yield the desired accuracy in the terminal conditions.

(4) A simplification of the display requirements towards a meter-type presentation of the predicted terminal errors is not recommended since pilots may desire information about their current status (i. e., the present state of the vehicle) and also information concerning their future flight path (i. e., the predicted trajectory in the altitude - velocity plane).

(5) Only two optimization parameters are required by the pilot to steer the planar vehicle model to the desired terminal conditions.

(6) In a mechanization of the predictive scheme, no transformation equations from vehicle to model coordinate system (see section 3. 2. 1) are required since an inertial navigation system could be used to operate in the same reference frame as the fast-time predictive model.

(7) From the experience gained in experimenting with the scheme, it is concluded that the work load is a function of the mission time. The work load is moderate initially, then decreases to zero, and finally, towards cutoff conditions, the work load increases again.

This is an area that requires further investigation. One possible method of measuring the work load is by defining a standard secondary task. The work load is then measured by the performance in this secondary task.

(8) The amount of operator training required for efficient operation of the manual guidance scheme is low.

The study of the Nominal Guidance Scheme was undertaken for purposes of comparison with the Predictive Model Guidance Scheme. On the basis of the simulation carried out in this study, the following conclusions were reached concerning the design and application of the nominal guidance scheme:

(1) This study was conducted with a planar model of the ROT vehicle dynamics. The model also assumes a perfect control system, and the pilot's only function in the guidance loop is to steer the vehicle along the nominal. The conclusions of this phase of the study should be re-evaluated using a three-dimensional model for the vehicle along with either an automatic or manual control system.

(2) The altitude-versus-altitude-rate display format for presentation of the nominal trajectory is recommended over the altitude-versus-velocity and altitude-versus-flight-path-angle. This selection is made on the basis of a relative measure of the pilot work load and the resulting errors in the desired terminal condition.

(3) A display of the predicted state, based on derivative information of the present state, was used in the study. Experience indicates that the predicted-state display is not required if the present state remains on the nominal trajectory. If the present-state display is off, the nominal, the predicted-state display is useful to the pilot in steering back to the nominal. It is concluded that the predicted-state display is not absolutely essential for the nominal guidance scheme.

Additional pilot training, however, is required if the prediction display is not used.

(4) In addition to a display of the nominal trajectory along with the vehicle's present state, a meter-type presentation of the present state is a definite requirement for the terminal phase of the mission. The use of the meter presentation of the present state results in an improvement in the terminal error by almost an order of magnitude. The meter presentation of body attitude is useful throughout the flight, whereas the remaining information of the present state is useful towards the end of the flight.

(5) The display requirements have been determined during this study. The actual implementation of these displays requires further study. Possibilities include a continuous cathode-ray-tube (CRT) presentation of the nominal along with the present state and a CRT presentation of the present state and a plastic overlay display of the nominal trajectory. The usefulness of electroluminescence over the conventional cathode ray tube as a display device should be considered.

(6) It is recommended that the control $\dot{\theta}$ be used during the first stage and the control θ for second-stage guidance; $\dot{\theta}$ is used in the first stage due to the simplified nominal control, whereas θ is used in the second stage because of fewer integrations between response and control.

(7) The effects of random disturbances due to winds are negligible on the pilot's ability to manually steer the vehicle along a nominal trajectory. The effects would not be negligible with the inclusion of rotational dynamics to the model.

As mentioned previously, the Nominal Guidance Scheme was studied for purposes of comparison with the Predictive Model Guidance Scheme. This comparison was based on such factors as:

- Accuracy
- Pilot work load
- Mission flexibility
- Fuel requirements
- Display requirements
- Computational requirements
- Training requirements
- Pilot's role

Table 2-1 summarizes the comparison of the NGS with the PMGS. The PMGS is accurate, flexible, fuel-optimal, and the pilot work load is low. The computer and display requirements are moderate. On the other hand, the NGS is simple, has basically no computer requirements, and the display requirements are low. These low computation and display requirements assume there are no requirements for display of the nominal trajectory. The NGS, however, is less accurate than the PMGS; it is not flexible; it is not fuel-optimal if large disturbances are present; and the pilot work load is higher than that of the PMGS. Thus, the basic tradeoff between the two schemes is between an accurate, fuel-optimal, flexible, low work load scheme and a manual guidance scheme which is simple and which has low computer and display requirements.

Typical terminal errors with the PMGS were 1700 feet in altitude and 0.007 degree in flight-path angle. The corresponding errors with the NGS were 2200 feet and 0.17 degree.

Table 2-1. Comparison of the Nominal and Predictive Model Guidance Schemes

Vehicle Stage	Guidance Scheme	Pilot Workload	Fuel Requirement	Complexity		Mission Flexibility	Terminal Error
				Computer	Display (CRT)		
Stage 1	MGS	Low	Near Optimum (function of off-nominal I. C., external disturbances and parameter variations)	Low-if nominal is not stored in computer Moderate-if nominal is stored in computer	Moderate-if CRT is used to display nominal Low-otherwise	No	
	PMGS	Moderate	Near Optimum (function of approximations in fast-time model)	Moderate	Moderate	Yes	
Stage 2	NGS	High	Non-optimum	Low	Moderate-if CRT is used to display nominal Low-otherwise	No	Typical Errors: Altitude = 1700 ft Flight-path angle 0.007°
	PMGS	Low	Optimum	Moderate	Moderate	Yes	Typical Errors: Altitude = 2200 ft Flight path angle = 0.17°

SECTION 3
ACCOMPLISHMENTS AND RESULTS

3.1 GENERAL

The statement of the guidance objectives for man-rated vehicle with reference to the terminal conditions is relatively simple. To be specific, the problem consists in arriving at a desired altitude and geographical coordinate with a specified velocity and flight-path angle with an intact vehicle. In this study, a model with motion restricted to a plane is assumed, and the desired terminal condition is injection into a 100-nautical-mile circular orbit. This requires reaching the desired altitude of 608,020 feet with a specified velocity of 25,570.5 ft/sec and a zero flight-path angle.

In addition to satisfying these terminal conditions, the trajectory must also be a solution accounting for thrust limitations, structural limitations and constraints placed on the payload and other contents, including human occupants. Trajectories which minimize the fuel, and hence maximize the payload, or which meet the desired terminal conditions at a specified time are also an important consideration. For the two-stage reusable orbital transport (ROT) used as an example in this study, the vehicle thrust is limited in both stages, and the total load factor is limited to 3 g's. The fuel required is minimized in order to maximize the payload delivered in orbit. With the additional assumption of a steady burn in both stages, the minimum fuel criteria is equivalent to the minimum time criterion.

In summary, a trajectory generated for the ROT model is considered optimal if the load factor constraint is satisfied along the trajectory, the terminal conditions are satisfied, and the time required to go from given initial conditions to the desired terminal conditions is minimum.

Two manual optimal guidance schemes were defined and evaluated during this contract. These schemes are called the Predictive Model Guidance Scheme (PMGS) and the Nominal Guidance Scheme (NGS). Both approaches are fuel-optimal in nature. The model scheme generates fuel-optimal trajectories for the predictive model used in the guidance scheme. This prediction model trajectory is also very close to optimal for the actual ROT vehicle model used in the study. The nominal scheme uses a fuel-optimal nominal trajectory about which the pilot guides the vehicle during ascent. The predictive model approach, as implemented, is new and represents a significant advance to the use of optimal control theory to manual guidance. The nominal guidance scheme, although not new in concept, was studied as a basis for evaluating the predictive model approach and to determine which stage of the boost trajectory the two schemes are more applicable when considering such factors as pilot workload, fuel expenditure, guidance mechanization complexity, and mission flexibility.

In the following subsections, each of these guidance schemes is described in general and then in some detail for the model used in the study. The variability of the errors in the terminal conditions obtained with each method are indicated, and a typical learning curve for each method is presented. This learning curve is based on a single operator and on the results obtained in one session. A summary and recommendation for further study for each method is included. The final section compares and evaluates each of the manual optimal guidance schemes.

3.2 THE PREDICTIVE MODEL GUIDANCE SCHEME

This subsection includes a general description of one of the optimal manual guidance schemes considered in the study. A block diagram of this predictive guidance scheme is given in Figure 3-1. The discussion consists of a general description and then progresses to a more detailed explanation of the equations used, the pilot's role in the method, and the displays required.

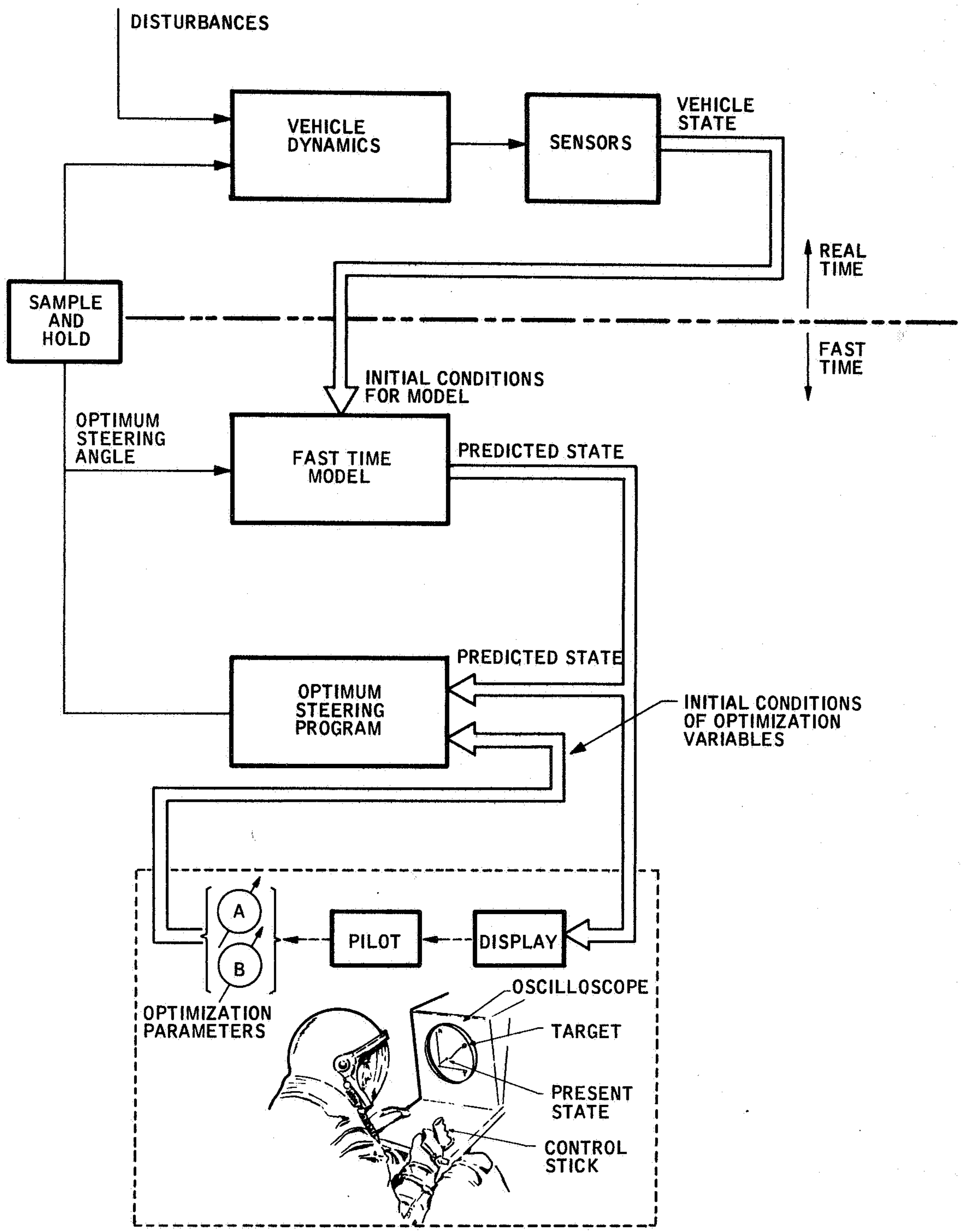


Figure 3-1. Block Diagram of Predictive Model Guidance Scheme

3.2.1 System Description

3.2.1.1 General -- A fuel-optimal closed-loop guidance scheme for any aerospace booster vehicle is highly desirable; however, a closed-loop automatic guidance scheme which does not depend on a precomputed nominal trajectory is, mathematically, very complex. Even when the associated mathematical problems have been solved, the onboard computer requirements are formidable. In most cases, the guidance scheme is closed-loop during the vacuum portion of the flight. Furthermore, these closed-loop automatic guidance schemes may not have the flexibility of being able to change the mission requirements during the actual mission or correct for large deviations from the nominal mission trajectory and still yield a new optimum trajectory.

Rather than a closed-loop scheme, one might consider an optimal open-loop guidance scheme. In this case, the mathematical problems are relatively easy to solve in both the atmospheric phase and the vacuum portion of the mission. In the open-loop schemes, the steering function is determined as a function of time for an assumed nominal vehicle model. This time history is then used as a steering program for the actual vehicle and, in principle, steers the vehicle from some given initial condition to a desired terminal condition. The accuracy of the open-loop approach depends on an exact model of the vehicle and its environment. Due to wind disturbances, control system failure and variations in vehicle parameters, fairly large deviations from the desired trajectory may occur. For example, the uncontrolled lateral drift in a Saturn-V class vehicle is in order of one mile at the end of the first stage. Thus, a completely open-loop approach is not satisfactory. A hybrid scheme, however, is feasible. It employs the advantages of both the open-loop and closed-loop schemes -- the inherent accuracy of a closed-loop scheme and the mathematical tractibility of an optimal open-loop scheme. The hybrid scheme consists in repetitively solving the open-loop problem as the flight progresses, thus closing the guidance loop each time a new solution is obtained to the open-loop problem. An interplanetary space mission which involves one midcourse guidance correction is an example of such an approach. The loop is closed once -- approximately midway between the launch point and the target. However, in the boost case this loop is closed many times, dependent on disturbances and model prediction accuracy.

For man-rated booster vehicles, the use of the pilot in repetitively solving the open-loop problem greatly reduces the computer requirements over those for a completely automatic closed-loop guidance scheme. The basic tradeoff between a completely automatic and manual scheme was shown in Table 1-1. Furthermore, with a manual guidance scheme, the mission is quite flexible in that it is possible to change the mission goals during the flight. The following is an example. Suppose the original mission is a boost into a 200-mile circular orbit. Further, suppose, at an altitude of 20 miles, the mission is changed to a 100-mile circular orbit due to equipment malfunction in the first stage. If fuel permits, the manual closed-loop guidance scheme, to be described, would also steer the vehicle along a fuel-optimal path to the new target orbit.

3.2.1.2 System Description for the Reusable Orbital Transport -- As mentioned previously, the scheme combines the advantages of both open-loop and closed-loop guidance schemes. The presence of the pilot in the loop reduces the computer requirements as well as making the guidance scheme flexible to in-flight mission changes. The pilot performs the iteration required in solving the open-loop problem.

As the name, "The Predictive Model Guidance Scheme", implies, the basic feature of the guidance scheme is a model of the vehicle which operates in an accelerated time scale. With such a model, the pilot can get an accurate prediction of the future trajectory of the vehicle. The accuracy of the prediction of the vehicle's future response is influenced by the accuracy of the fast-time model as well as by unknown disturbances which may occur at some future time. The fast-time model should be simple in order to minimize the computer speed and computational requirements and yet should generate a fairly accurate predicted trajectory for the real vehicle. This accurate prediction reduces the pilot workload as will be shown later. A tradeoff is involved between the accuracy of the fast-time model and the accuracy of the resulting predicted trajectory.

The block diagram of this predictive model guidance scheme was given in Figure 3-1. The diagram consists of four main parts; a block representing the real world vehicle dynamics, a second block representing a prediction model of the vehicle dynamics which operates in fast time, and a pilot-display loop around this fast-time prediction model. For the reusable orbital transport (ROT) under consideration, the command input to the vehicle is body pitch attitude. Sensors are assumed available which measure the vehicle's present state, i.e., altitude, velocity, and flight-path angle. The vehicle's present state is the initial condition for the fast-time model. With the use of optimization theory -- in particular, the calculus of variations or Pontryagin's Maximum Principle -- two optimization parameters are chosen by the pilot which determine a fuel-optimal steering function for the fast-time prediction model. These two optimization parameters are chosen such that the trajectory generated by the fast-time model passes through the desired terminal conditions. The initial portion of optimum steering function for the fast-time model is converted to real time through a sample and hold scheme and used as a command signal for the real vehicle. Of course, the predicted trajectory generated by the fast-time model is updated repetitively.

It is the union of these concepts, optimization theory and predictive manual guidance, which is the unique and significant aspect of this study. Optimization theory and, in particular, its use in defining optimal trajectories and its application to automatic schemes have been studied in detail in recent years. Also, feasibility studies have been carried out to determine the potential use of a pilot in a booster vehicle guidance loop. Finally, these two areas of research have now been integrated to form a manual optimal guidance scheme.

Although, in principle, the predictive model guidance scheme is applicable to all missions, it does have some practical limitations. The model method approaches a truly optimal closed-loop system as the rate at which the open-loop problem is solved increases. For the pilot to be effective in repetitively solving the open-loop problem, the solution loop should be fast enough so that the changes in the repetitive solution appear to be almost continuous. A finite amount of time is necessary to numerically integrate the equations of motion in the predictive model. In view of this, a solution rate of one complete fast-time solution per second was chosen. The pilot or operator was found to be effective in the manual scheme with this solution rate. This solution rate, however, specifies the time allotted for computation of the trajectory for the fast-time model. The fast-time model is governed by a set of differential equations which must be integrated numerically to determine the trajectory. An increase in the complexity of these differential equations and in the time required to move from the vehicle present state to the target state increase the required computation time for the predicted trajectory. The complexity in the predictive model equations of motion can be reduced by appropriate simplifications to the predictive model.

A second difficulty in cases with a long flight time is that the sensitivity of the desired terminal conditions to the optimization parameters increases. From an earlier phase of this study(1), it was determined that five-significant-figure accuracy is required on the optimization parameters to generate an optimum trajectory from first-stage initial conditions to the target conditions. This order of accuracy on the optimization variables yielded errors in the resulting terminal conditions in the order of 10^3 feet in altitude and 10^{-2} degrees in flight-path angle. At the end of the first stage, however, only four-significant-figure accuracy is required to generate an optimal trajectory which yields terminal errors of the same order of magnitude. The required accuracy of the optimization variables decreases as the flight time decreases.

In the hybrid computer simulation used in this study, only three-significant-figure accuracy could be obtained from the analog computer. In view of this sensitivity, the predictive guidance scheme was studied for the second stage only. Even then, the required four-figure accuracy implied that the least significant figure of the optimization parameters was within the noise level of the analog portion of the hybrid simulation system. The effect of this noise in the analog computer, however, is degrading only in the early portion of the flight; i.e., the sensitivity of the desired terminal conditions to the optimization parameters decreases as the vehicle state approaches the desired terminal conditions.

In this study, the predictive model approach was studied for the vacuum portion of the flight only. A second manual guidance scheme, the nominal guidance scheme described in 3.3, is recommended for first-stage guidance. Both the sensitivity of the terminal conditions to the optimization parameters during the initial portion of the flight (i.e., during first stage) and the complexity of the predictive model required for first-stage guidance make the nominal guidance scheme described in 3.3 more attractive as a first-stage manual guidance scheme. This combination of two guidance schemes, one for each stage, is similar to the approach taken for the boost phase of the Saturn-V: guide by following a nominal trajectory during first stage and then use a closed-loop fuel-optimal guidance scheme during the second stage. The use of the predictive model guidance scheme in the total proposed guidance system for a boost vehicle is discussed in Section 4. In the second stage, the flight time is approximately 340 seconds, and the equations of motion are relatively simple. With an optimum choice of coordinate system for the predictive model and appropriate simplifications to the equations of motion, a solution rate of one predictive model solution every second was achieved. As stated earlier, this solution rate was chosen since the operator was found to be effective in the manual scheme.

Figure 3-1 provided a functional block diagram of the predictive model guidance scheme. The details of the method are shown in Figures 3-2, 3-3, 3-4, and 3-5. This manual guidance scheme was studied for the vacuum phase of the flight, and the equations presented in figures are for this vacuum phase. The description of the method is divided into the following portions: vehicle dynamics and transformation equations; model dynamics and transformations; optimum steering program and transformations, and finally, the pilot-display link.

Figure 3-2 shows the equations used in simulating the reusable orbital transport (ROT) vehicle dynamics and kinematics. Appendix A provides a more detailed description of equations of motion used for the ROT vehicle. The equations in Figure 3-2 are valid for the vacuum phase of the mission. Since a different coordinate system is used for the fast-time predictive model, the required transformation equations are also given. These transform the present

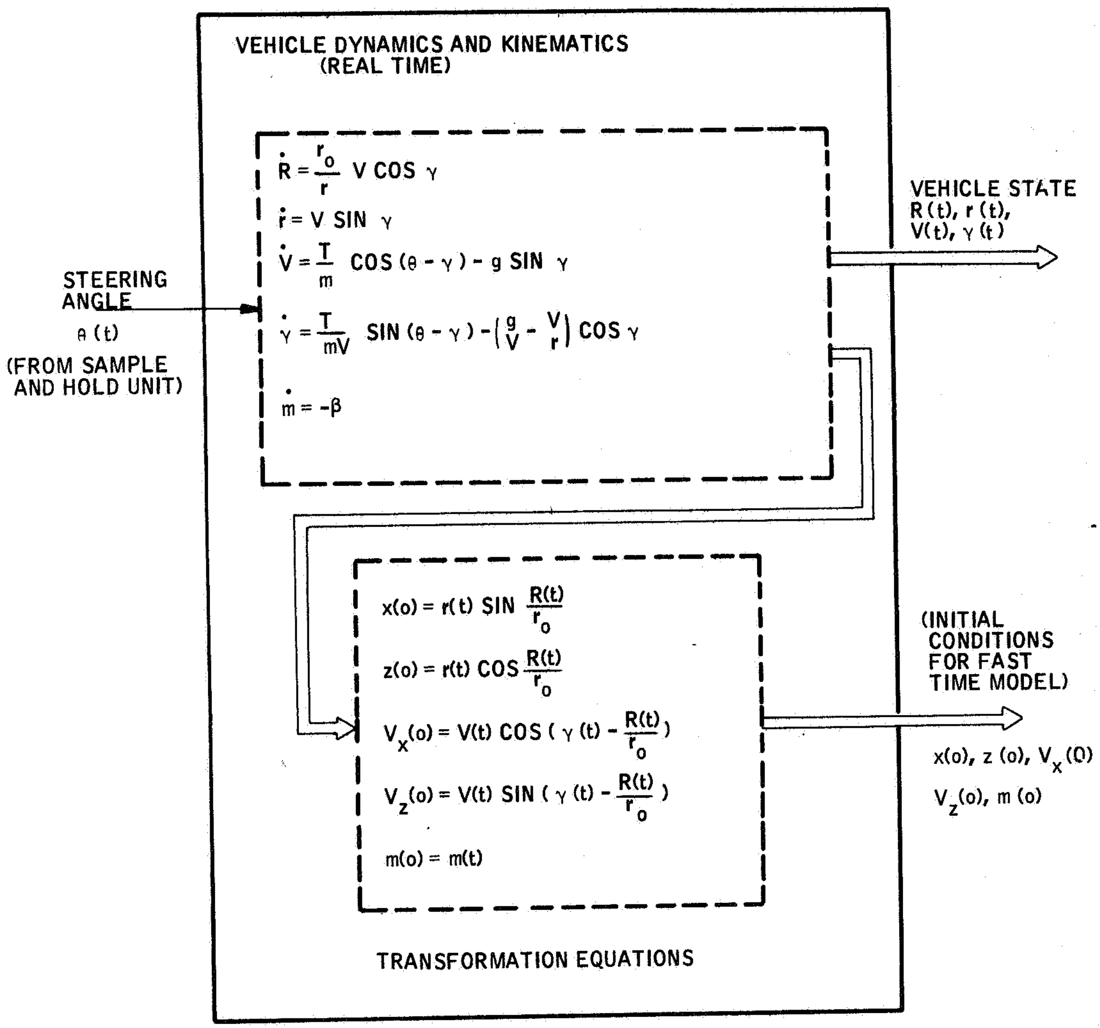


Figure 3-2. Vehicle Dynamics and Transformations

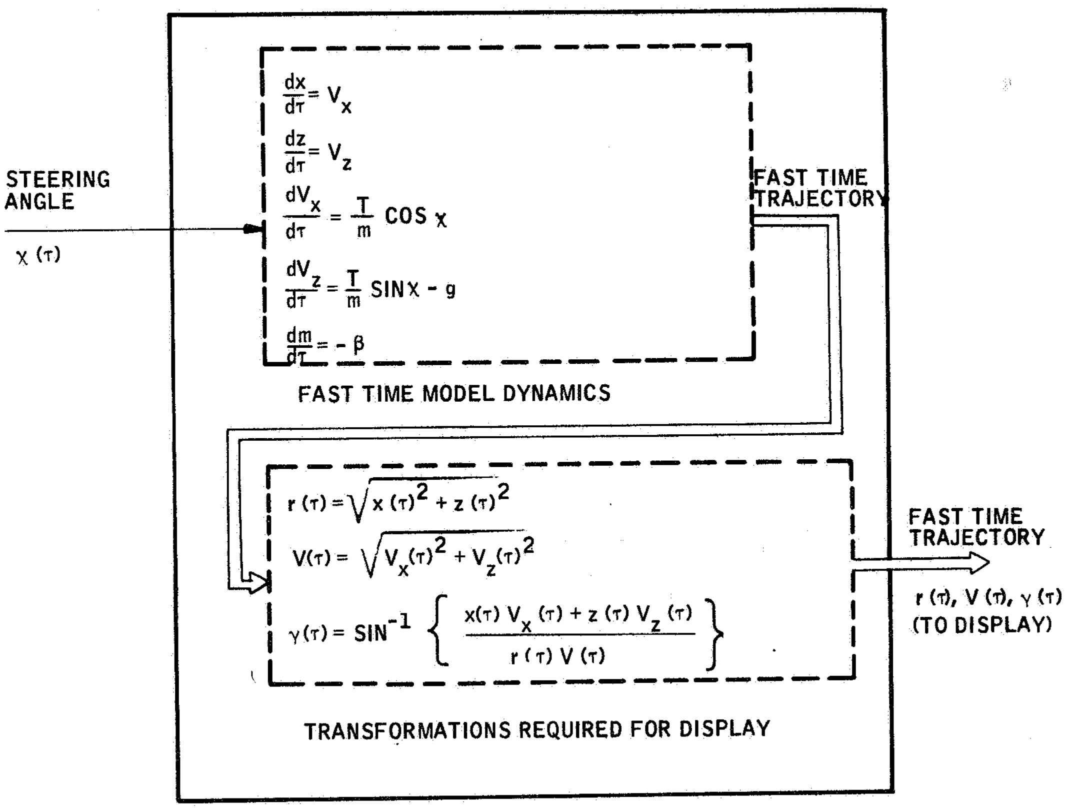


Figure 3-3. Fast-Time Model Dynamics and Transformations

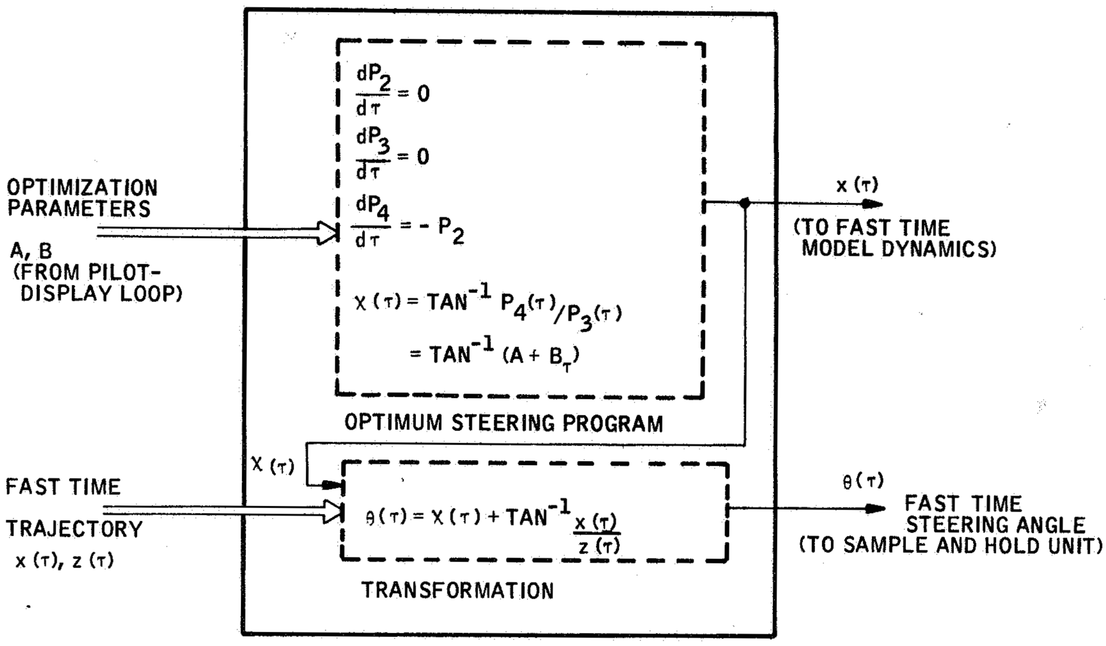


Figure 3-4. Optimum Steering Program and Transformations

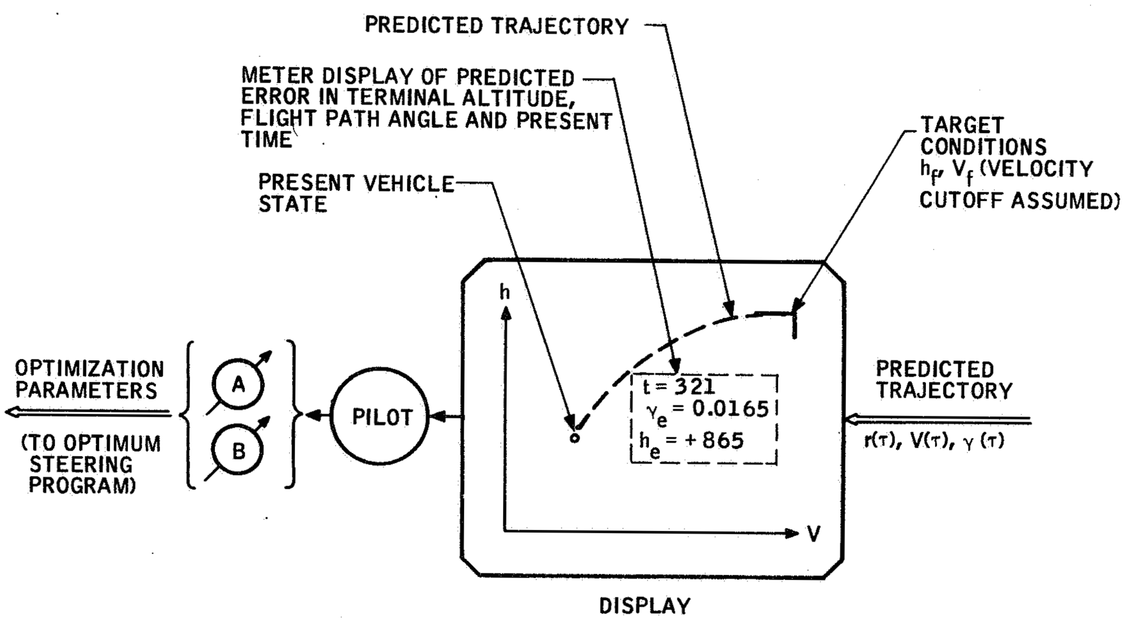


Figure 3-5. Pilot - Display Link

state of the real-time vehicle in a flight-path coordinate system into initial conditions for the fast-time predictive model in a rectangular coordinate system. In an actual implementation of this guidance scheme, these transformations between coordinate systems would not be required since inertial sensors would be used on board the vehicle. In effect, the real vehicle state would be described in the same coordinate system as the predictive model.

Figure 3-3 shows the equations of motion used in the fast-time predictive model. An inertial coordinate system was used for the predictive model because the equations for the optimization variables uncouple from the equations of motion in such a coordinate system. For this coordinate system the predicted state input to the optimum steering program in Figure 3-1 is not present. This reduces the computer requirements to some extent. Since the predicted trajectory is displayed using the same coordinate system as the vehicle, the required transformation equations are also given. To emphasize the difference in time scale between the vehicle and fast-time model, the symbol τ is used to indicate fast time. Three coordinate systems were considered for the fast-time model before choosing the system of Figure 3-3. The equations of motion as well as the optimization equations and transformation equations are presented in Appendix B.

Figure 3-4 shows the optimum steering program for the predictive model. In the general case, the equations for the optimization variables (the p_i's) are functions of the state variables; hence, a numerical integration would be required to solve for the optimum steering angle. Due to the inertial coordinate system chosen for the predictive model, the equations for the optimization variables are uncoupled from the state equations and can be solved in closed form. Thus, a time history of the optimal steering function $\chi(\tau)$ is available in closed form. The two parameters A and B defining $\chi(\tau)$ are really the initial conditions for the optimization variables. If a fast-time solution is generated every second, the correct values of A and B required will also change. These changes, however, are predictable. Once correct values for A and B have been found, succeeding values of A are given by the relation

$$A_{new} = A_{old} + B_{old} \text{ (one solution per second assumed)}$$

With this aid, the pilot has only to make minor corrections to the A and B parameters each second. These minor corrections are required because of the inaccuracy of the fast-time model. It is possible to replace the pilot's task of making small corrections to A and B by an automatic system. If only small corrections were necessary, then the increase in computation requirements due to the automatic scheme could be tolerated. However, if large corrections to A and B are required due to unknown disturbances, the required automatic system would be much more complex. The human pilot is adaptive in nature and can perform the minor corrections or, if required, more major corrections to A and B, thus greatly reducing the computational requirements of a completely automatic system.

Simplifications in the fast-time model were required to yield a closed-form expression for the optimization variables. A flat earth model is assumed, and the constant value for the gravitational acceleration was taken as 31.0. This is the average value of the true value of gravity between the staging and terminal altitude. Further small-angle assumptions were used to reduce the computation time for the predictive model. Figure 3-4 also gives the transformation for the steering angle (χ) of the predictive model.

Figure 3-5 shows the pilot-display loop for the predictive model guidance scheme. As shown, a CRT-type presentation is used for displaying the predicted trajectory. The initial point of the predicted trajectory is the present state of the vehicle. The desired terminal state is displayed on the scope, and the pilot's task is to adjust the parameters A and B so that the predicted trajectory satisfies the desired terminal conditions. To circumvent the scaling problems with such a display, a meter-type presentation is also used to give the predicted terminal error in altitude and flight-path angle. The predicted time before velocity cutoff is also displayed. The actual meter-type presentation used in the simulation is shown on Figure 3-5. Photographs of the CRT displays used for this guidance scheme are shown in Figure 3-6 and 3-7. Figure 3-6 shows the predicted trajectory before the pilot has corrected the

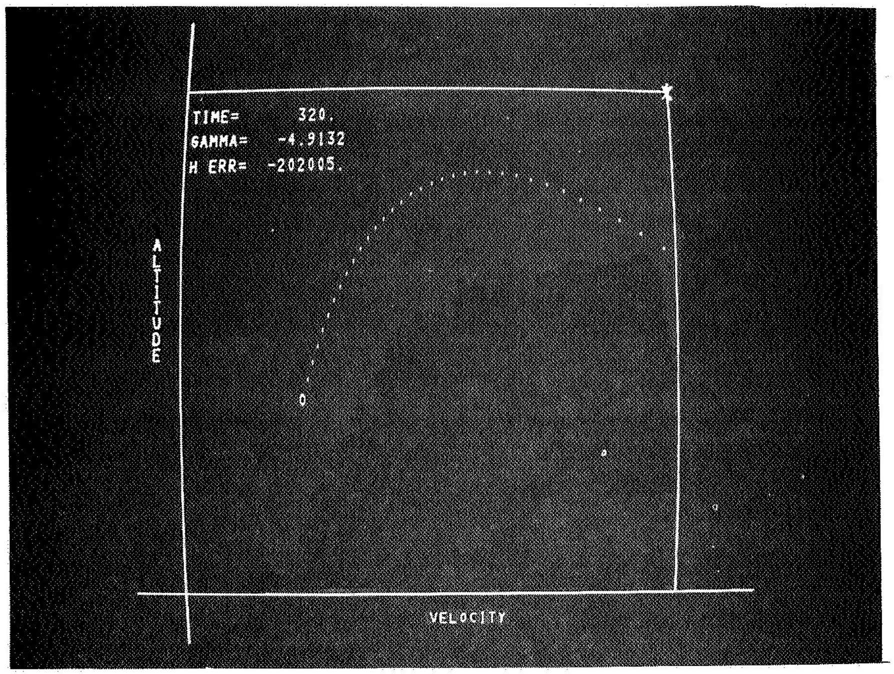


Figure 3-6. CRT Display - Predicted Trajectory Before Adjustment

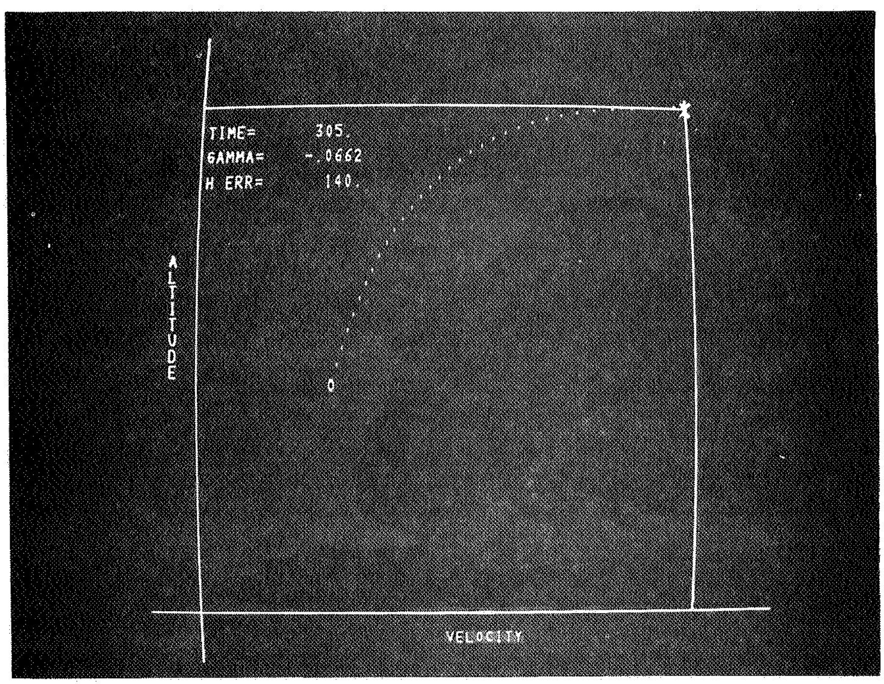


Figure 3-7. CRT Display - Predicted Trajectory After Adjustment

optimization parameters. Figure 3-7 shows the predicted trajectory after the pilot has adjusted the parameters A and B. Notice that the predicted terminal error in Figure 3-7 is 140 feet on altitude and -0.066 degree on flight-path angle. The symbol o on the figures represents the vehicle present state.

The pilot's task in this guidance scheme is to continually adjust the optimization parameters A and B to minimize the predicted error in the altitude and flight-path angle. In detail, the operations are as follows:

(1) The pilot selects values for A and B.

(2) The computer then integrates the predictive model equations of motion and displays the resulting trajectory.

(3) On the basis of the resulting error in the predicted terminal conditions, the pilot makes an adjustment to the parameters A and B.

(4) This process is repeated at the rate of one fast-time solution per second until values for A and B are determined which yield zero error in the predicted terminal conditions.

As indicated earlier, two displays are used to aid the pilot in his task. The one which gives the pilot a display of predicted trajectory in the altitude versus velocity plane is a pursuit display[4]. A pursuit display is defined as containing two moving elements, one representing the actual vehicle state and the second representing the desired state. There is no separate indicator of the error. In this application, however, the pursuit display has only one moving state since the desired terminal state is not a time-varying target. The predicted terminal condition is displayed as a part of the predicted trajectory along with the desired terminal condition is also displayed. On the basis of the errors between these two terminal conditions, the pilot makes an adjustment to the optimization parameters. This type of display is extremely useful in the gross sense, i.e., when the values of A and B are such that the fast-time trajectory is far from the desired. With the display of the predicted trajectory, the operator soon learns how A and B "shape" the trajectory and, hence, how A and B effect the predicted terminal error. A second meter-type display is required to display the predicted terminal errors in the altitude and flight-path angle after the pilot has made gross adjustments to the predicted trajectory with the use of the meter display of the predicted terminal errors. This compensatory display was used rather than scale changes on the pursuit display because of its simplicity. A compensatory display contains one moving element, representing the error in the vehicle state. In this application, this error is the difference in the predicted terminal state and the desired terminal state.

It is possible that an experienced operator could use simply the above compensatory display of the predicted terminal errors. In this simplified display, no CRT presentation is required. Although there are no CRT requirements, very little reduction in computation requirements is expected due to this simplified display. The reason is that the predictive model equations still must be integrated numerically to determine the predicted terminal state. The change in displays is shown in Figure 3-8. With such a compensatory display, two meters could be used to present the predicted terminal errors to the pilot. Although the display requirements can be simplified by this technique, the simplification is not recommended since the pilot does not know "where he is" (i.e., the vehicle state) and does not know "where he is going" (i.e., a display of the predicted trajectory) With such a compensatory display, the operator does not have the capability of "shaping the trajectory" with the optimization parameters which he does have with the CRT presentation of the predicted trajectory.

Various experiments were made with an operator to determine the applicability of this predictive model guidance scheme. The results of these experiments are presented in the following two subsections.

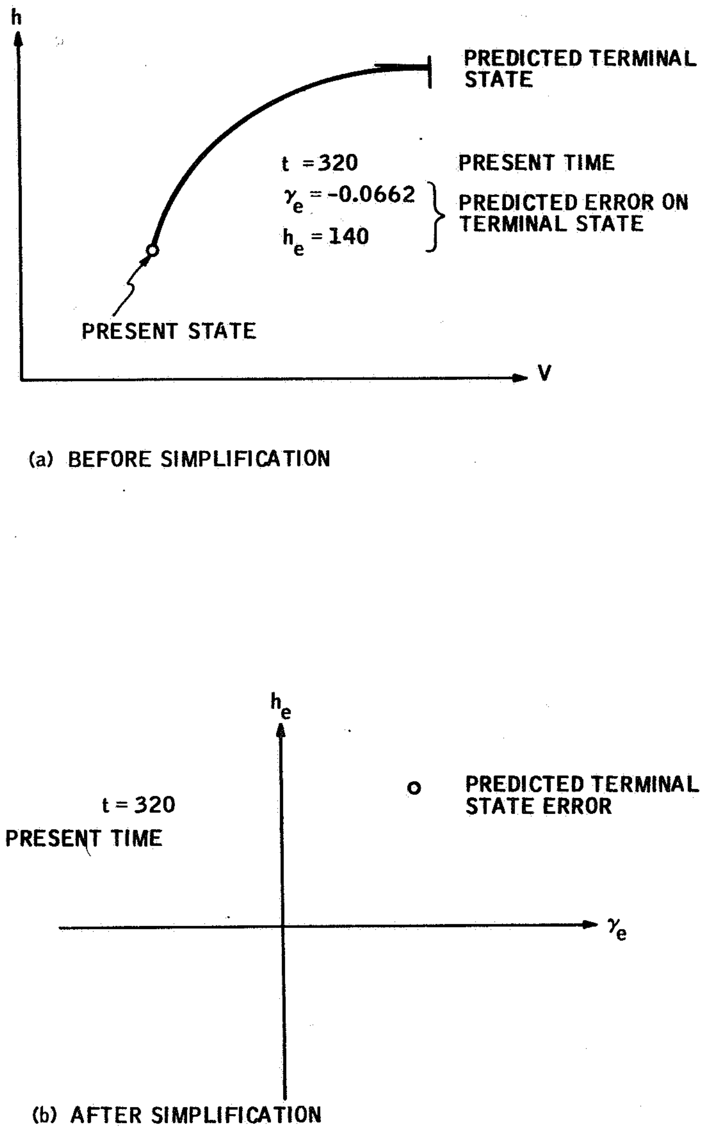


Figure 3-8. Simplification of the Display for the Predictive Model Guidance Scheme

3.2.2 Variability of Results with the Predictive Model Guidance Scheme

A series of eight runs with one experienced operator were made to obtain an estimate of the variability of the results which can be expected with the predictive model guidance scheme. As mentioned previously, the predictive model guidance scheme was studied for the second stage. The nominal guidance scheme is recommended for the first stage. With this nominal scheme, the pilot steers the vehicle to remain on a predetermined nominal trajectory. At the end of the first stage, however, deviations from the nominal trajectory can be expected. The conditions at the end of the first stage are initial conditions for the predictive model scheme.

To give the predictive model scheme a fair test, off-nominal initial conditions were chosen for each run. The operator was not informed of the initial conditions. These initial conditions differed from the nominal values by roughly ±10 percent. This figure of ±10 percent for off-nominal initial conditions was determined after an examination of the results obtained with the nominal guidance scheme (see 3.3). All the values of the state variables (i.e., altitude, velocity, and flight-path angle) at the end of the first stage were within ±10 percent of the nominal values.

Figure 3-9 shows the trajectories generated in runs 1 through 6, and Figure 3-10 shows the corresponding steering functions.

At the beginning of each run the optimization parameters were set to the values which were correct for the nominal initial conditions. These nominal initial conditions are those which would occur if the first-stage guidance scheme were perfect. In real time, the operator made major corrections to these parameters A and B to account for the off-nominal initial conditions. This period of major correction lasted about 30 seconds. At that time, the values of A and B were adjusted so that the predicted trajectory approximately satisfied the terminal conditions. At this time, the approximate predicted errors in

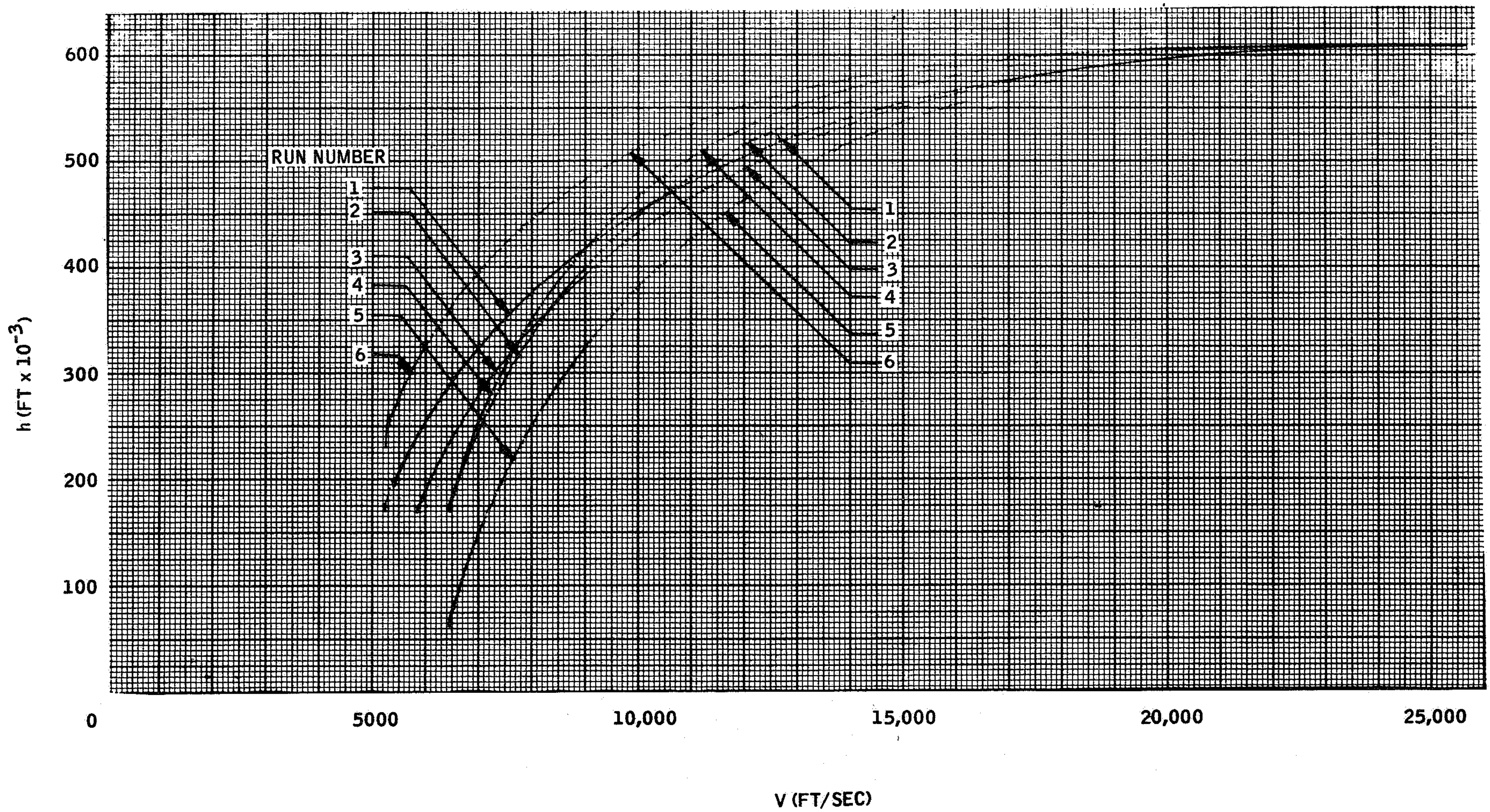


Figure 3-9. Altitude versus Velocity with Varying Initial Conditions Obtained with the Predictive Model Guidance Scheme

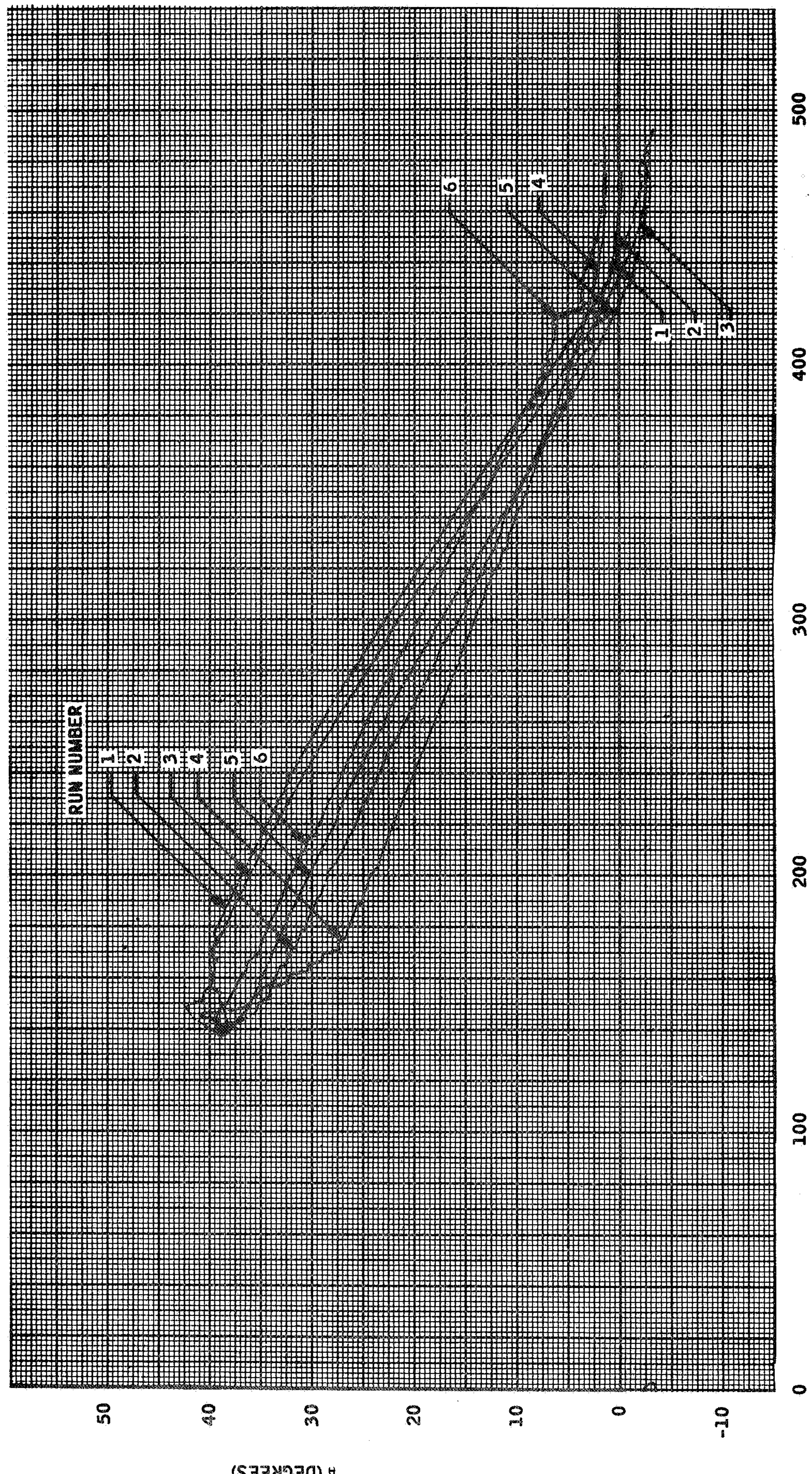


Figure 3-10. Body Attitude versus Time with Varying Initial Conditions Obtained with the Predictive Model Guidance Scheme

the terminal state were ±10,000 feet in altitude and ±0.5 degree in flight-path angle. If a more accurate prediction is attempted at this time, the pilot or operator is, in effect, attempting to track the noise in the simulation system. After this period of major corrections until approximately 100 seconds before the predicted cutoff time, the operator monitored the predicted trajectory and, if necessary, made small adjustments to the optimization parameters to keep the predicted errors in the terminal conditions within approximately 10,000 feet in altitude and 0.5 degree in the flight-path angle. At about 100 seconds before cutoff, the operator had to start making minor corrections to A and B in an effort to null out the predicted terminal errors. At this time, the sensitivity of the predicted terminal conditions to the optimization variables is reduced to the extent that the noise level in the simulation system has no effect on the optimization parameters. Thus, an extremely accurate prediction of the terminal conditions could be utilized. The effect on the steering angle of large corrections at the beginning and small corrections towards the end of the flight are evident in Figure 3-10. Table 3-1 displays the results of these runs. To evaluate each trajectory, a measure of terminal error is defined. The performance index, which is a measure of the mean square terminal error, is defined as

$$P.I. = \sqrt{\frac{\left(\frac{h_e}{h_{e_{max}}}\right)^2 + \left(\frac{\gamma_e}{\gamma_{e_{max}}}\right)^2}{2}}$$

where h_e and γ_e are the actual terminal errors incurred, and $h_{e_{max}}$ and $\gamma_{e_{max}}$ are the maximum errors tolerated in the terminal values of altitude and flight-path angle. In effect, $h_{e_{max}}$ and $\gamma_{e_{max}}$ act as weighting factors for the two errors. No appreciable error for velocity occurred because an automatic velocity cutoff was used in the study. The values used for $h_{e_{max}}$ and $\gamma_{e_{max}}$ were ±20,000 feet and ±0.1 degree. During this experiment, the operator was told to concentrate on the predicted terminal flight-path angle rather than the

Table 3-1. Data from Predictive Model Guidance Scheme (off-nominal initial conditions)

Run Number	Initial Conditions (at staging)			Final Conditions				P.I.
	V_o (ft/sec)	h_o (ft)	γ_o (deg)	t_f (sec)	h_f (ft)	V_f (ft/sec)	γ_f (deg)	
1	5,266	170,619	26.4	493	608,636	25,584	-0.0032	0.031
2	6,436	170,619	26.4	476	610,440	25,590	0.0003	0.086
3	5,851	170,619	23.7	484	611,161	25,573	-0.0000	0.111
4	6,436	170,619	29.0	475	609,240	25,576	-0.0004	0.043
5	6,436	63,419	29.0	479	606,190	25,594	-0.0125	0.109
6	5,266	187,681	29.0	493	609,372	25,580	0.0109	0.087
7	6,144	170,619	26.4	479	608,776	25,570	0.0065	0.053
8	5,851	170,619	26.4	484	608,686	25,583	-0.0053	0.043

predicted terminal altitude. The values for $h_{e_{max}}$ and $\gamma_{e_{max}}$ were chosen with this in mind. In this study, $h_{e_{max}}$ and $\gamma_{e_{max}}$ were used solely as weighting factors between h_e and γ_e.

Figure 3-11 is a plot of the performance index versus run number. The rms value of the performance index on the basis of these 10 runs is 0.0755. Many more runs would be required to get a mean and standard deviation for the two terminal errors involved, but this was not within the scope of the study. The purpose of this study was to determine the gross feasibility of the scheme. A more detailed study of the statistics of the error is definitely recommended on the basis of the present results.

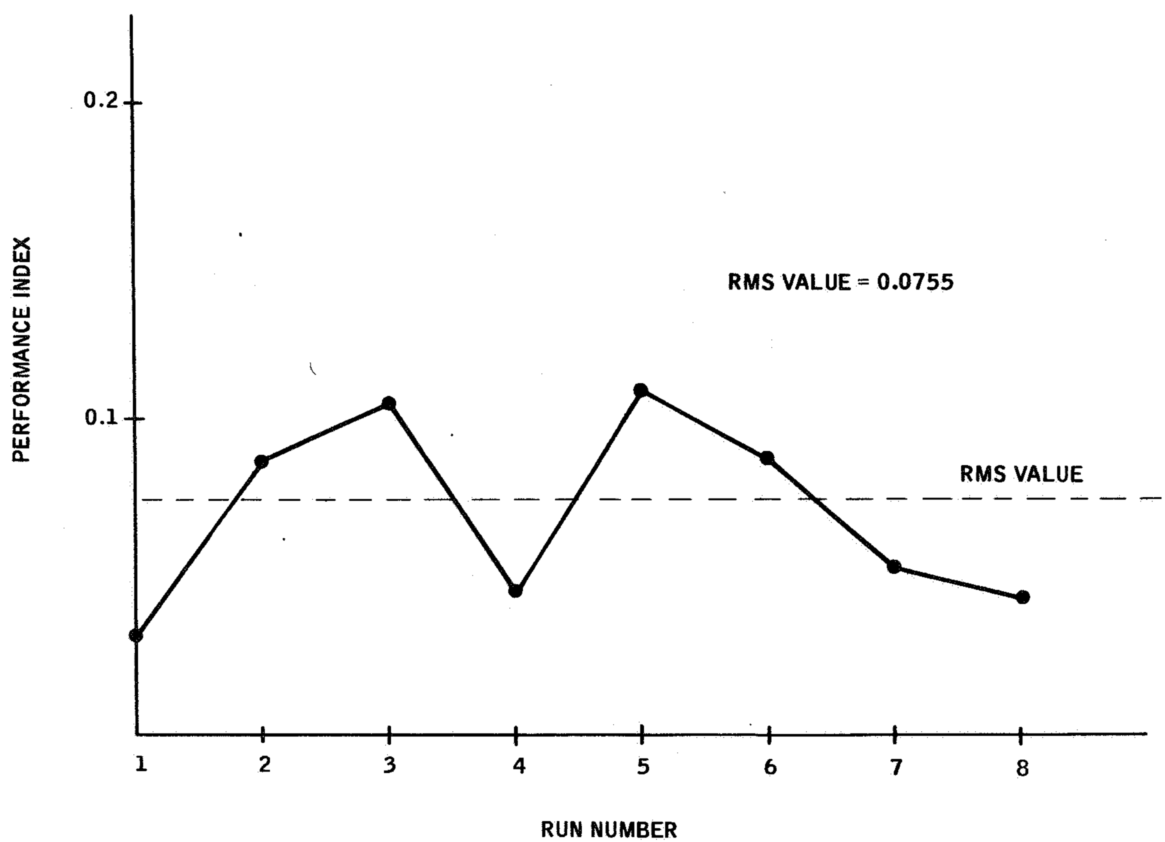


Figure 3-11. Variability Data for the Predictive Model Scheme

3.2.3 A Learning Curve for the Predictive Model Guidance Scheme

A series of 10 runs was made with one inexperienced operator to determine a typical learning curve. A learning curve is necessary so that the amount of training required to successfully implement the manual guidance scheme can be estimated. Each of these 10 runs began at a nominal set of initial conditions in the second stage. The optimization parameters were adjusted to the proper values before each run, and then only minor corrections were required during the flight. These corrections are required because of the inaccuracies in the predictive model. The performance index defined in 3.2.2 was used to evaluate the results of each trajectory. Although the time for each flight might have been included in the definition of the performance index, within the accuracy of numerical integration scheme used, no variability in the flight time was observed; hence, its relative effect on the performance would be zero. The numerical integration scheme employed in the real-time simulation used a 1-second step size; thus the final times obtained were accurate to within 1 second.

Table 3-2 lists the terminal errors and final times for the 10 runs made for the learning curve shows in Figure 3-12. As seen in this figure, the performance index actually increased in the second and third runs. This may be due to the operator experimenting with the system before he really understands its behavior. Figure 3-13 shows the results of four of these trajectories, and, as can be seen, there is really no variability in the trajectories. Figure 3-14 shows the corresponding steering functions for the four trajectories, and, as with the trajectories, there is little variability. These curves do, however, show where the pilot or operator made his corrections. Corrections to the optimization parameters were made towards the end of the flight. The effects of the sensitivity of the predicted terminal conditions to the optimization parameters decreases as the predicted flight time decreases. Before each flight, the optimization parameters were adjusted so that the predicted target error was as small as possible. Due to the decreased effect of system noise and due to the inaccuracy of the fast-time model, small corrections in the optimization parameters were required towards the end of the trajectory.

Table 3-2. Data from Predictive Model Guidance Scheme

Run Number*	Time, t_f (sec)	Altitude, h_f (ft)	Velocity, V_f (ft/sec)	Flight-Path Angle, γ_f (deg)	Altitude Error, h_e	Flight-Path Angle Error, γ_e	P.I.
1	484	609,907	25,580	0.0009	1,887	0.0009	0.069
2	484	609,977	25,579	0.0175	1,957	0.0175	0.142
3	484	611,622	25,575	0.0156	3,602	0.0156	0.169
4	484	610,005	25,576	0.0052	1,985	0.0052	0.079
5	484	610,260	25,578	0.0092	2,240	0.0092	0.103
6	484	606,950	25,583	0.0031	-1,060	0.0031	0.043
7	484	608,686	25,579	-0.0053	646	-0.0053	0.044
8	484	609,380	25,575	-0.0051	1,360	-0.0051	0.060
9	484	609,987	25,579	-0.0007	1,967	-0.0007	0.071
10	484	608,776	25,572	0.0065	756	0.0065	0.053

*All runs made with nominal second-stage initial conditions

t_o = 137 sec

r_o = 21.10219×10^6 ft

V_o = 5,851 ft/sec

γ_o = 0.4632 rad

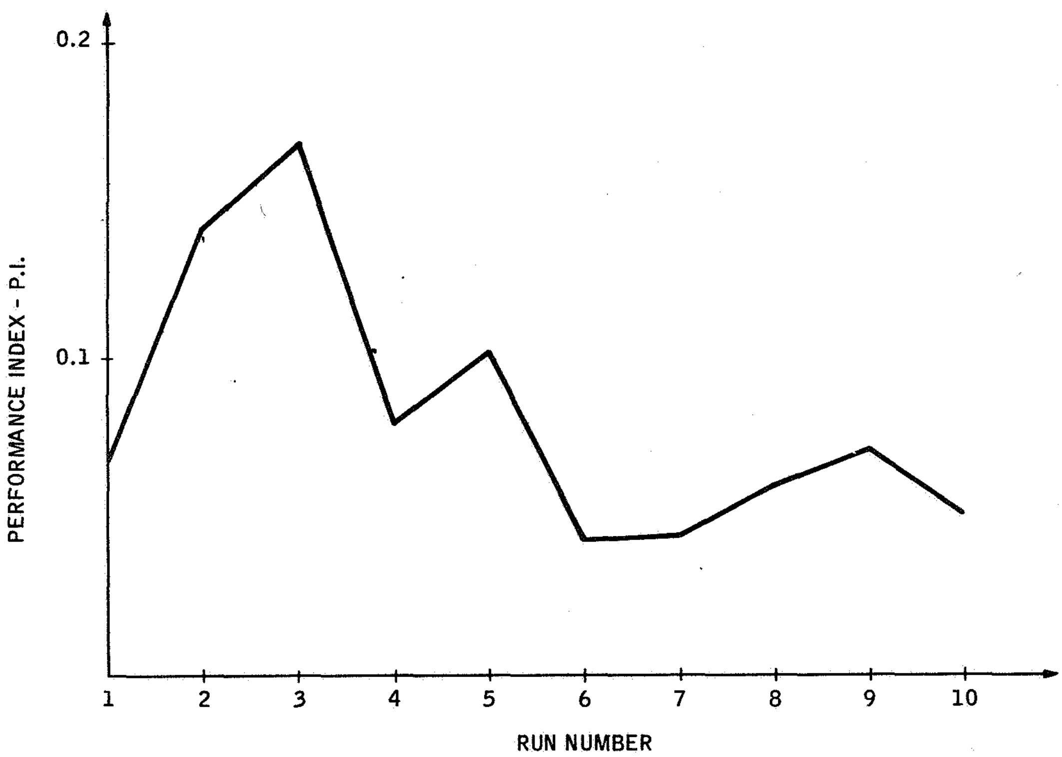


Figure 3-12. Learning Curve for the Predictive Model Guidance Scheme

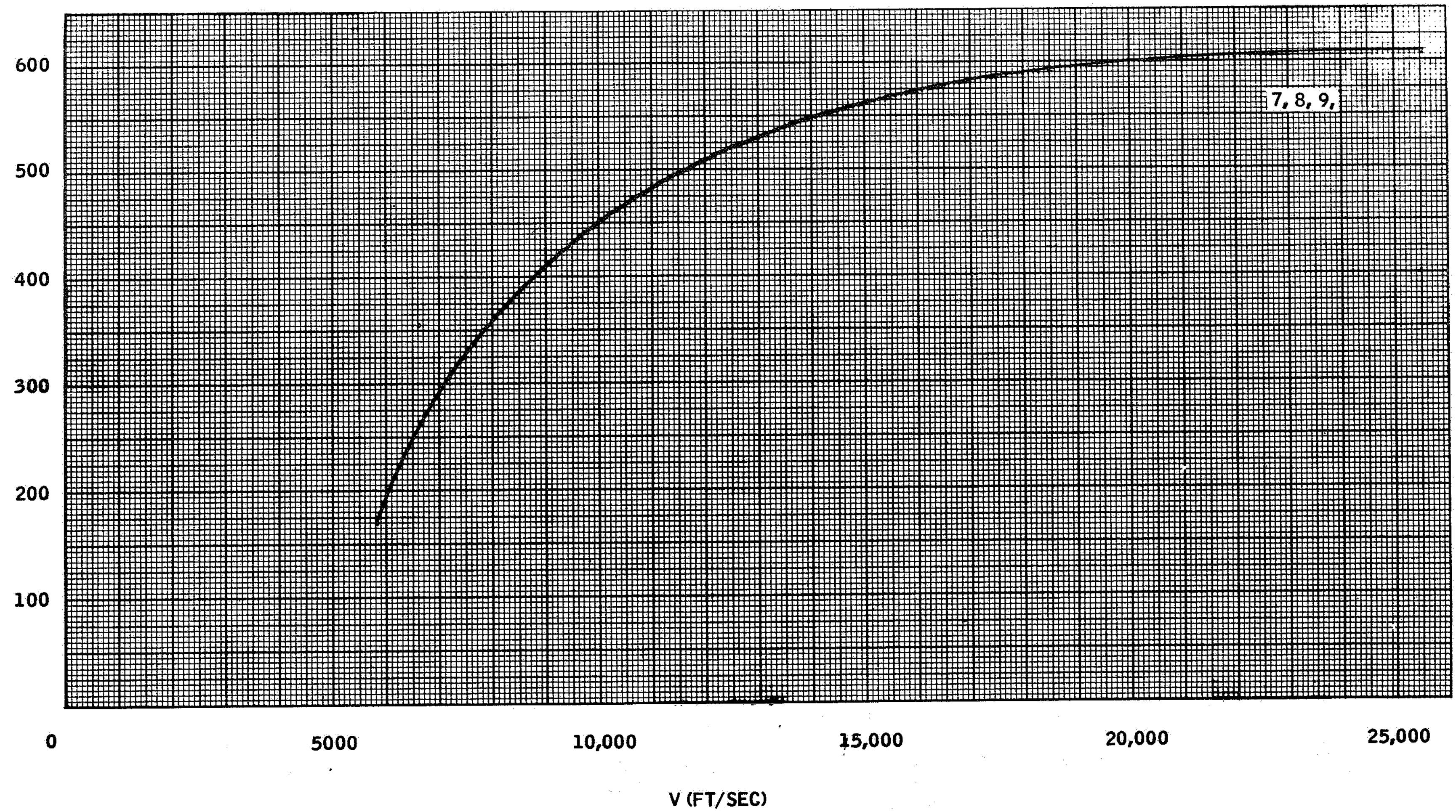


Figure 3-13. Attitude-versus-Velocity Trajectories for Second Stage Obtained with the Predictive Model Guidance Scheme

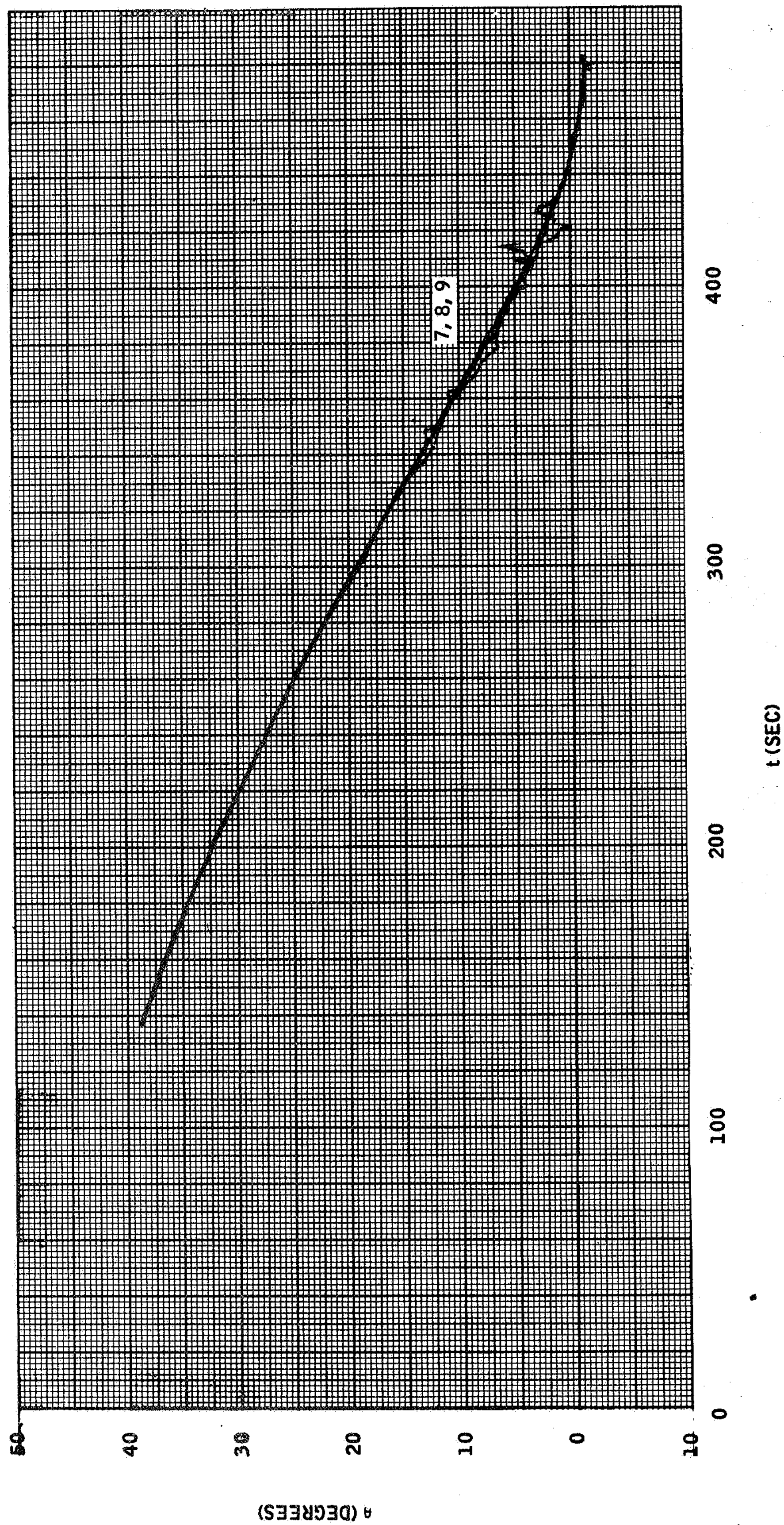


Figure 3-14. Body Pitch Attitude versus Time for Trajectories of Figure 3-13 using the Predictive Model Guidance Scheme

3.2.4 Summary and Recommendations

(1) The predictive model guidance scheme is capable of generating near-optimal trajectories from large deviations off the nominal trajectory for the second stage.

(2) The time the man-computer iterative operation requires for generating a near-optimal second-stage trajectory increases with off-nominal errors. However, within the energy and structural limits of the vehicle, this time delay is not excessive (30 seconds).

(3) After the pilot has generated the new near-optimal second-stage trajectory, the pilot guidance work load is low. During the first part of the second-stage trajectory (30 seconds), he performs a guidance function largely because of the sensitivity of the optimization variables. Near the end of the trajectory, he performs a guidance function because of the inaccuracies of the prediction model.

(4) For about 2 1/2 minutes of the second stage, the pilot merely monitors the system. The work load during this portion of the mission would increase only as a result of unexpected disturbances which would produce a requirement to generate a new near-optimum trajectory from the disturbance point. This pilot work load would be identical to that described in (2).

(5) Due to the sensitivity of the optimization variables during the early portion of the trajectory, a nominal guidance approach is suggested. This is one of the reasons a nominal guidance approach was recommended for the first-stage trajectory for the ROT vehicle and mission.

(6) Another reason for a nominal guidance approach for the early atmospheric phases of the mission was the necessary complexity of the prediction model. This suggested that storage of optimal nominals during the first stage and performance of a manual control function to these nominals would be a less complex guidance approach.

(7) The storage of optimal nominals could be simply performed by placing overlays on the scope face and requiring the pilot to steer to these nominals.

(8) Further conclusions with respect to a nominal versus a predictive approach during early trajectory stages of missions should be evaluated on the basis of noise on the navigational sensors. It is this filtered noise that the pilot must operate with in order to generate the new optimal trajectories.

(9) The representative training curve of Figure 3-12 shows that no intensive training period is required, indicating a truly simple manual guidance scheme.

(10) From Table 3-1, the errors obtained in altitude and flight-path angle are well within typical target error specifications for boost missions.

(11) Further study is recommended to investigate the effect of typical sensor noise on pilot work load and energy requirements. This would then yield a PWL comparison to other manual schemes, such as manual guidance about a nominal trajectory.

3.3 THE NOMINAL GUIDANCE SCHEME

This subsection contains a general description of a manual guidance scheme which uses a nominal trajectory. This Nominal Guidance Scheme (NGS), although not new in concept, was studied to provide a basis for comparing the results obtained with the Predictive Model Guidance Scheme (PMGS). The NGS was studied for both stages so that the results of the PMGS could be properly evaluated. The general design problems for the NGS are described. After this description, a more detailed discussion of a nominal guidance scheme for the ROT vehicle is presented. The three types of displays evaluated during the study are discussed. The types of control and form of the prediction employed during the study are presented. A block diagram of the NGS is shown in Figure 3-15.

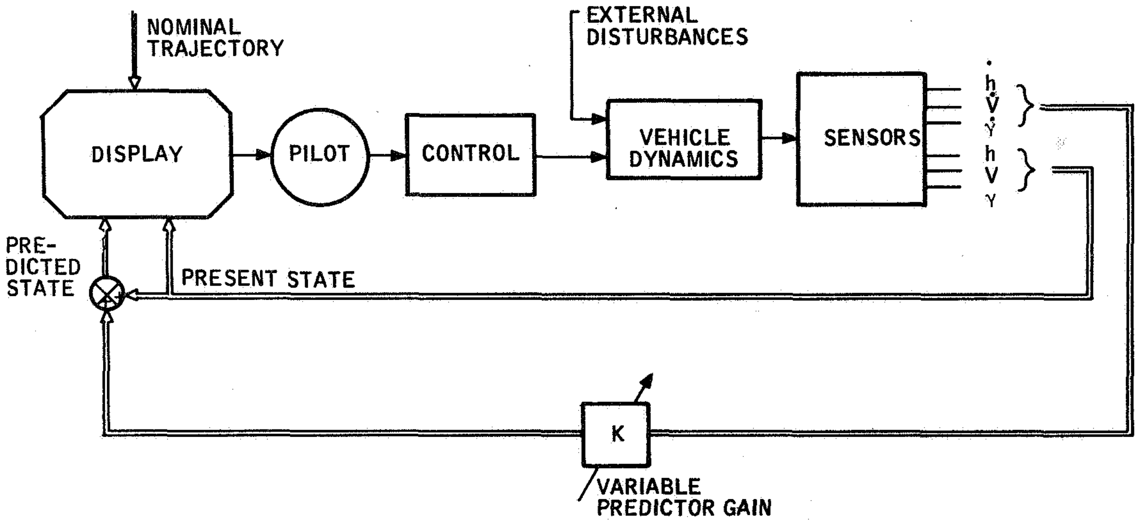


Figure 3-15. Block Diagram for Nominal Guidance Scheme

3.3.1 System Description

3.3.1.1 General -- One method of accomplishing the guidance objectives for a man-rated booster vehicle with significant lifting capabilities is to have man steer the vehicle along some nominal trajectory. By following this nominal trajectory, the guidance objectives of reaching the desired terminal state with an intact vehicle will be satisfied. Various disturbances exist, all of which tend to force the vehicle's state away from the nominal. For this reason, the nominal control (steering) function is not entirely satisfactory, and some means of providing a correction to account for the disturbances must be provided. This is a task for the pilot. On the basis of some form of display of the vehicle's present status, the pilot must provide a corrective control function which steers the vehicle back to the nominal trajectory.

The most obvious problem in the implementation of a nominal manual guidance scheme is the manner in which the nominal trajectory is displayed to the pilot. A second area of consideration is the type of control input that the pilot uses. The final problem area is the type of prediction(5) the pilot has available. This prediction gives the pilot an indication of the vehicle's state at some future time.

There are a number of ways of displaying the nominal trajectory to the pilot. In the most general sense, the possible displays divide into two types: pursuit and compensatory displays(4). The pursuit display contains two pieces of moving information, the actual vehicle state (i.e., altitude, velocity, and flight-path angle) and the desired nominal vehicle state. With a pursuit display, there is no separate indicator representing the error; error is estimated from the difference between elements representing the present vehicle state and desired nominal vehicle state. The compensatory display contains one moving piece of information, representing the present error state. The error is the difference between the actual state and the desired state; however, there is no separate indication of the actual and the desired states. Good tracking with a compensatory display results in little movement of the error state. The pursuit display permits the pilot to see the future desired state and the actual present state, whereas, with the compensatory display, the pilot cannot anticipate the future state since only the present error is displayed. The pursuit display enables the pilot to initiate corrective actions slightly before they are required. A block diagram of a manual nominal guidance scheme using a pursuit display is shown in Figure 3-16. The same system using a compensatory display is shown in Figure 3-17.

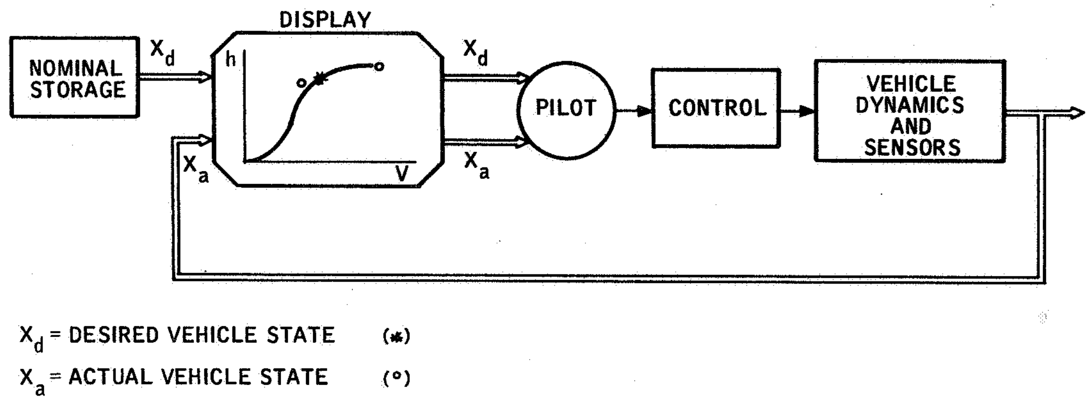


Figure 3-16. Nominal Guidance System with a Pursuit Display

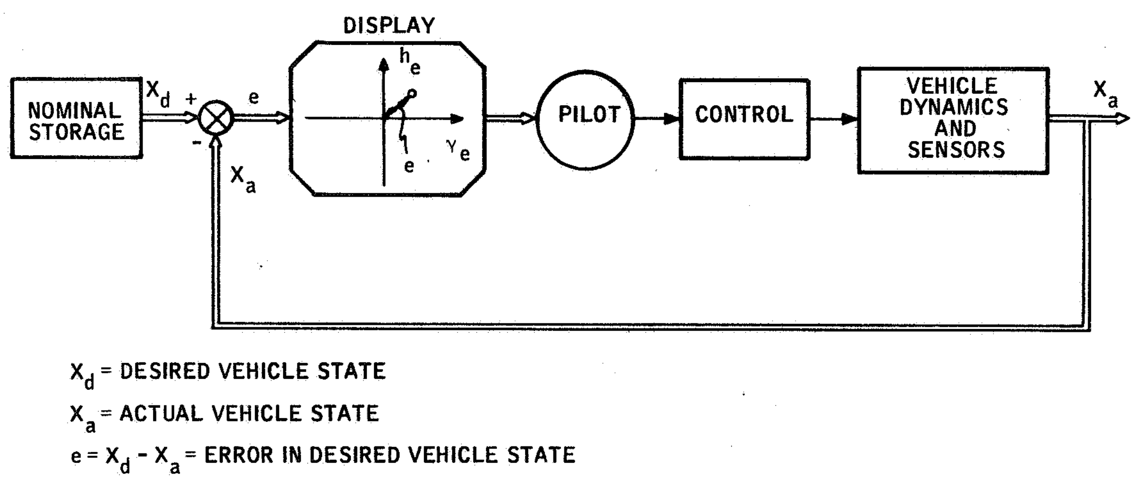


Figure 3-17. Nominal Guidance System with a Compensatory Display

3.3.1.2 System Description for the Reusable Orbital Transport -- This nominal guidance scheme was studied for the complete boost phase of the ROT. Although the nominal guidance scheme is recommended for the first stage only, it was studied for both stages. In this way, the predictive model scheme described in 3.2 could be evaluated with this more conventional nominal approach. The basic advantage of the predictive model scheme over the nominal scheme is its accuracy. Results show that the performance index for the predictive model scheme is nearly an order of magnitude better than that for the nominal scheme. The disadvantage of the predictive model scheme is that the computer requirements are higher than for the nominal scheme.

In this study, a fuel-optimal trajectory was generated for a set of initial conditions which are considered typical. A planar model was used for the ROT, and the vehicle parameters chosen are considered average. The details of the model and coordinate system are included in Appendix A. This fuel-optimal trajectory, which satisfies all the given initial conditions, the desired terminal conditions, and also satsifies the total load factor constraint, is henceforth called the nominal trajectory. The initial conditions used are called nominal initial conditions, and the values for the vehicle parameters are called nominal values.

A block diagram of this nominal guidance scheme was shown in Figure 3-15. The equations used in simulating the vehicle motion are listed in Appendix A. It is assumed that sensors are available that measure the vehicle state in a flight-path coordinate system. The sensors measure the vehicle altitude (h), altitude rate ($\dot{h}$), vehicle flight-path angle (γ), flight-path angle rate ($\dot{\gamma}$), vehicle velocity (V), and velocity rate ($\dot{V}$).

Figure 3-15 shows external disturbances acting on the vehicle. These disturbances can be considered as arising from various sources. Due to the random nature of the atmosphere, disturbances due to wind are present during the first stage. There are two additional random variables which have the same effect as disturbances. The model for the vehicle is based on some best estimate of the vehicle parameters, but deviations from these parameters will exist. The effect of these small deviations is the same as disturbances. Secondly, the nominal trajectory is based on a given set of initial conditions, and small deviations have an effect similar to external disturbances in that the vehicle is forced off the nominal trajectory. In the study, three wind profiles were used as typical disturbances. When testing for the effects of winds, a wind profile was chosen at random for each run without the knowledge of the operator.

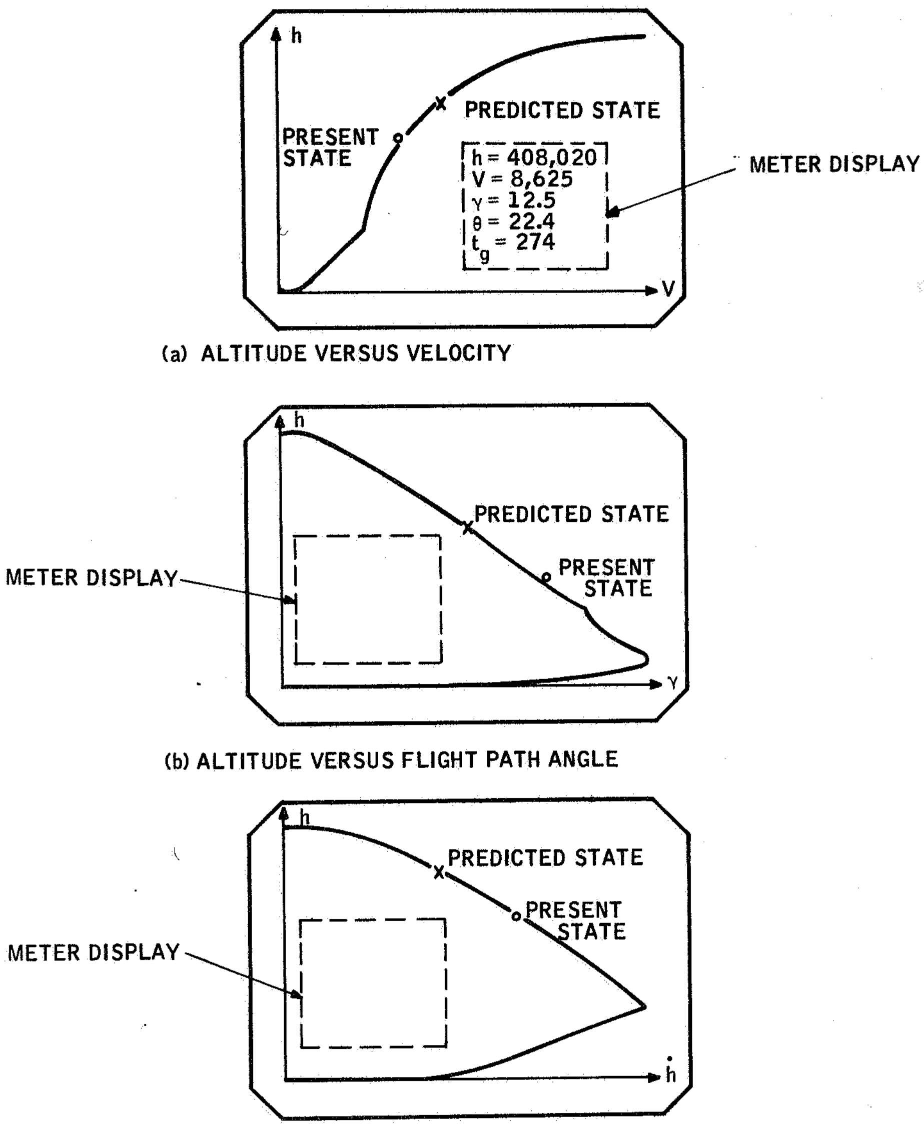
In order for the pilot to provide a corrective control function to account for these various disturbances, some sort of display is required. The two general types of displays, pursuit and compensatory, have been described (see Figures 3-16 and 3-17). For the nominal guidance scheme, a pursuit display was chosen over the compensatory display since the pilot usually wants to know "where he is" (i.e., the present state of the vehicle) and "where he should be going" (i.e., a display of the nominal trajectory). For this model vehicle, the desired nominal trajectory is a curve in three-dimensional space or, equivalently, it is specified by the time history of the vehicle's altitude, velocity, and flight-path angle.

There are a number of possible displays of the nominal trajectory. These include altitude versus velocity, altitude versus altitude rate, and altitude versus flight-path angle. These three different displays for the nominal trajectory were evaluated during this study to determine which display enabled the pilot to yield the best performance. The results of these display evaluations are presented in the following subsections. Figure 3-18 shows the general shapes of these three different displays for the nominal trajectory, and Figure 3-19 shows actual photographs of these display formats. Recall that the desired target conditions are

$$h_f = 608,020 \text{ ft}$$

$$V_f = 25,570.5 \text{ ft/sec}$$

$$\gamma_f = 0$$

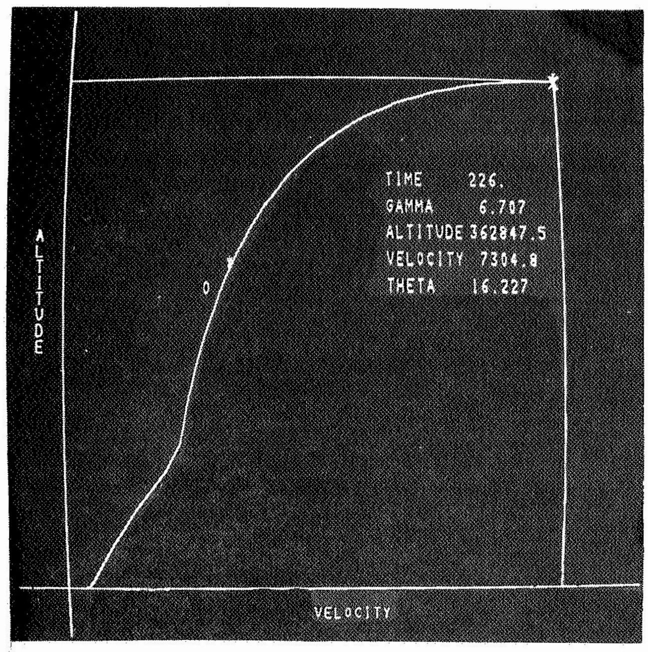


(a) ALTITUDE VERSUS VELOCITY

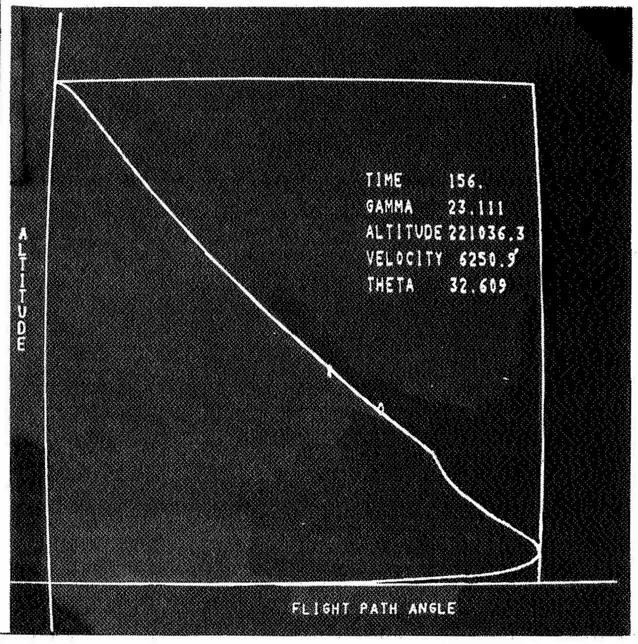
(b) ALTITUDE VERSUS FLIGHT PATH ANGLE

(c) ALTITUDE VERSUS ALTITUDE RATE

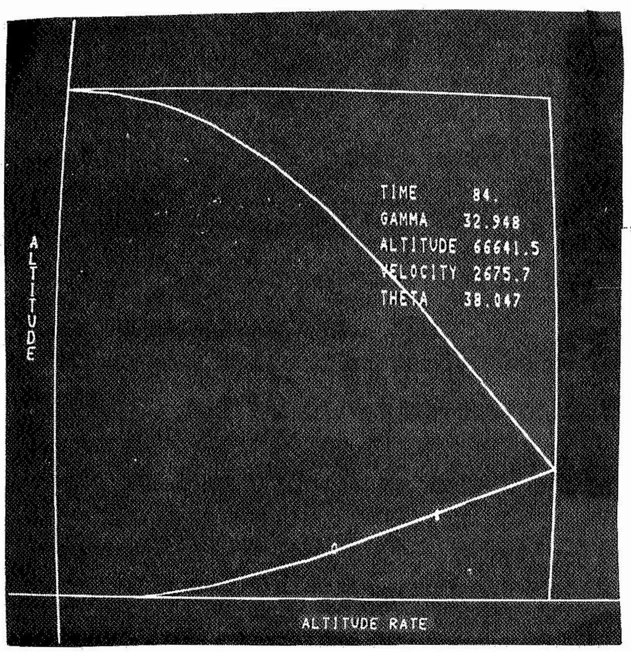
Figure 3-18. Display Formats for Nominal Guidance Scheme



(a)



(b)



(c)

Figure 3-19. Photographs of Displays Used in Nominal Guidance Scheme and that an automatic velocity cutoff was used in the simulation. With the altitude-versus-velocity display [Figure 3-18(a)], the target condition on γ must be inferred from the condition that $dh/dV = 0$ on the display. Since a velocity cutoff is used, the proximity to cutoff is apparent with this display. With the altitude-versus-flight-path-angle display [Figure 3-18(b)], the target condition on h and γ is displayed. Since velocity is not displayed, the operator has no indication of the proximity to cutoff. The terminal condition on h and γ is also displayed on the altitude-versus-altitude-rate display since $\dot{h} = 0$ is equivalent to $\gamma = 0$. Again, there is no indication of the proximity to cutoff with this display. All these shortcomings with the three displays can be overcome by using a meter-type presentation of the vehicle's present state. In the study, a meter display of the following quantities was used: altitude (h), velocity (V), flight-path angle (γ), body attitude (θ), and nominal time-to-go (t_g). This meter presentation is particularly useful towards the end of the flight. Figure 3-18(a) shows this meter display.

Three types of control command signal were tested during the study: body pitch attitude (θ), attitude rate ($\dot{\theta}$), and a combination of θ and $\dot{\theta}$. Although there are more integrations between the control input and the vehicle response when $\dot{\theta}$ is used, it was found to be advantageous in cases where the command input signal θ is approximately linear with time. These control combinations, θ, $\dot{\theta}$, and the combination of θ and $\dot{\theta}$, were evaluated during the study.

Because of the inherent time lags between the input signal and the vehicle response due to the vehicle dynamics, the pilot should be provided with some means for evaluating the control input immediately, rather than waiting for the vehicle response. To remedy this problem of time delays between the control input and vehicle response, some type of prediction is required.

One type of prediction which is very easily implemented is based exclusively on the vehicle response at the moment of prediction. This type of prediction is applicable for relatively short times only. The absolute value of the prediction time however depends on the dynamic response of the vehicle. Prediction by this method is a problem of approximation. As an example, suppose the predicted value of the function $x(t)$ is desired at some future time $t+\tau$. This function x at time $t+\tau$ (i.e., the predicted value) may be expressed as a power series evaluated at the present time t:

$$x(t+\tau) = x(t) + \tau\dot{x}(t) + \frac{\tau^2}{2}\ddot{x}(t) + \text{higher order terms}$$

This series is truncated, and the result yields an approximation for the predicted value of the function x. The approximation is fairly accurate for small values of τ, and, of course, the error increases with large values of τ.

In Figure 3-18, a predicted state symbol (x) is shown on each display. In each case, this predicted state was obtained with the prediction scheme just described. For example, in the h-versus-V display, the predicted state is given by the point $h(t+\tau)$ and $V(t+\tau)$. These values are determined by

$$h(t+\tau) = h(t) + \tau\dot{h}(t)$$

$$V(t+\tau) = V(t) + \tau\dot{V}(t)$$

In all cases, the power series was truncated after the second term. The variable predictor gain K shown in Figure 3-15 is the prediction time τ in the above relations. It was determined that a variable prediction time is useful in the nominal guidance scheme. For example, a prediction time of about 10 seconds is satisfactory for the first stage whereas 20 or 30 seconds is more appropriate for second-stage guidance. The usefulness of a prediction display depends on the accuracy of the prediction. Prediction times in the order of 10 seconds for the first stage and 20 to 30 seconds in the second stage were determined experimentally. The resulting predicted state was accurate enough to be useful.

The results from a number of experiments are presented in the following subsections. With these results, the three display formats are evaluated on the basis of a measure of the pilot work load and the resulting errors in the terminal conditions. Results are also presented, based on 14 runs made with the use of the best of the three display formats, which yield an rms value for the performance index. This index is a measure of the errors in the desired terminal condition. These runs were made with off-nominal initial conditions and off-nominal parameter values. Conclusions are drawn regarding the effects of disturbances due to typical wind profiles. Based on 45 runs made to evaluate the nominal guidance scheme, the utility of the display of the predicted vehicle state in the guidance scheme is described. The display of the predicted state was found to be useful only if the present state was off the nominal. In such cases, the display aided the operator in steering the present state back to the nominal trajectory. Also, the type of control found to be most advantageous in the pilot's control task is described. The control of attitude rate ($\dot{\theta}$) during the first stage and attitude (θ) during the second stage was determined to be most useful.

3.3.2 Display Evaluation

This subsection contains results with which the three display formats are evaluated. These display formats are altitude versus velocity (h versus V), altitude versus flight path angle (h versus γ) and altitude versus altitude rate (h versus $\dot{h}$). The displays are evaluated on the basis of a performance index which is a measure of the terminal error and also on the basis of a pilot work load factor.

The results in this subsection were all obtained with the same relatively experienced operator. In all cases, the operator used a combination of θ and $\dot{\theta}$ for control in the first stage and θ for a control in the second stage. The three displays of the nominal trajectory provided a presentation of the vehicle's present and predicted state as well as a meter-type presentation of the present state, i.e., time, altitude, velocity, flight-path angle, and attitude.

To evaluate the displays, a measure of the pilot work load is required. The measure used in this study was the rms deviation of the control function θ from the nominal control function. If $\bar{\theta}$ represents the nominal control function and θ represents the actual control used by the pilot, then the pilot work load factor (WLF) is defined as

$$\text{WLF} = \sqrt{\frac{1}{t_f} \int_0^{t_f} (\bar{\theta} - \theta)^2 \, dt}.$$

Three runs were made for each display with no wind disturbances, nominal initial conditions and nominal vehicle parameters. The trajectories and corresponding control functions are presented in Figures 3-20 to 3-25. Figures 3-20 and 3-21 present results obtained with the h-versus-V display. As is shown by the time history of the controls, manual guidance in the first stage is relatively easy compared to the second stage where the operator makes major corrections to θ and usually overcorrects so that a trajectory which oscillates about the nominal trajectory results. The form of the control in run 2 during first stage was not typical. In this run, the operator had a negative bias on $\dot{\theta}$ which he was unaware of until about 120 seconds after takeoff.

Figures 3-22 and 3-23 present results obtained with the h-versus-γ display. Figure 3-23 shows that with this display the pilot's control function is relatively smooth compared with that of the h-versus-V display. The trajectory shown in Figure 3-22 is also very smooth and regular in second stage.

Figures 3-24 and 3-25 present results obtained using the h-versus-$\dot{h}$ display. The control functions shown in Figure 3-25 are smoother than those obtained with either of the other two displays. The trajectories shown in Figure 3-24 are extremely smooth and regular. Figure 3-26 is a flow diagram which indicates the integrations between small changes in the vehicle state and small

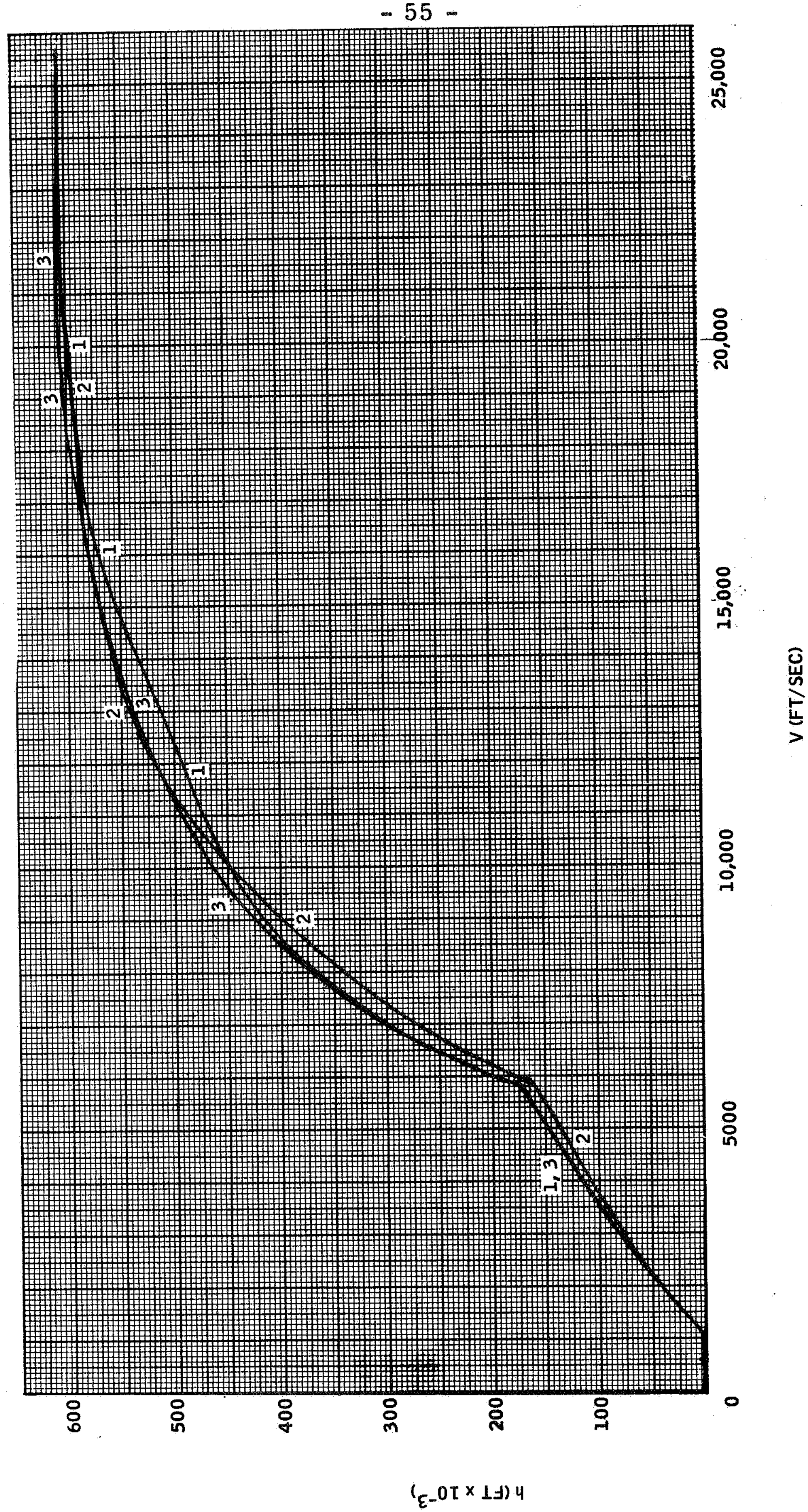


Figure 3-20. Altitude-versus-Velocity Trajectories Obtained with Nominal Guidance Scheme using Altitude-versus-Velocity Display Format

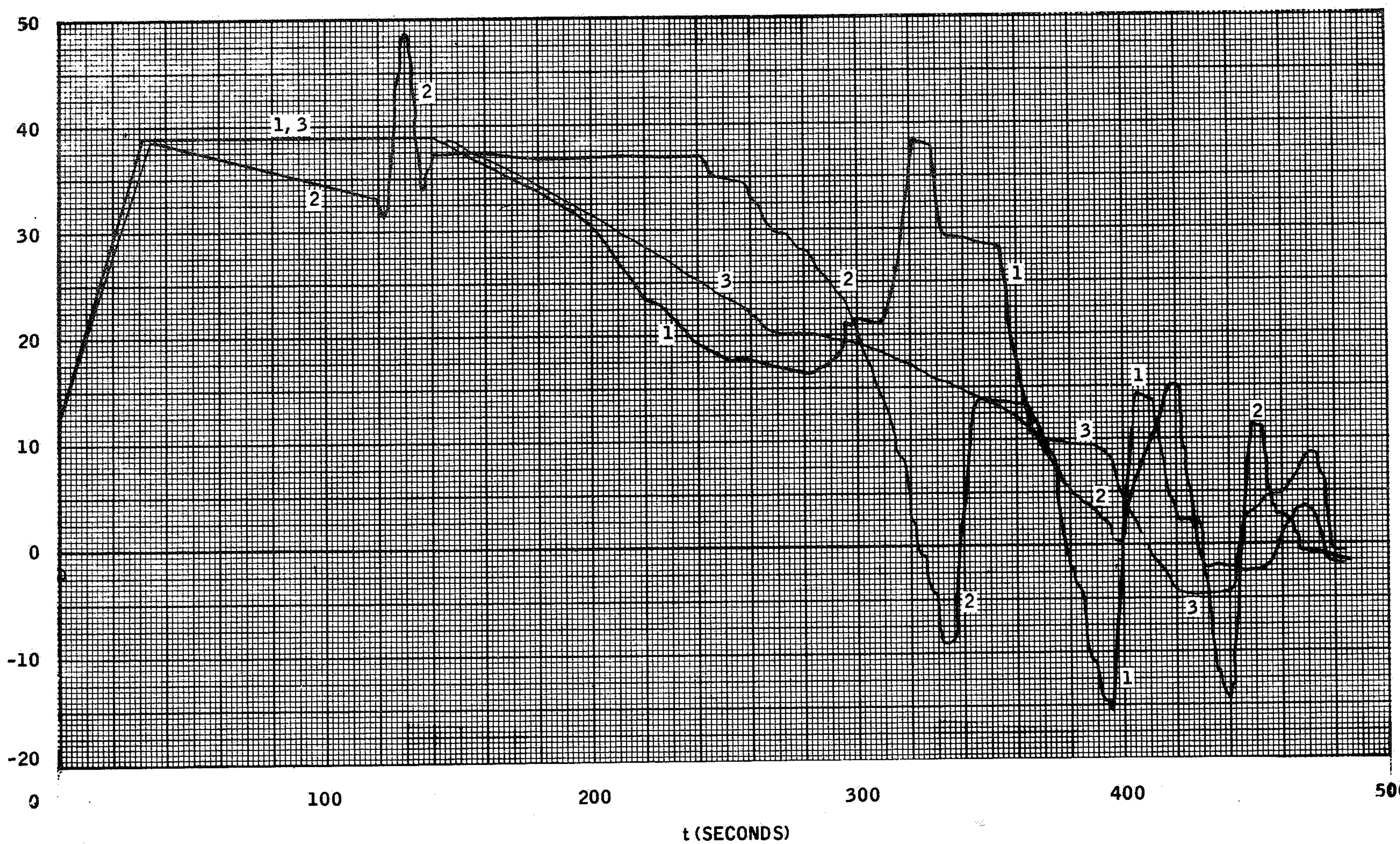


Figure 3-21. Attitude versus Time for Trajectories in Figure 3-20 using Altitude-versus-Velocity Display Format

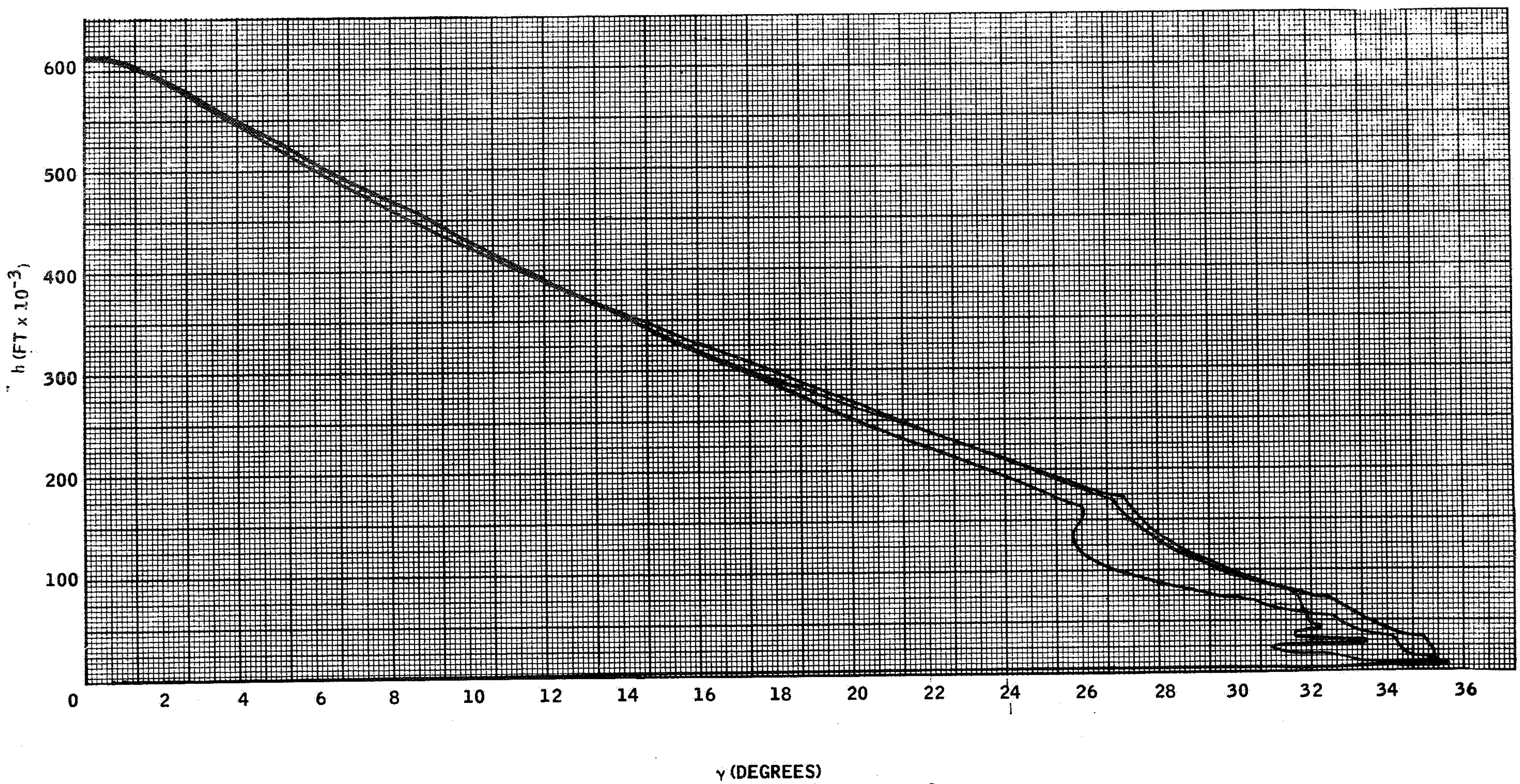


Figure 3-22. Altitude-versus-Flight-Path-Angle Trajectories Obtained with Nominal Guidance Scheme using Altitude-versus-Flight-Path-Angle Display Format

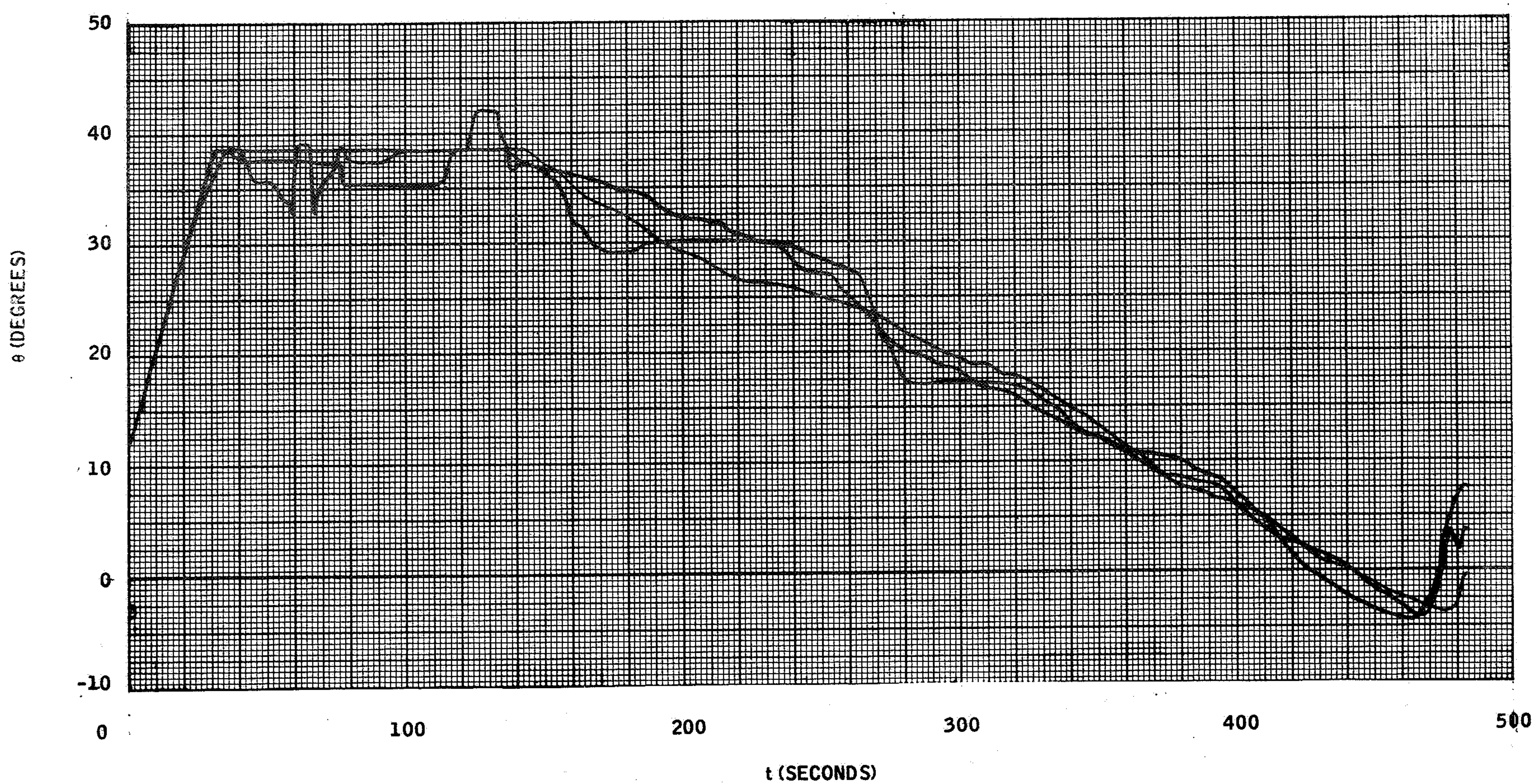


Figure 3-23. Attitude versus Time for Trajectories in Figure 3-22 using Altitude-versus-Flight-Path-Angle Display Format

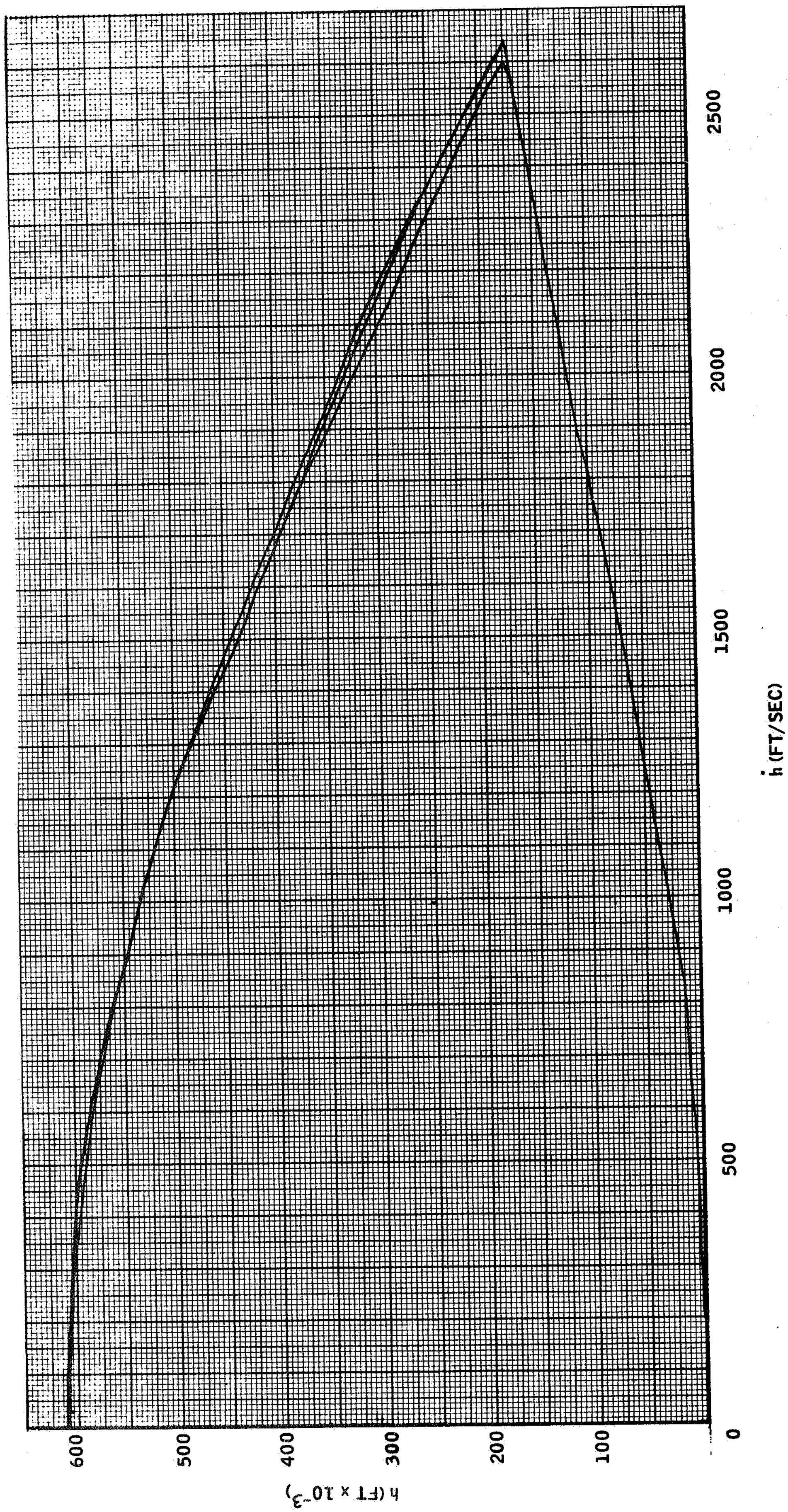


Figure 3-24. Altitude-versus-Altitude-R te Trajectories Obtained with Nominal Guidance Scheme using Altitude-versus-Altitude-Rate Display Format

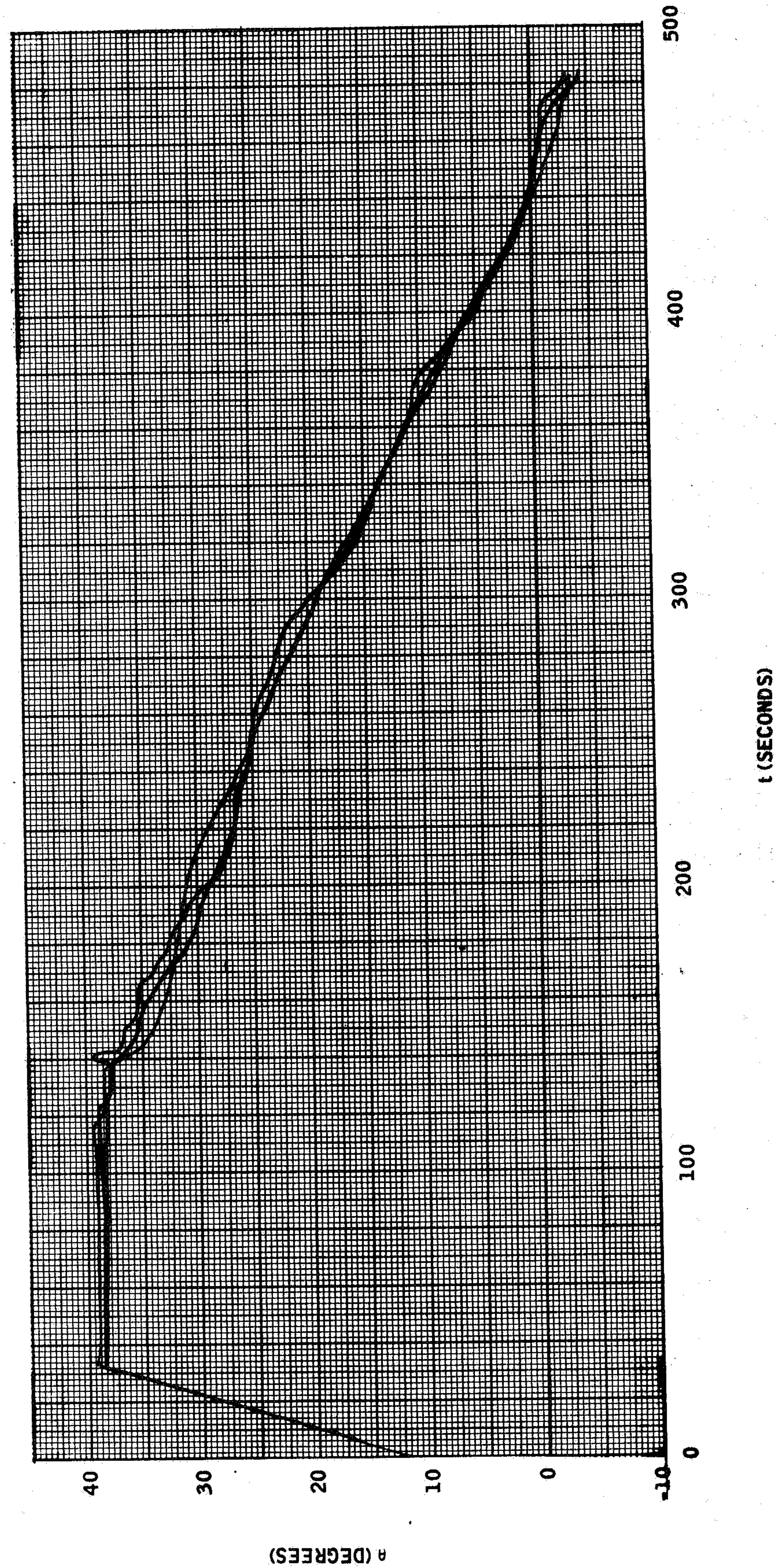


Figure 3-25. Attitude versus Time for Trajectories in Figure 3-24 using Altitude-versus-Altitude-Rate Display Format

changes in the vehicle angle of attack ($\delta\alpha$). The flow diagram is based on the perturbation equations to the vehicle equations of motion during the second stage.

The pilot work load factor based on the root mean square error from the nominal control is shown in Figure 3-27. As expected from an examination of the previous trajectories, this work load factor is higher for the h-versus-V display. The other two displays, h versus γ and h versus $\dot{h}$, have approximately the same value for the work load factor.

On the basis of the defined pilot work load factor and on the data analyzed, the h-versus-$\dot{h}$ is definitely superior to the h-versus-V display and slightly better than the h-versus-γ display.

In addition to considering the pilot work load, as a means of evaluating displays, a measure of the terminal error incurred with each method is required. A series of runs were made with each display format to evaluate the displays on the basis of terminal errors. A performance index (P.I.) is defined which is a measure of the terminal error.

$$P.I. = \sqrt{\frac{\left(\frac{h_e}{h_{e_{max}}}\right)^2 + \left(\frac{\gamma_e}{\gamma_{e_{max}}}\right)^2}{2}}$$

The terms h_e and γ_e are the terminal errors in altitude and flight-path angle and the terms $h_{e_{max}}$ and $\gamma_{e_{max}}$ are numbers which, in effect, weight the importance of errors in altitude and flight-path angle to the performance index. The numbers used in this study are 20,000 feet and 0.1 degree, respectively.

Table 3-3 lists the results obtained from 31 runs. These runs were all made with nominal initial conditions and nominal vehicle parameters. The effects of winds were determined with these runs. The results are used to evaluate

PERTURBATION EQUATIONS FOR VACUUM PHASE

$\delta h = a_{12}\,\delta V + a_{13}\,\delta\gamma$

$\delta V = a_{21}\,\delta h + a_{23}\,\delta\gamma + b_2\,\delta\alpha$

$\delta\gamma = a_{13}\,\delta h + a_{32}\,\delta V + a_{33}\,\delta\gamma + b_3\,\delta\alpha$

WHERE

$a_{12} = \mathrm{SIN}\,\gamma \qquad a_{13} = V\,\mathrm{COS}\,\gamma$

$a_{21} = -g/r \qquad a_{23} = -g\,\mathrm{COS}\,\gamma \qquad b_2 = \frac{-T}{m}\mathrm{SIN}\,\alpha$

$a_{31} = (g/_r\,V - V/_r{}^2)\,\mathrm{COS}\,\gamma$

$a_{32} = {}^{-T}/_{mV^2}\,\mathrm{SIN}\,\alpha + (\frac{g}{V^2} + \frac{1}{r})\,\mathrm{COS}\,\gamma$

$a_{33} = (\frac{g}{V} - \frac{V}{r})\,\mathrm{SIN}\,\gamma$

$b_3 = {}^{T}/_{mV}\,\mathrm{COS}\,\alpha$

TYPICAL VALUES

$t = 200$
$h = 3.16 \times 10^5$ FT.
$\gamma = 16.6°$
$\alpha = 15.5°$
$m = 8 \times 10^3$ SLUGS
$V = 7.3 \times 10^3$ FT/SEC
$T = 3.05 \times 10^5$

$a_{12} = 0.3$
$a_{13} = 7 \times 10^3$
$a_{21} = -1.5 \times 10^{-6}$
$a_{23} = -30$
$b_2 = -11$
$a_{31} = 1.8 \times 10^{-10}$
$a_{32} = 0.4 \times 10^{-6}$
$b_3 = 5 \times 10^{-3}$

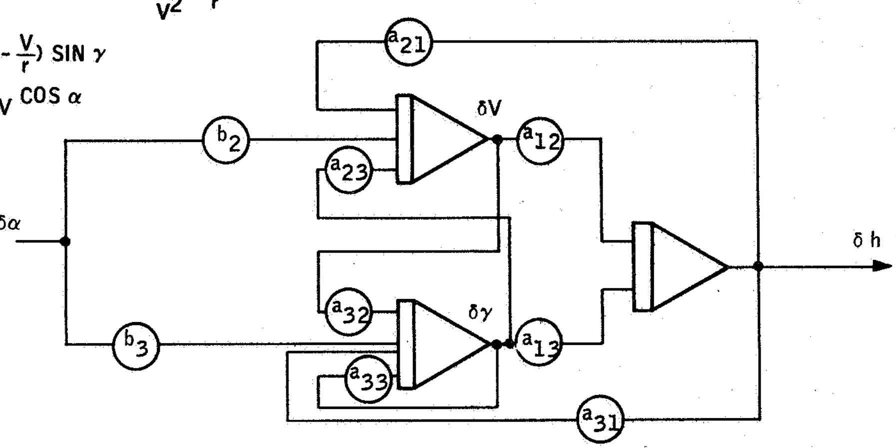


Figure 3-26. Flow Diagram for Perturbation Equations

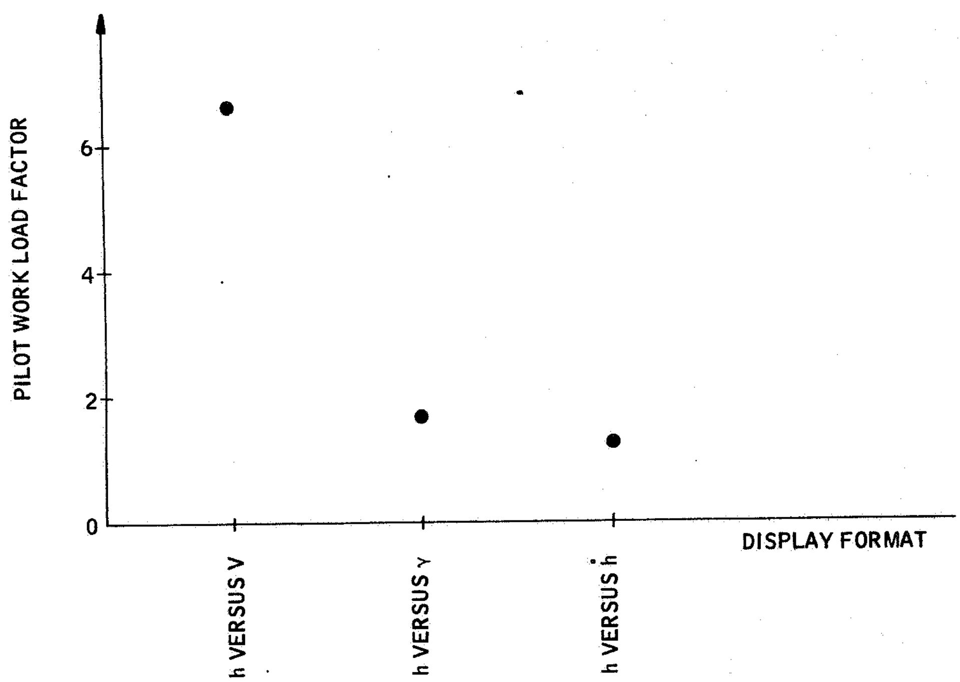


Figure 3-27. Work Load Factor versus Display Format

Table 3-3. Data From Nominal Guidance Scheme to Evaluate Display Formats

Run No.	Display	Wind* (percent)	Terminal Altitude Error h_e (ft)	Terminal Flight-Path Angle Error γ_e (deg)	Final Time t_f (sec)	Terminal Velocity V_f (ft/sec)	P.I.
1	h vs V	0	383	-.183	486	25,578	1.294
2	h vs V	0	4,719	-.447	486	25,647	3.165
3	h vs V	0	8,021	0.311	487	25,633	2.217
4	h vs V	0	4,972	-.059	485	25,593	0.453
5	h vs V	0	2,008	0.057	485	25,539	0.409
6	h vs V	0	212	0.040	484	25,676	0.283
7	h vs V	99	-341	0.159	484	25,642	1.124
8	h vs V	50	-3,606	-.127	484	25,581	0.907
9	h vs V	99	-1,384	0.031	485	25,667	0.224
10	h vs V	0	1,311	0.040	486	25,550	0.286
11	h vs V	0	-2,504	-.031	485	25,581	0.113
12	h vs V	0	-2,876	0.053	484	25,624	0.388
13	h vs V	0	-2,020	-.030	484	25,580	0.223
14	h vs V	0	2,322	-.135	486	25,652	0.958
15	h vs V	0	1,340	-.062	486	25,587	0.441
16	h vs γ	0	-435	-.009	484	25,626	0.065
17	h vs γ	0	-2,662	0.056	485	25,642	0.407
18	h vs γ	0	-592	0.041	484	25,649	0.290
19	h vs γ	0	516	-.058	484	25,664	0.411
20	h vs $\dot{h}$	0	-2,117	-.039	484	25,666	0.286
21	h vs $\dot{h}$	0	-2,046	-.042	484	25,577	0.306
22	h vs $\dot{h}$	99	-1,033	-.039	484	25,649	0.278
23	h vs $\dot{h}$	0	943	0.053	484	25,665	0.376
24	h vs $\dot{h}$	99	201	0.003	484	25,599	0.022
25	h vs $\dot{h}$	0	-1,502	0.003	484	25,574	0.057
26	h vs $\dot{h}$	0	-382	-.040	484	25,664	0.286
27	h vs $\dot{h}$	0	1,052	0.065	484	25,664	0.462
28	h vs $\dot{h}$	0	1,320	0.039	484	25,662	0.279
29	h vs $\dot{h}$	0	2,040	0.083	484	25,663	0.592
30	h vs $\dot{h}$	0	2,300	0.106	484	25,587	0.754
31	h vs $\dot{h}$	0	139	-.067	484	25,663	0.475

Nominal initial conditions:

γ_o = 1 degree

V_o = 650 ft/sec

h_o = 0

* See Appendix A for a description of wind profiles.

the different displays on the basis of the terminal error. All the runs used to obtain a performance index for the display were made by the same relatively experienced operator. All runs were made with the same control, i.e., $\dot{\theta}$ in the first stage and θ during the second stage. This combination of controls was determined to be most useful over-all. Also, every run was made with the same initial condition on θ at the beginning of first stage. The three displays of the nominal trajectory had a presentation of the vehicle present and predicted state as well as a meter-type presentation of the present state, i.e., time, altitude, velocity, flight-path angle, and attitude.

For the h-versus-V display, runs 8 through 15 were used to determine an rms value for the performance index; for h-versus-γ, runs 16 through 19 were used; and for h-versus-$\dot{h}$, runs 20 through 31 were used. The performance index versus run number and the rms value of the performance index versus display format are shown in Figure 3-28.

Based on the results in Figures 3-27 and 3-28, both the h-versus-$\dot{h}$ and h-versus-γ are preferred over the h-versus-V display format. There is a significant reduction in the pilot work load index (PWLI) (see Figure 3-27) with the h-versus-$\dot{h}$ and h-versus-γ displays. The h-versus-$\dot{h}$ display has a minimum value for the PWLI. There is also a reduction in the rms value of the performance index (P. I.) with the h-versus-$\dot{h}$ and h-versus-γ displays over the h-versus-V display (see Figure 3-28). The h-versus-γ display yielded a minimum value for the P.I. However, the value for the P.I. for the h-versus-$\dot{h}$ and h-versus-γ displays are so close that these two displays should be judged equal on the basis of the performance index.

In summary, the h-versus-$\dot{h}$ and h-versus-γ display formats are judged superior to the h-versus-V display on the basis of pilot work load and the terminal errors.

The one operator, who performed in all the runs presented using the nominal guidance scheme, preferred the h-versus-$\dot{h}$ display over the other three.

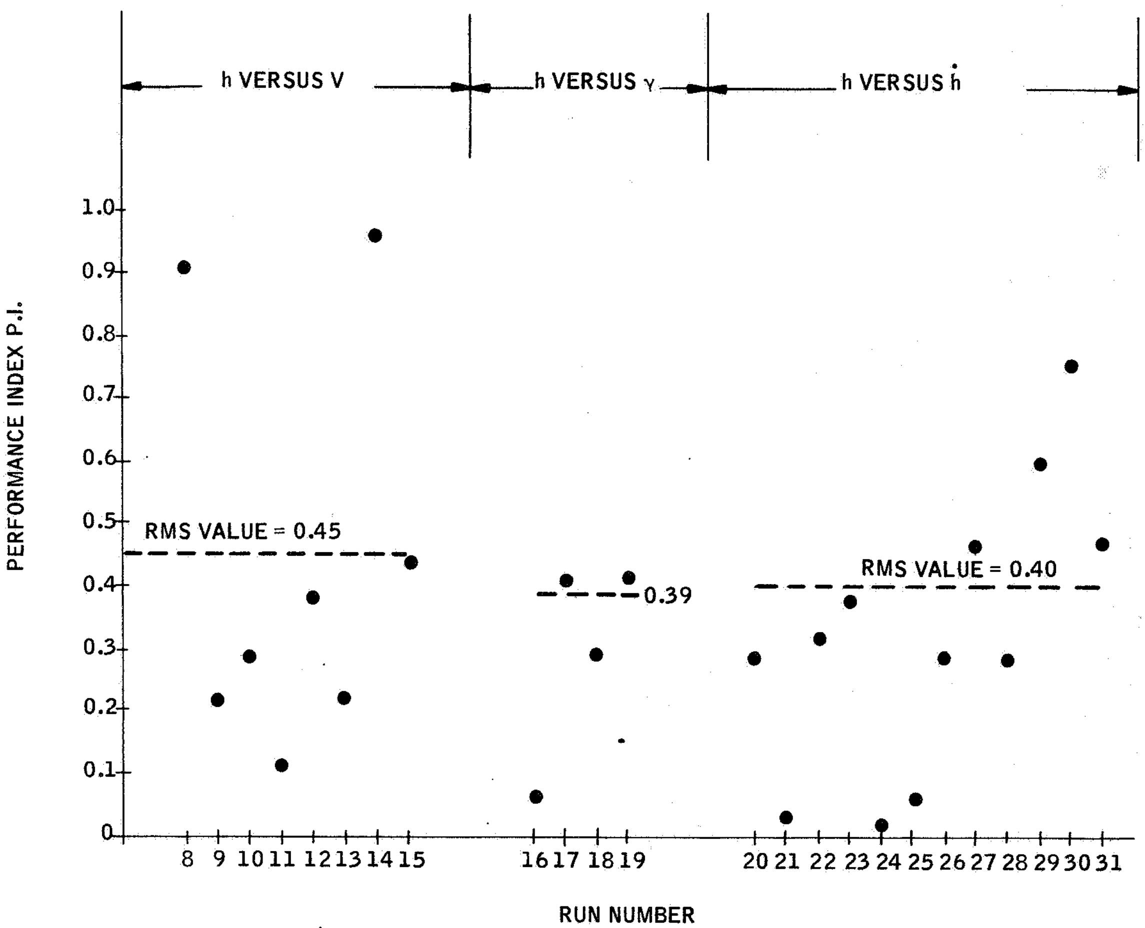


Figure 3-28. Performance Index versus Run Number

This operator found, that with experience, this display format was the easiest to follow over-all. As a result of this evaluation on the basis of performance index, pilot work load index, and personal opinion of one experienced operator, the h-versus-$\dot{h}$ display format was used to determine a measure of the variability in the terminal errors incurred using this nominal guidance scheme. These results are presented in the following subsection.

3.3.3 Variability in the Performance Index for the Nominal Guidance Scheme

A series of 14 runs with one experienced operator was made to obtain an estimate of the variability of the terminal errors which can be expected with the nominal guidance scheme. The display format used was altitude versus altitude rate (h versus $\dot{h}$). This display was found to be the best of the three displays evaluated during this study. In all cases, the operator was presented with a display of the predicted vehicle state with an adjustable prediction time and a display of the present vehicle state; both in the h-versus-$\dot{h}$ plane. In addition to this pursuit-with-prediction display, the operator was also given a meter-type presentation of the vehicle's present state, i.e., velocity, altitude, flight-path angle, body attitude and nominal time to cutoff. A photograph of the display used is shown in Figure 3-19(c). The control, which the operator found most suitable in all cases, was attitude rate ($\dot{\theta}$) during the first stage and attitude (θ) during the second stage. Each run was made with the same initial value for θ in the first stage.

The results from these 14 runs are presented in Table 3-4. Runs were made with off-nominal initial conditions in the first stage and off-nominal vehicle parameters. Vehicle parameters such as the aerodynamic characteristics and the vehicle weights at takeoff and at staging were varied from their nominal values by ± 10 percent. This nominal guidance scheme was used for both the first and second stages for this study. The results obtained are used to compare the predictive model scheme with this more conventional nominal guidance scheme. The results of this comparison are presented in 3.4. The

Table 3-4. Data From Nominal Guidance Scheme with Off Nominal Initial Conditions

Run No.	Display	Initial Condition Changes From Nominal	Wind*	Terminal Altitude Error h_e (ft)	Terminal Flight Path Angle Error γ_e (deg)	Final Time t_f (sec)	Terminal Velocity V_f (ft/sec)	Performance Index P.I.
32	h vs $\dot{h}$	γ_o = 10°	0	-3,810	0.467	484	25,609	3.313
33	h vs $\dot{h}$	V_o = 550°	0	-1,560	0.023	485	25,634	0.172
34	h vs $\dot{h}$	V_o = 750	0	864	0.173	482	25,602	1.224
35	h vs $\dot{h}$	m_o = -5%	0	-980	0.060	479	25,626	0.426
36	h vs $\dot{h}$	m_o = -5% m_2 = -5%	0	2,230	0.017	481	25,664	0.144
37	h vs $\dot{h}$	m_o = +5% m_2 = +5%	0	4,753	0.236	509	25,664	1.676
38	h vs $\dot{h}$	V_o = 750	0	-334	-.039	482	25,588	0.278
39	h vs $\dot{h}$	V_o = 550	0	2,308	0.092	485	25,620	0.656
40	h vs $\dot{h}$	γ_o = 10°	0	583	0.044	483	25,600	0.312
41	h vs $\dot{h}$	C_{L_α} = +10% C_{D_o} = +10%	0	3,416	-.037	484	25,630	0.288
42	h vs $\dot{h}$	C_{L_α} = -10% C_{D_o} = -10%	0	1,011	-.067	483	25,664	0.475
43	h vs $\dot{h}$	m_o = +5%	0	-1,334	-.089	493	25,594	0.631
44	h vs $\dot{h}$	m_o = -5%	0	-102	-.078	479	25,661	0.552
45	h vs $\dot{h}$	m_o = -5% m_2 = -5%	0	456	.388	464	25,639	2.745

* Nominal Initial Conditions:

γ_o = 1 degree
V_o = 650 ft/sec
h_o = 0
m_o = 4.7124×10^4 slugs
m_2 = 9.1078×10^3 slugs (mass at beginning of second stage
C_{L_α} and C_{D_o} are given in Figure A2 of Appendix A.

** See Appendix A for a description of the wind profiles used in the study.

performance index used as a measure of the terminal error on the flight-path angle and altitude is the same as defined for the predictive model scheme and also used for the display evaluation. Figure 3-29 presents the performance index versus the run number along with the rms value of the performance number. This figure yields an estimate of the variability in the performance index which can be expected with the nominal guidance scheme.

In summary, an rms value of 0.92 was obtained for the performance index with the nominal guidance scheme. Such a value could, for example, indicate an error of about 0.13 degree in flight-path angle and a 3000-foot error in altitude. The best display format was used along with a predicted vehicle state and meter-type presentation of the vehicle's present state. This value is used in 3.4 as a means of evaluating the manual nominal guidance scheme and the manual predictive model guidance scheme.

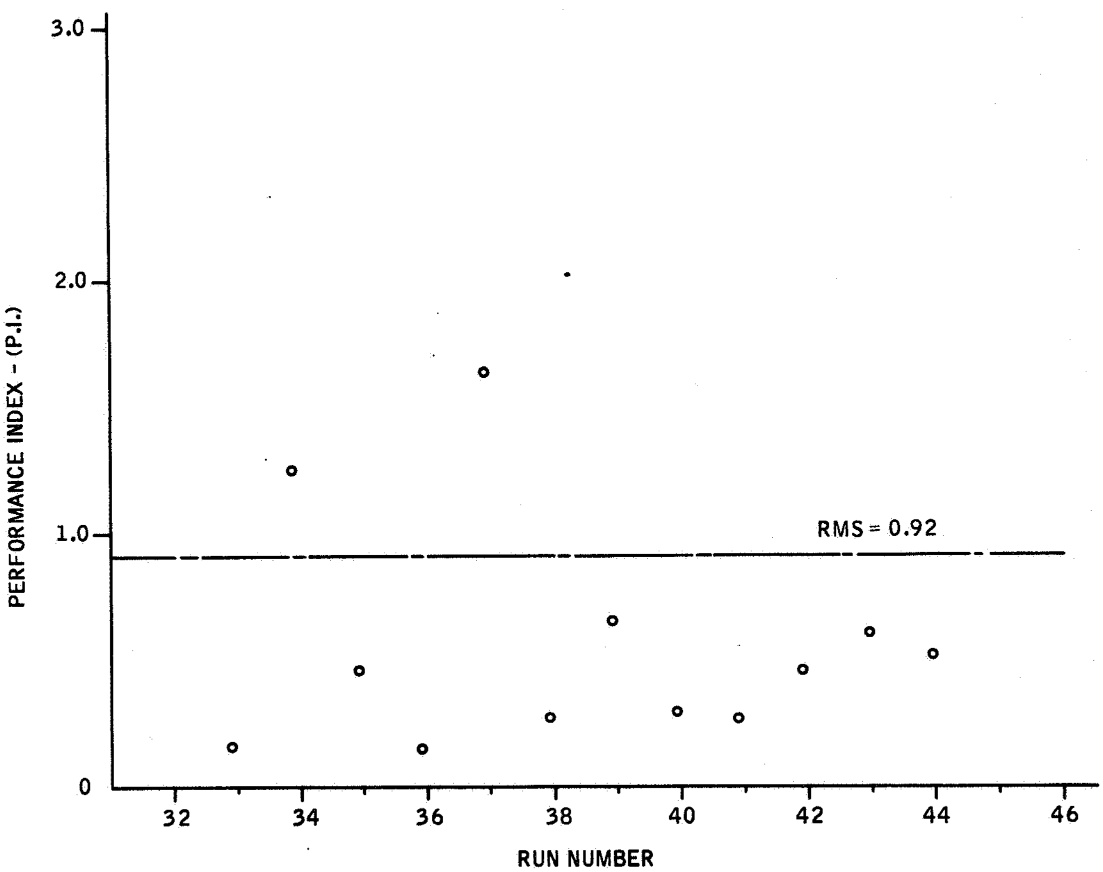


Figure 3-29. Variability of Performance Index with Nominal Guidance Scheme

3.3.4 A Learning Curve for the Nominal Guidance Scheme

A series of six runs was made with one inexperienced operator and a single training period to determine a typical learning curve. A learning curve is necessary so that the amount of training required to successfully implement this manual scheme can be estimated. Although multiple-subject testing and a number of training periods would be necessary for a good estimate of the amount of training required, it is felt that the data presented is valuable in that it provides a rough estimate of the required training. Multiple-subject testing was not in the scope of the study.

The results of these runs are presented in Table 3-3, runs 1 through 6. In each case an altitude-versus-velocity display format was used. The present and predicted vehicle state were displayed on the nominal trajectory. Also, a meter-type display was used to present the vehicle's present state, i.e., altitude, velocity, flight-path angle, attitude, and time. The performance index defined in 3.2.2 was used to evaluate the results of each trajectory.

The results are presented in Figure 3-30 in the form of a learning curve. As shown in this figure, the performance actually increased in the second run. A similar behavior was observed in the learning curve for the predictive model scheme (see Figure 3-12). This may be due to the operator experimenting with the system before he really understands its behavior.

3.3.5 Summary and Recommendations

(1) Prediction based on derivative information of the present state was used in the study. The prediction time was adjustable. It was found that the display of the predicted state was ignored during most of the run if the present state was on the nominal. If large disturbances caused excursions from the nominal curve, then the predicted state display was useful in returning to the nominal. With sufficient training, the display of the predicted vehicle state is not required.

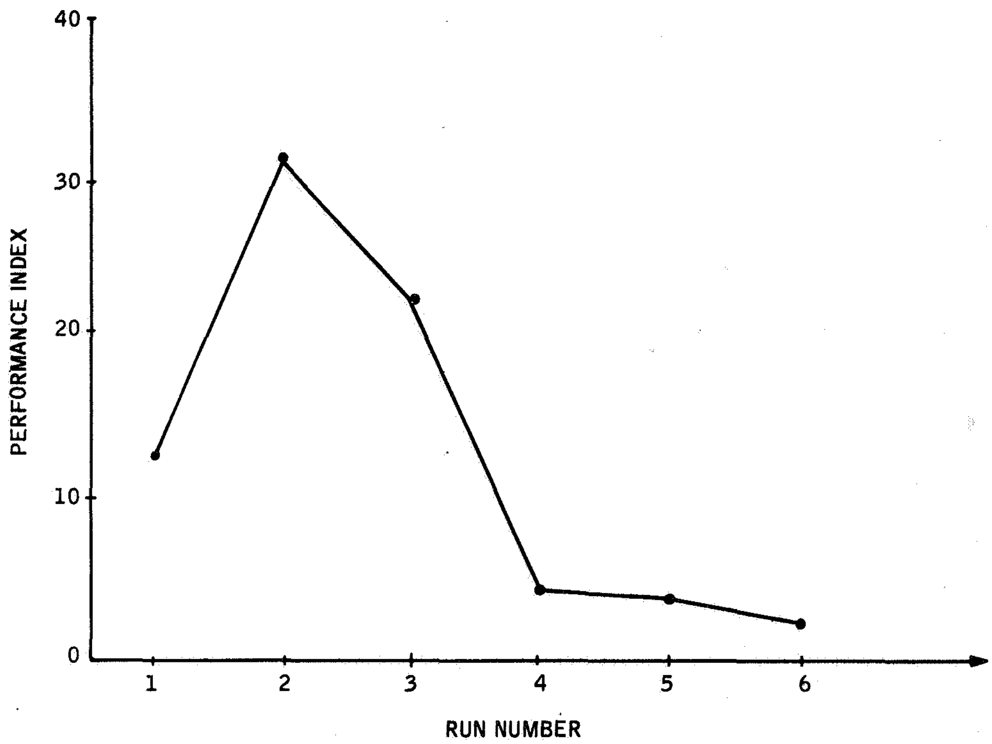


Figure 3-30. Learning Curve for Nominal Guidance Scheme

(2) The control which was found to be most advantageous to the operator was attitude rate ($\dot{\theta}$) during the first stage and attitude (θ) during the second stage. The $\dot{\theta}$ control is particularly useful in the first stage due to the relatively large changes in θ required in the first 40 seconds (from about 10 to 40 degrees in 40 seconds). In all runs, a programmed control program was used during the first stage. The control program consisted of an initial value of θ and a constant value of $\dot{\theta}$ until θ reached 38 degrees, at which time $\dot{\theta}$ was set to zero. The resulting constant attitude control was used until staging occurred. These values were obtained by approximating the nominal control. Only minor small corrections to this programmed control were required during the first stage. A similar programmed control in the form of a constant value for $\dot{\theta}$ was attempted for the second stage.

This control was not as effective as the control θ for the second stage primarily because of the increase in integrations between the control and vehicle response.

(3) The effects of typical wind disturbances on man's ability to control the vehicle to a nominal trajectory were almost negligible. Due to the relatively high initial velocity of the vehicle (V_o = 650 ft/sec) as opposed to the Saturn-V where $V_o = 0$, the vehicle velocity is always much higher than the wind velocity. This results in a relatively small value for the induced angle of attack due to wind; hence, the disturbing effect of the wind is negligible. With the inclusion of the vehicle rotational dynamics, however, it is felt that the effects of wind disturbances would no longer be negligible.

(4) The altitude-versus-altitude-rate (h-versus-$\dot{h}$) and altitude-versus-flight-path-angle (h-versus-γ) were found to be superior to the altitude-versus-velocity (h-versus-V) display format. This evaluation was made on the basis of the pilot work load and on the basis of errors in the desired terminal conditions.

(5) In addition to the pursuit display which presents the nominal trajectory along with the present and predicted vehicle states, a meter-type display of the vehicle present state was required. This display is required as the vehicle state approaches the terminal conditions. The pilot or operator then focuses his attention on the meter display rather than on the display of the nominal trajectory.

(6) An rms value of 0.92 for the performance index was obtained on the basis of 14 runs. These runs were made with off-nominal initial conditions using an h-versus-$\dot{h}$ display format. As an example of the meaning of this value of 0.92, a flight-path angle error of 0.13 degree and altitude error of 3000 feet yields this value for the P.I.

(7) This study of the nominal guidance scheme was conducted with a planar model of the ROT vehicle dynamics. The model also assumes a perfect control system and the function of man in the guidance loop is to perform the steering command signal. The conclusions of this phase of the study should be reevaluated using a three-dimensional model for the vehicle along with either an automatic or manual control system.

3.4 A COMPARISON OF THE PREDICTIVE MODEL GUIDANCE SCHEME AND THE NOMINAL GUIDANCE SCHEME

This subsection compares the two manual guidance schemes on the basis of:

- Accuracy
- Pilot work load
- Mission flexibility
- Fuel requirements
- Display requirements
- Computational requirements
- Training requirements
- Pilot's role

3.4.1 Accuracy

Accuracy in the two guidance schemes is a measure of how well the desired terminal conditions are satisfied. In both schemes, an automatic velocity cutoff is assumed so that the desired terminal velocity condition is satisfied automatically in both schemes. The remaining terminal conditions are altitude (h_f) and flight-path angle (γ_f). For the circular target orbit used as a study example, the desired terminal conditions on altitude and flight-path angle are:

h_f = 608,020 feet

γ_f = 0 degree

Since the target orbit parameters are more sensitive to γ_f than h_f, in both guidance schemes, the operator was instructed to concentrate more on obtaining the desired γ_f than the desired h_f. The performance index (P.I.) defined in 3.2.2 is a measure of the errors in the desired terminal conditions.

In both guidance schemes, a series of runs was made with off-nominal initial conditions. The results of these runs are tabulated in Table 3-1 for the Predictive Model Guidance Scheme (PMGS) and in Table 3-4 for the Nominal Guidance Scheme (NGS). The rms value of the P.I. for the PMGS is 0.07; for the NGS 0.9. The rms value of altitude error and flight-path angle error for the PMGS was 1760 feet and 0.007 degree, respectively. The corresponding errors for the NGS were 2180 feet and 0.17 degree.

In summary, the performance index, or accuracy, obtained with the PMGS is an order of magnitude better than that with the NGS. Figure 3-31 illustrates the order of improvement in the performance index.

3.4.2 Pilot Work Load

The pilot work load for each scheme is based on a qualitative judgment rather than on an absolute measure of the pilot work load. Further effort is required to get an absolute measure of the pilot work load in performing the guidance functions in the proposed manual guidance schemes. A relative measure is easier to define. For instance, in evaluating various display formats used in the NGS, a relative measure of work load was used. This relative measure of work load is not satisfactory to compare the two different guidance schemes.

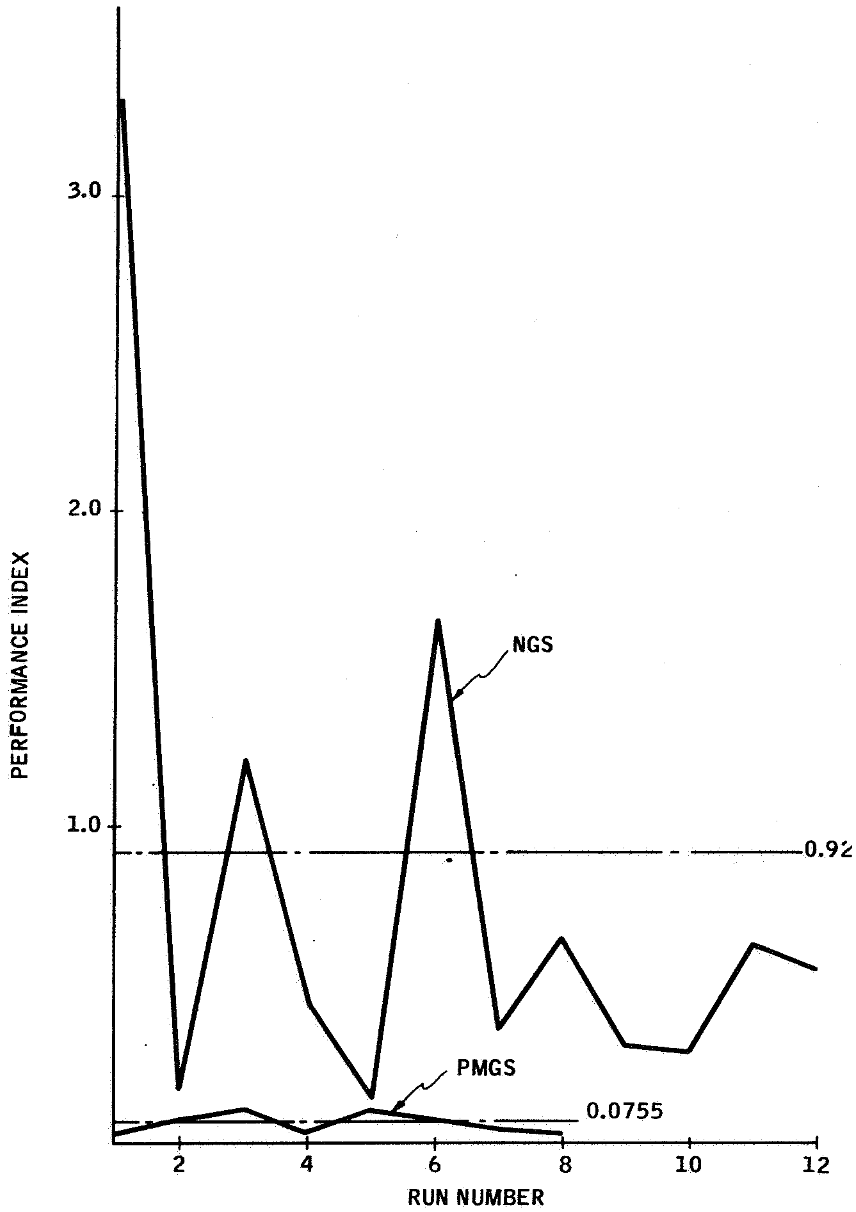


Figure 3-31. A Comparison of the Performance Index versus Run Number for Each Guidance Scheme

In the NGS, the pilot is continually controlling the vehicle attitude to keep the present state of the vehicle on the nominal trajectory. In the PMGS however, the pilot's task consists of an initial adjustment period in which the optimization parameters are adjusted so that the predicted trajectory approximately satisfies the desired terminal conditions. After this period of 30 to 40 seconds, the pilot's task consists of monitoring the predicted terminal error. During the final portion of the mission, the pilot makes a finer adjustment of the optimization parameters to null out the predicted terminal errors. This last period of adjustment (100 seconds) requires continuous attention from the pilot due to the inaccuracies in the fast-time model.

In summary, the pilot work load is lower for the PMGS than for the NGS. The NGS requires a continuous effort by the pilot, whereas the PMGS only requires an initial and final period of optimization parameter adjustment by the pilot.

3.4.3 Mission Flexibility

With the NGS, once the flight commences, no alterations to the nominal flight path can be made unless provision is made to store more than one nominal trajectory. On the other hand, the PMGS allows the pilot to steer to a new target orbit at any point in the mission. Furthermore, the pilot steers the vehicle to the new target orbit along a fuel-optimal path.

3.4.4 Fuel Requirements

Both manual guidance schemes are fuel-optimal in nature. The PMGS generates fuel-optimal trajectories for the predictive model and for the model used in this study; the prediction model trajectory is very close to optimal for the actual ROT vehicle model. The NGS uses a fuel-optimal trajectory about which the pilot guides the vehicle during the boost ascent. If there are no external disturbances present, then both schemes are fuel-optimal. If disturbances are present which force the vehicle state off the nominal trajectory, the NGS requires the pilot to steer back to the nominal. This is no longer the fuel-optimal path to the target conditions. With the PMGS, however, the pilot generates a new fuel-optimal path to the target conditions.

In summary, both schemes are fuel-optimal under ideal conditions, i.e., no disturbances or parameter variations. With disturbances, the PMGS generates a more economical flight path than the NGS.

3.4.5 Display Requirements

The NGS requires a display of one nominal trajectory, whereas the PMGS requires a display of a new predicted trajectory every second. Both schemes require a CRT-type display of the trajectory as well as a display of the vehicle's present state. Both schemes require a meter-type presentation: a presentation of the predicted terminal error for the PMGS and a presentation of the present vehicle state for the NGS.

In summary, the display requirements for both schemes are moderate. The computational requirements for the displays required in the PMGS are higher than in the NGS.

3.4.6 Computer Requirements

Apart from the computation requirements for displaying the nominal trajectory, the computer requirements for the NGS are zero. For the PMGS, the guidance computer must numerically integrate the predictive model equations of motion to cutoff conditions once each second. These equations are shown in Figure 3-4 as "Fast-Time Model Equations".

To estimate the computer requirements for the PMGS, the following assumptions are made:

(1) No coordinate transformations are required between the vehicle sensor outputs and the fast-time model.

(2) The fast-time trajectory is displayed in flight-path coordinate system.

(3) A simple rectangular integration scheme is used with a variable step size. Step size is adjusted so that 34 points are calculated for predicted trajectory. At staging this corresponds to a step size of 10 seconds.

(4) An automatic velocity cutoff is used.

(5) The storage and computation time requirements are based on the computer characteristics given in Table 3-5. These characteristics are typical of Saturn Launch Vehicles.[6]

With these assumptions, the requirements are:

(1) Estimated storage capacity - 300 words

(2) Estimated computation time - 650 msec. Since a fast time solution is required every second, the required computation time is 650 msec every second.

(3) D/A converters - three required to drive CRT displays and meters.

(4) A/D converters - three required to input vehicle sensor data to digital computer.

Further study on the effects of simplification of the equations of motion for the fast-time model is recommended before describing in detail the computational requirements for the PMGS. With sufficient assumptions (e.g., small

Table 3-5. Computer Characteristics for Saturn Launch Vehicles

Characteristic	Description
Type	Stored program, general purpose, serial, fixed point, binary
Clock	2.048-MHz clock, 4 clocks per bit, 512 kilobits per second
Speed	Add-subtract and multiply-divide simultaneously
Add Time, Accuracy	82 microsec, 26-bit
Multiply Time, Accuracy	328 microsec, 24-bit
Mult-Hold Time, Accuracy	410 microsec, 24-bit
Divide Time, Accuracy	656 microsec, 24-bit
Memory	Random access toroidal store
Storage Capacity	Up to a maximum of 32,768 28 bit words in 4096-word modules
Word Length	Memory work, 28 bits; two instructions may be stored in one memory work
Data	26 bits plus 2 parity bits
Instruction	13 bits plus 1 parity bit
Input/Output	
External	Computer programmed
Input/Output Control	External interrupt provided
Component Count (est.)	40,800 silicon semiconductors and cermet resistors; up to 917,504 toroid cores
Reliability (est.)	0.996 probability of success for 250 hours using TMR logic and duplex memory modules
Packaging	Structure constructed of magnesium-lithium material, designed to house 73 electronic pages and 8 memory modules
Weight (est.)	30 kg (four memory modules)
Volume (est.)	0.07 cubic meters
Power (est.)	150 watts (four memory modules)

angles and constant mass), a closed-form expression can be obtained for the predicted trajectory. This simplification reduces the computational requirements; however, the pilot work load increases because the fast-time predictive model is a less accurate model for the real vehicle. This tradeoff between model accuracy or, equivalently, computer complexity and pilot work load requires further study. There may also be an increase in the typical errors in the terminal conditions with a simpler predictive model due to the increase in pilot work load.

3.4.7 Pilot Training Requirements

Although the determination of the training requirements for both schemes was outside the scope of the study, typical learning curves were determined for both schemes. In each case, data was obtained from one training session and with one inexperienced operator. The two training curves obtained for the manual guidance schemes are shown in Figure 3-32. Both curves show an increase in performance index after the first run; however after five runs, the performance index is fairly steady in both schemes. On the basis of this limited testing, no undue amount of training is required in either guidance scheme. Figure 3-32 shows the improvement in performance index obtained with the PMGS over the NGS.

3.4.8 Pilot's Role

The guidance objective for the study vehicle with reference to the terminal conditions consists in arriving at a desired altitude with a specified velocity and flight-path angle. In the NGS, the task of guiding the vehicle to the desired terminal conditions is translated into the maintenance of the nominal trajectory which passes through the terminal conditions. The pilot's role in steering the vehicle along the nominal trajectory results in satisfying the guidance objective. With the PMGS, the task of guiding the vehicle to the

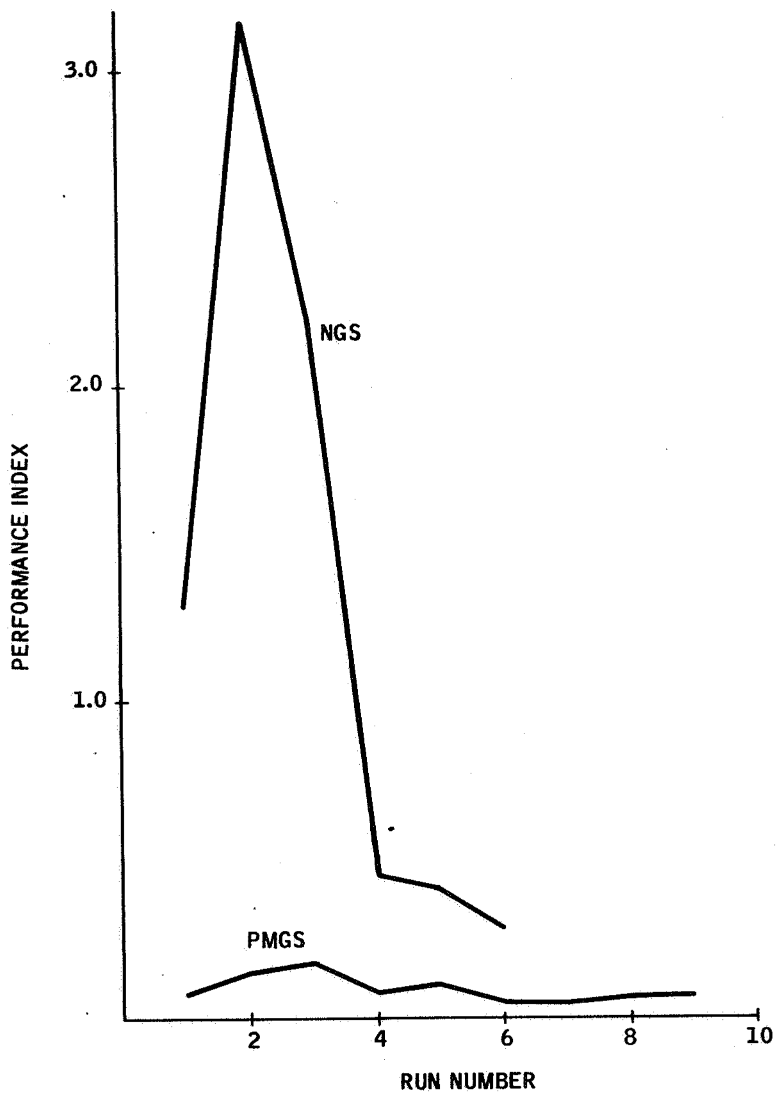


Figure 3-32. A Comparison of the Learning Curves for Both Guidance Schemes

desired terminal conditions is translated into a task of keeping the vehicle's predicted trajectory passing through the desired terminal conditions. Since a new predicted trajectory is generated each second from the vehicle's present state, the pilot's task results in satisfying the guidance function.

3.4.9 Summary

Table 3-6 summarizes the comparison of the NGS with the PMGS. The PMGS is accurate, flexible, fuel-optimal, and the pilot work load is low. The computer and display requirements are moderate. On the other hand, the NGS is simple, has basically no computer requirements, and the display requirements are low. These low computation and display requirements assume there are no requirements for display of the nominal trajectory. The NGS, however, is less accurate than the PMGS; it is not flexible; it is not fuel-optimal if large disturbances are present; and the pilot work load is higher than that of the PMGS. Thus, the basic tradeoff between the two schemes is between an accurate, fuel-optimal, flexible, low work load scheme and a manual guidance scheme which is simple and which has low computer and display requirements.

Typical terminal errors with the PMGS were 1700 feet in altitude and 0.007 degree in flight-path angle. The corresponding errors with the NGS were 2200 feet and 0.17 degree.

Table 3-6. Comparison of the Nominal and Predictive Model Guidance System

Vehicle Stage	Guidance Scheme	Pilot Workload	Fuel Requirement	Complexity		Mission Flexibility	Terminal Error
				Computer	Display (CRT)		
Stage 1	MGS	Low	Near Optimum (function of off-nominal I. C., external disturbances and parameter variations)	Low-if nominal is not stored in computer Moderate-if nominal is stored in computer	Moderate-if CRT is used to display nominal Low-otherwise	No	
	PMGS	Moderate	Near Optimum (function of approximations in fast-time model)	Moderate	Moderate	Yes	
Stage 2	NGS	High	Non-optimum	Low	Moderate-if CRT is used to display nominal Low-otherwise	No	Typical Errors: Altitude = 1700 ft Flight-path angle 0.007°
	PMGS	Low	Optimum	Moderate	Moderate	Yes	Typical Errors: Altitude = 2200 ft Flight path angle = 0.17°

SECTION 4
PRELIMINARY SYSTEM APPROACHES

4.1 GENERAL

Two possible manual guidance systems are proposed on the basis of results from the present study, however, the hybrid scheme described here is the recommended system. This selected system approach has the following desirable characteristics:

- Good accuracy
- Low pilot work load
- Minimum fuel requirements
- Good mission flexibility
- Display and computation requirements are not excessive

4.2 THE HYBRID SYSTEM

The hybrid system is a combination of both manual guidance schemes: the Nominal Guidance System during the first stage and the Predictive Model Guidance Scheme during the second stage. This combination of two guidance schemes, one for each stage, is similar to the approach taken for the boost stage of the Saturn-V, i.e., guide by following a nominal trajectory during first stage and then use a closed-loop fuel-optimal guidance scheme during the second stage.

The hybrid system incorporates the advantages of both guidance schemes. Due to the "basic" path feature(1) of the optimal nominal trajectory in the atmosphere, the concept of steering back to the optimal nominal trajectory yields a resulting trajectory which is close to fuel-optimal. The PMGS is more complex if used in the first stage due to the increase in sensitivity of the terminal conditions to the optimization parameters and the increase in the complexity of the predictive model. The pilot work load in the NGS is low in the first stage since a programmed nominal control with small adjustments works sufficiently well. In view of these advantages for the NGS and disadvantages of the PMGS, the NGS is recommended as a manual guidance scheme during the first stage.

In the second stage, the sensitivity of the terminal conditions to the optimization parameters is not a problem. Also, the predictive model for this vacuum phase is fairly simple and presents no computation problems. These were the two disadvantages to the use of the PMGS in the first stage. The PMGS is fuel-optimal since the scheme generates repetitively a predicted fuel-optimal trajectory from its present state. It is flexible in that the target specifications can be changed during the flight. It was shown in 3.4 that the terminal error produced with the PMGS is more than 10 times lower than that with the NGS. In view of these advantages, for the PMGS, it is recommended as a manual guidance scheme during the second stage.

4.3 THE NOMINAL GUIDANCE SYSTEM

The Nominal Guidance System employs the NGS during both stages. The one advantage of this scheme over the PMGS for use in the second stage is the computer and display requirements. If an overlay-presentation of the nominal trajectory on the CRT face is used rather than storing the nominal in the onboard guidance computer, then the computer requirements are zero. The display requirements, assuming a plastic overlay, consist of the vehicle present state displayed on a CRT along with a meter-type presentation of the present state of the vehicle. If the nominal trajectory is stored in the onboard computer, then the display requirements are basically the same as the PMGS during second stage.

The Nominal Guidance System sacrifices the accuracy and flexibility of the Hybrid System for a decrease in computation requirements.

4.4 SUMMARY AND RECOMMENDATIONS

Figure 4-1 summarizes the two proposed manual guidance system approaches. The advantages of each system are also presented. Although the hybrid system requires more computer requirements in the second stage than does the nominal guidance system, it is advantageous to add this computer complexity to reduce the errors in the desired terminal conditions and flexibility.

Stage 1	Stage 2
Nominal Guidance Scheme	Predictive Model Guidance Scheme

- Accurate
- Low pilot work load
- Fuel-optimal
- Mission flexibility
- Moderate computer and display requirements

Hybrid Manual Guidance System
(a recommended approach)

Stage 1	Stage 2
Nominal Guidance Scheme	Nominal Guidance Scheme

- Low computer requirements
- Low display requirements

Nominal Guidance System

Figure 4-1. Proposed Manual Guidance Systems

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APPENDIX A
REAL-TIME MODEL SIMULATION

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REAL-TIME MODEL SIMULATION

A flight-path coordinate system was used in the real-time simulation of the ROT. The force diagram in this coordinate system is shown in Figure A1. The equations of motion including the effects of wind disturbances are as follows:

$$\dot{R} = \frac{r_o}{r} V \cos \gamma$$

$$\dot{r} = V \sin \gamma$$

$$\dot{V} = \frac{T}{m} \cos(\theta - \gamma) - \frac{D}{m} \cos \epsilon - \frac{L}{m} \sin \epsilon - g \sin \gamma$$

$$\dot{\gamma} = \frac{T}{mV} \sin(\theta - \gamma) + \frac{L}{mV} \cos \epsilon - \frac{D}{mV} \sin \epsilon - \left(\frac{g}{V} - \frac{V}{r}\right) \cos \gamma$$

$$\dot{m} = -\beta$$

where

$$T = c^* \beta$$

$$D = q(h, V) S C_D$$

$$L = q(h, V) S C_L$$

$$\sin \epsilon = V_w \sin \frac{\gamma}{V_A}$$

$$\cos \epsilon = \frac{V - V_w \cos \gamma}{V_A}$$

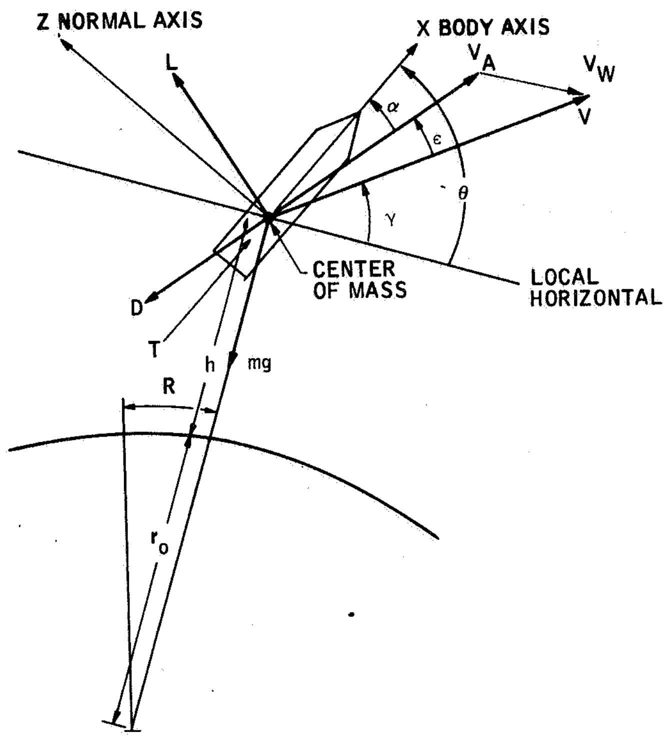

Figure A1. Force Diagram

$$V_A^2 = V^2 + V_w^2 - 2VV_w \cos \gamma$$

$$q = \frac{1}{2} \rho(h) V^2$$

$$\rho(h) = \rho_o e^{-h/\lambda}$$

$$h = r - r_o$$

$$C_D = C_{D_o}(M) + C_{L_\alpha}(M) \alpha^2$$

$$C_L = C_{L_\alpha}(M) \alpha$$

$$M = \frac{V}{a(h)}$$

$$\alpha = \theta - \gamma - \varepsilon$$

$$g = g_o \left(\frac{r_o}{r} \right)^2$$

The following constants are given for the model:

c^*_1 = 8,417 ft/sec

β_1 = 216 slugs/sec

c^*_2 = 14,490 ft/sec

β_2 = 21.05 slugs/sec

t_s = 136.7 sec

m_o = 4.7124×10^4 slugs

m_2 = 9.1078×10^3 slugs

S = 5,083 ft^2

ρ_o = 0.002377 $slugs/ft^3$

λ = 23,600 ft

g_o = 32.17 ft/sec^2

The nominal 100-nm circular target orbit is specified by the terminal values of r, V, and γ.

$$r_f = 21.53402 \times 10^6 \text{ ft}$$

$$V_f = 25,570.5 \text{ ft/sec}$$

$$\gamma_f = 0$$

The total load factor limited to 3 g's. This was satisfied by throttling the engines whenever the constraint was met. This occurs for about 5 seconds at the end of the first stage and for about 30 seconds at the end of the second stage. Otherwise, the maximum value of the mass flow rate β was chosen.

The aerodynamic data used in the model are given in Figure A2. Figure A3 presents the speed of sound versus altitude and atmospheric density versus altitude models which were used in the model. The wind profiles used in this study were developed using the standard non-directional synthetic wind concept. The effective wind has a horizontal velocity in the orbit plane and as shown in Figure A1, this wind adds a positive angle ϵ to the angle of attack α. The statistics of the winds are for May through November launches from Cape Kennedy. Figure A4 presents the 50th, 80th, 90th, 95th and 99th percentile synthetic wind profile envelopes. Three representative winds were used in the study: the case with no wind and the 50th and 99th percentile synthetic wind profile envelopes.

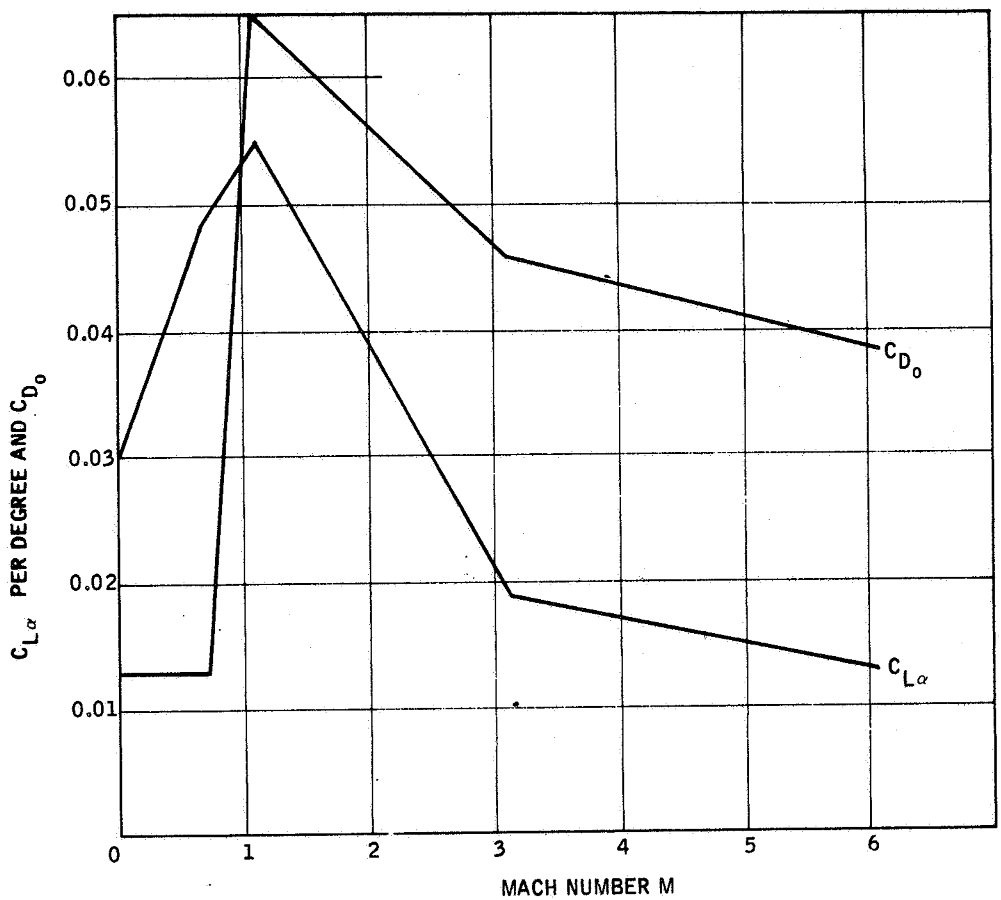

Figure A2. Aerodynamics Coefficients

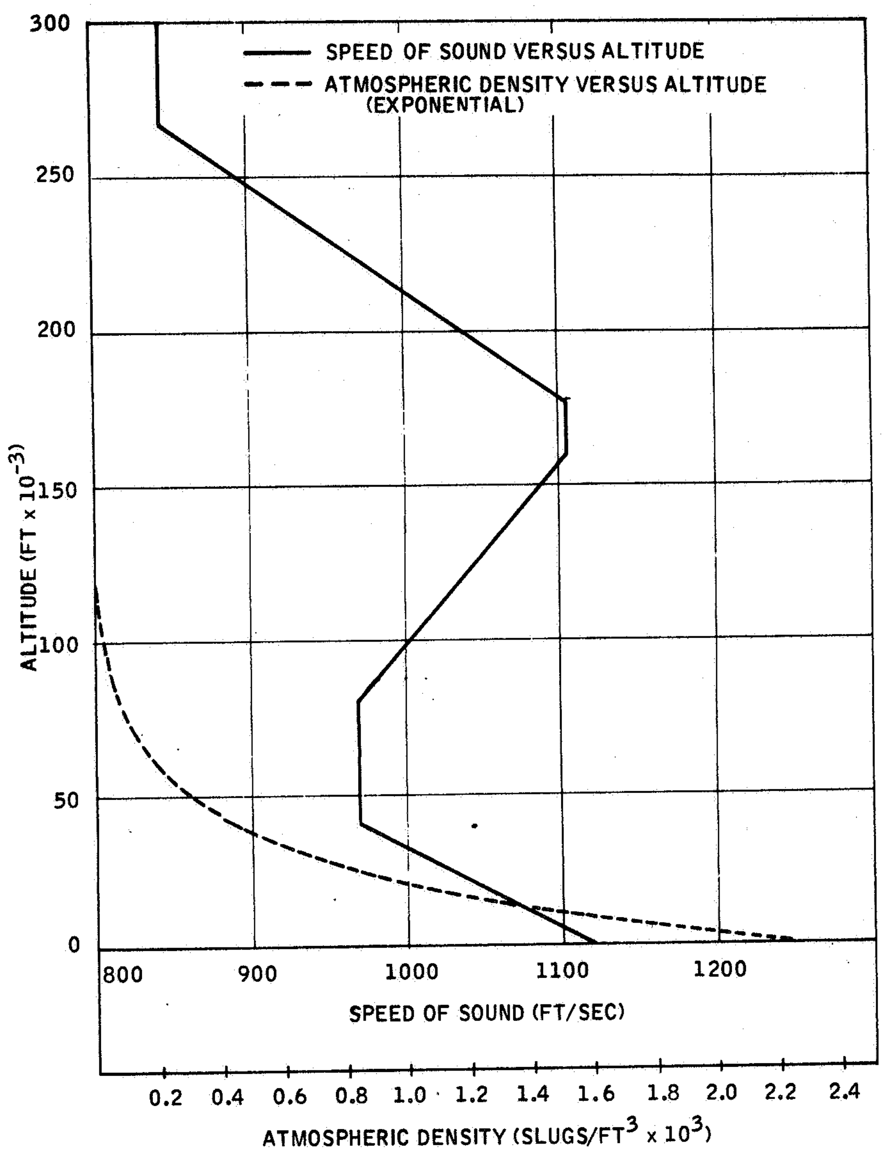

Figure A3. Speed of Sound and Atmospheric Density versus Altitude

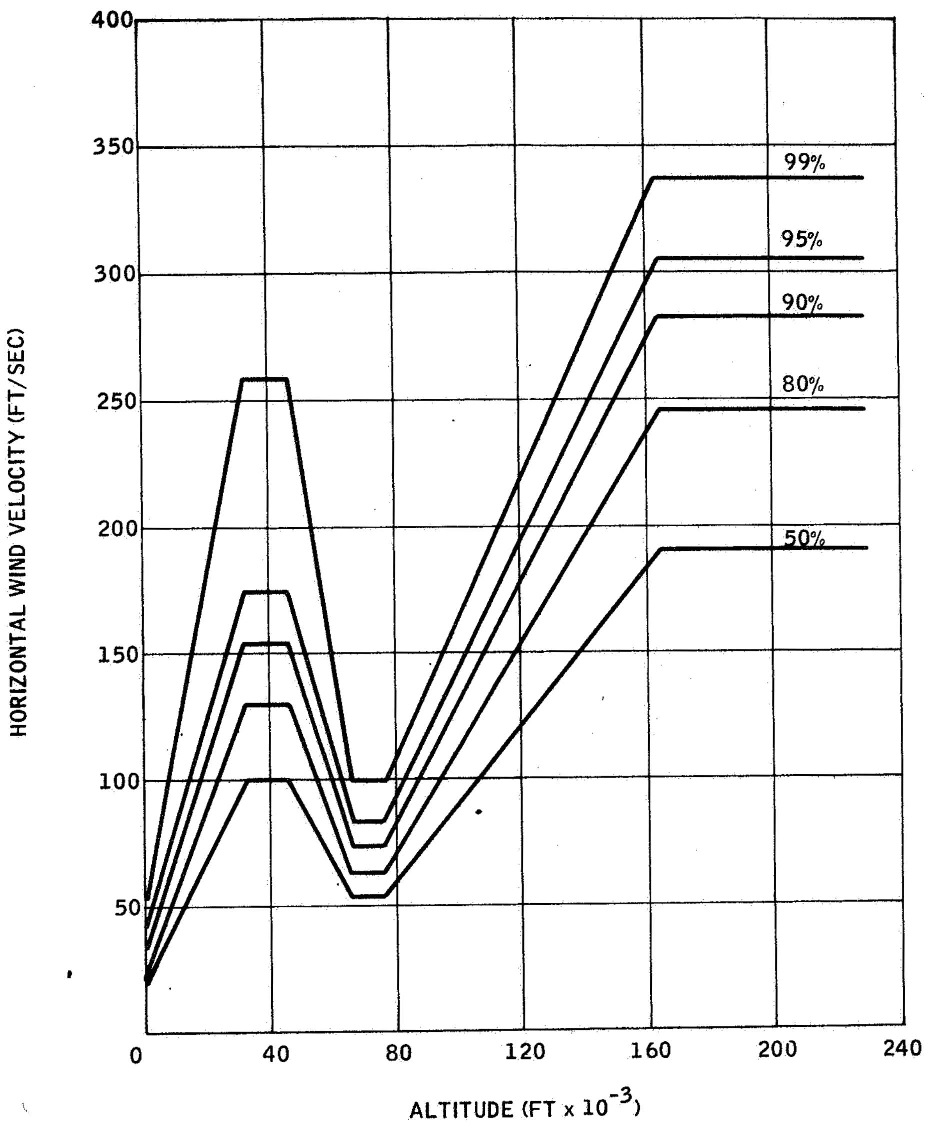

Figure A4. Wind Speed Envelopes

APPENDIX B
COORDINATE SYSTEMS FOR FAST-TIME PREDICTION MODEL

APPENDIX B
COORDINATE SYSTEMS FOR FAST-TIME PREDICTION MODEL

This appendix describes three different coordinate systems considered for the fast-time model. The system equations, adjoint equations, the equation for the optimal steering angle, and specifications for the target orbit are determined for each case. On the basis of using a flight-path coordinate system for the real-time simulation, the necessary transformations from the fast-time model to the real-time model are determined. In all three cases, the equations developed are valid only for the second stage. It is assumed that the vehicle is outside the sensible atmosphere in the second stage. The results are summarized in Table B1.

I. THE FLIGHT PATH COORDINATE SYSTEM

The flight path coordinate system is shown in Figure B1.

System Equations

$$\dot{R} = \frac{r_o}{r} V \cos \gamma$$

$$\dot{r} = V \sin \gamma$$

$$\dot{V} = \frac{T}{m} \cos \alpha - g \sin \gamma$$

$$\dot{\gamma} = \frac{T}{mV} \sin \alpha - \left(\frac{g}{V} - \frac{V}{r}\right) \cos \gamma$$

$$\dot{m} = - \beta$$

Table B1. Comparison of Predictive Model Coordinate Systems

Coordinate System	Relative Accuracy of Model	Relative Complexity of System Equations	Relative Complexity of Adjoint Equations	Relative Complexity of Transformations	Relative Expected Difficulty of Man's Task of Choosing I. C.'s on Adjoint Equations
I	High	High	High	None required	High
II	High	Medium	Medium	Medium	High
III	Medium	Low	Can be solved in closed form	High	Low

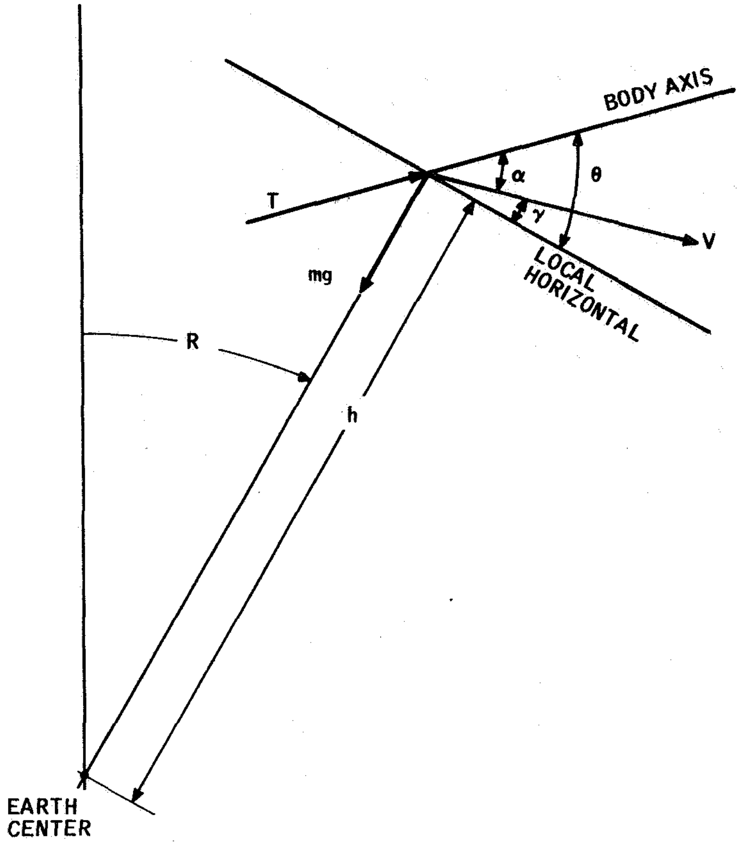

Figure B1. Flight Path Coordinate System

Since this coordinate system for the fast-time model is identical with the real-time simulation, no coordinate transformations are required. From previous work on trajectory optimization, it is known that the control variable, α, is small ($|\alpha| < 15°$) for the nominal trajectory. Thus small-angle approximations to cos α and sin α are a legitimate approximation. Another simplification consists in using a constant value for g. The value of this constant is an average between the value of gravity at staging and at the terminal conditions.

Adjoint Equations

$$\dot{p}_1 = 0, \quad p_1(t_f) = 0 \text{ implies } p_1(t) = 0$$

$$\dot{p}_2 = p_4 \frac{V}{r^2} \cos \gamma$$

$$\dot{p}_3 = -p_2 \sin\gamma + p_4 \left[\frac{T}{mV^2} \sin\alpha - \left\{ \frac{g}{V^2} + \frac{1}{r} \right\} \cos\gamma \right]$$

$$\dot{p}_4 = -p_2 V \cos\gamma + p_3 g \cos\gamma - p_4 \left\{ \frac{g}{V} - \frac{V}{r} \right\} \sin\gamma$$

In deriving the adjoint equations, it is assumed that the term g in the system equations is constant. The subscripts 1, 2, 3, and 4 refer to R, r, V, and γ respectively.

Boundary Conditions

The boundary conditions on the adjoint equations are $p_1(t_f) = 0$ and $p_2(t_f)$, $p_3(t_f)$, and $p_4(t_f)$ unspecified.

Optimal Control (minimum time)

$$\alpha = \tan^{-1} \left[\frac{p_4}{p_3 V} \right]$$

Target Specifications

$$r(t_f) = r_f$$

$$V(t_f) = V_f$$

$$\gamma(t_f) = \gamma_f$$

II. LOCAL VERTICAL COORDINATE SYSTEM

The local vertical coordinate system is shown in Figure B2.

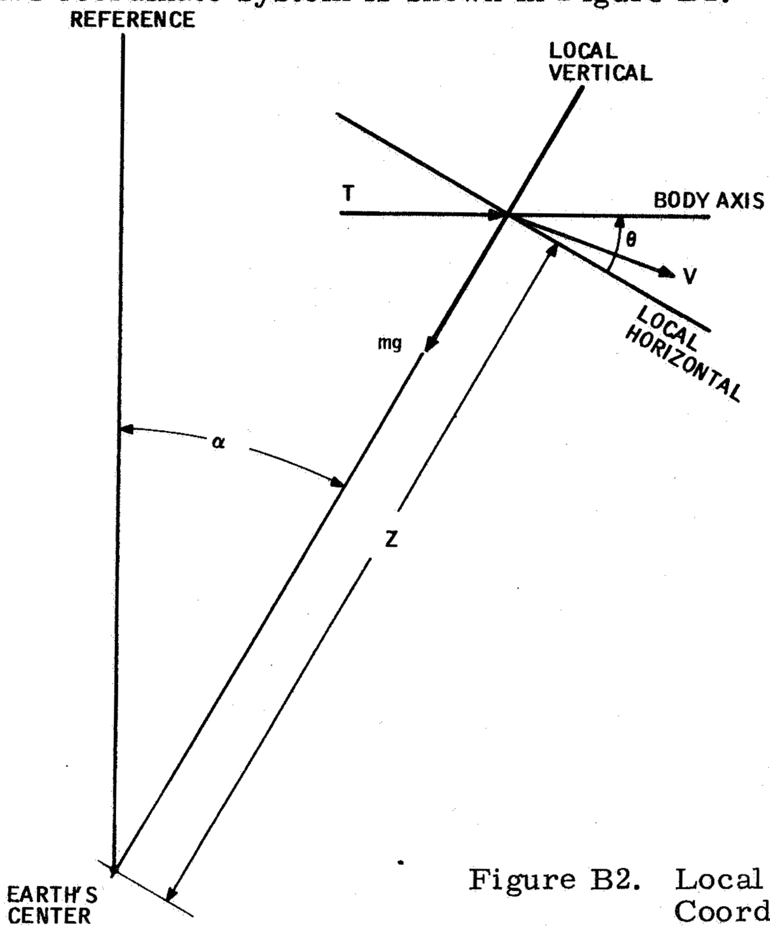

Figure B2. Local Vertical Coordinate System

System Equations

For planar motion, one of the coordinates is defined along the local vertical and the other along the local horizontal. The resulting equations of motion are:

$$\dot{x} = r_o \frac{V_x}{z}$$

$$\dot{z} = V_z$$

$$\dot{V}_x = \frac{T}{m} \cos \theta - \frac{V_x}{Z} V_z$$

$$\dot{V}_z = \frac{T}{m} \sin \theta - g + \frac{V_x^2}{Z}$$

$$\dot{m} = - \beta$$

Adjoint Equations

The subscripts 1, 2, 3, and 4 refer to x, z, V_x, and V_z.

$$\dot{p}_1 = 0, \quad p_1(t_f) = 0 \text{ implies } p_1(t) = 0$$

$$\dot{p}_2 = p_1 r_o \frac{V_x}{Z^2} - p_3 \frac{V_x V_z}{Z^2} + p_4 \frac{V_x^2}{Z^2}$$

$$\dot{p}_3 = - p_1 \frac{r_o}{Z} + p_3 \frac{V_z}{Z} - 2p_4 \frac{V_x}{Z}$$

$$\dot{p}_4 = -p_2 + p_3 \frac{V_x}{Z}$$

As in case I, g is assumed constant in the derivation of the adjoint equations.

Boundary Conditions

The terminal conditions are $p_1(t_f) = 0$ and $p_2(t_f)$, $p_3(t_f)$, and $p_4(t_f)$ unspecified.

Optimal Control (minimum time)

$$\theta = \tan^{-1} \frac{p_4}{p_3}$$

Target Specifications

$$z(t_f) = r_f$$

$$\left[V_x^{\,2}(t_f) + V_z^{\,2}(t_f) \right]^{1/2} = V_f$$

$$V_z(t_f) = 0$$

Transformations

Since the coordinate system for the real-time model differs slightly from this proposed coordinate system for the predictive model, transformations are required to transform the present state of the vehicle into initial conditions for the predictive model. These are:

$$x = R$$

$$z = r$$

$$V_x = V \cos \gamma$$

$$V_z = V \sin \gamma$$

If the display of the predictive model trajectory is made in the coordinate system of the real-time model, then the following additional transformations are required:

$$V = \sqrt{V_x^{\ 2} + V_z^{\ 2}}$$

$$\gamma = \tan^{-1} \frac{V_z}{V_x}$$

III. INERTIAL COORDINATE SYSTEM - FLAT EARTH APPROXIMATION

The inertial coordinate system is shown in Figure B3.

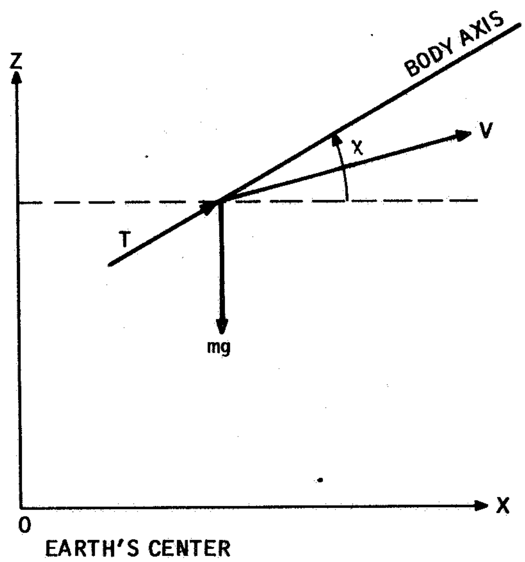

Figure B3. Inertial Coordinate System

System Equations

$$\dot{x} = V_x$$

$$\dot{z} = V_z$$

$$\dot{V}_x = \frac{T}{m} \cos \chi$$

$$\dot{V}_z = \frac{T}{m} \sin \chi - g$$

$$\dot{m} = - \beta$$

Adjoint Equations

The subscripts 1, 2, 3, and 4 refer to x, z, V_x, and V_z respectively.

$$\dot{p}_1 = 0$$

$$\dot{p}_2 = 0$$

$$\dot{p}_3 = -p_1$$

$$\dot{p}_4 = -p_2$$

In writing these adjoint equations, the value of g is assumed constant.

Boundary Conditions

The boundary conditions on the adjoint variables are:

$$p_1(t_f) = 0$$

$p_2(t_f)$, $p_3(t_f)$, $p_4(t_f)$ unspecified;

hence, the solutions for the adjoint variables are:

$$p_1(t) = 0$$

$$p_2(t) = p_{20}$$

$$p_3(t) = p_{30}$$

$$p_4(t) = -p_{20}t + p_{40}$$

where p_{20}, p_{30}, and p_{40} are the unspecified initial conditions.

Optimal Control (minimum time)

$$\chi = \tan^{-1} \frac{p_4(t)}{p_3(t)}$$

$$= \tan^{-1} \left\{ \frac{p_{40}}{p_{30}} - \frac{p_{20}t}{p_{30}} \right\}$$

$$= \tan^{-1} \{A + B\,t\}$$

The constants A and B must be chosen so that the resulting solution of the system equations passes through the target conditions.

Target Specifications

$$x^2(t_f) + z^2(t_f) = r_f^2$$

$$V_x^2(t_f) + V_z^2(t_f) = V_f^2$$

$$x(t_f)\,V_x(t_f) + z(t_f)\,V_z(t_f) = 0$$

Transformations

Since the coordinate system for the real-time model differs from this proposed coordinate system for the predictive model, transformations are required to determine the initial conditions for the predictive model. These are:

$$x = r \sin \frac{R}{r_o}$$

$$z = r \cos \frac{R}{r_o}$$

$$V_x = V \cos \left(\gamma - \frac{R}{r_o} \right)$$

$$V_z = V \sin \left(\gamma - \frac{R}{r_o} \right)$$

If the predictive model trajectory is displayed using the coordinate system of the real-time model, then the following additional transformations are required:

$$r = \sqrt{x^2 + z^2}$$

$$V = \sqrt{V_x^{\,2} + V_z^{\,2}}$$

$$\gamma = \sin^{-1} \left\{ \frac{xV_x + zV_z}{rV} \right\}$$

$$\theta = \chi + \tan^{-1} \frac{x}{z}$$

Figure B4 shows both the inertial and flight path coordinate systems.

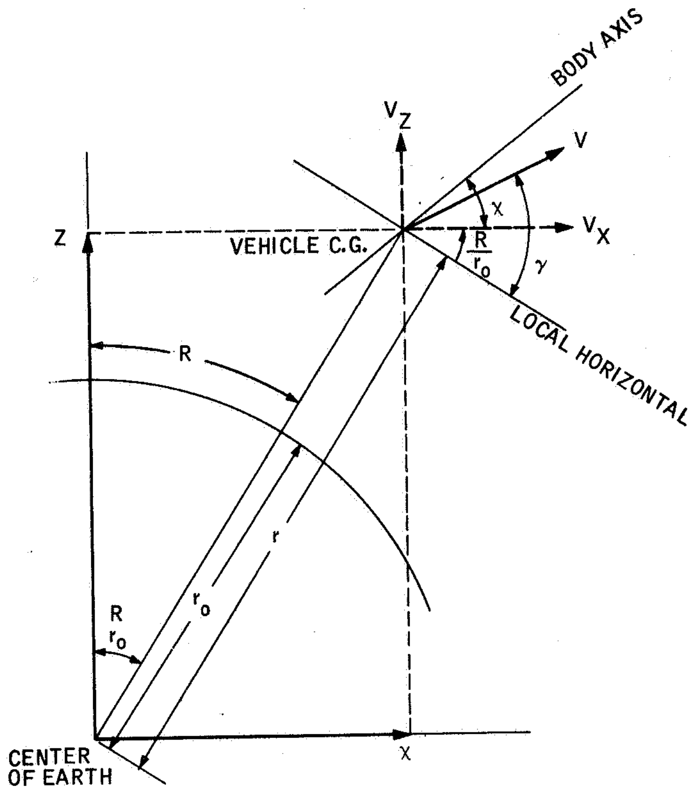

Figure B4. Inertial and Flight Path Coordinate System

APPENDIX C
EXPERIMENTAL EQUIPMENT

APPENDIX C
EXPERIMENTAL EQUIPMENT

COMPUTER

The computer used for the numerical portions of the study was the SDS 9300 digital computer combined with a scope display and analog/digital linkage system. The SDS 9300 computer is a high-speed, medium-word-length machine specifically designed for hybrid simulations, real-time control, and rapid scientific computation. Its characteristics include:

- 24-bit word plus parity bit
- 48-bit word for floating point arithmetic
- 24K word memory, all directly addressable in octal locations starting at 00000
- 0.7-microsecond memory access time, 1.75-microsecond cycle time
- 1.75-microsecond add time fixed point, 14.0-microsecond floating point
- 7.0-microsecond multiply time fixed point, 12.25-microsecond floating point

The display unit connected to the 9300 hybrid facility is a DD40. This 19-inch CRT is capable of plotting 120,000 points per second, 80,000 alphanumeric characters per second, or 20,000 vectors per second. An Adage 770 link and analog computer together form the analog/digital linkage system. Inputs and outputs are terminated on the A/D console patch for easy access.

In this study, the digital computer was used to provide a real-time simulation of the ROT vehicle dynamics. In one of the manual guidance schemes studied, the digital computer was also used to simulate a fast-time model of the ROT vehicle. Adjustments to the steering program were made in real time by the operator by a potentiometer through the A/D link. Other inputs to the program, such as variable winds, off-nominal initial conditions, or variations in the vehicle parameters, were made by typewriter. Figure C1 shows a typical man-computer-display combination.

DISPLAYS

Displays were devised to investigate the information requirements for effective manual guidance. All displays used in the study were two-dimensional, CRT presentations generated by the digital computer. Two basic types of presentations were used. One type was a display of a trajectory, for instance, the altitude versus velocity of the complete nominal trajectory or the altitude versus velocity of the predicted trajectory. The second type of display presented information in a digital meter form. This type of presentation was used to display the present status of the flight. Figure C2 shows typical displays used in the nominal guidance scheme and Figure C3 typical displays used in the predictive model scheme. The symbol 0 in both figures represents the present vehicle state, and the symbol x in Figure C2 represents the predicted vehicle state.

PROGRAMS

Computer programs were written for this study in SDS Fortran IV. Logic flow diagrams and listings of these programs are contained in Part II of this report. One program, employing a manual nominal guidance scheme, contains the equations for the vehicle dynamics and the display generation instructions. The second program, using a predictive model manual guidance scheme, contains the vehicle equations for both the real time and fast-time models as well as the display generation instructions for the associated displays.

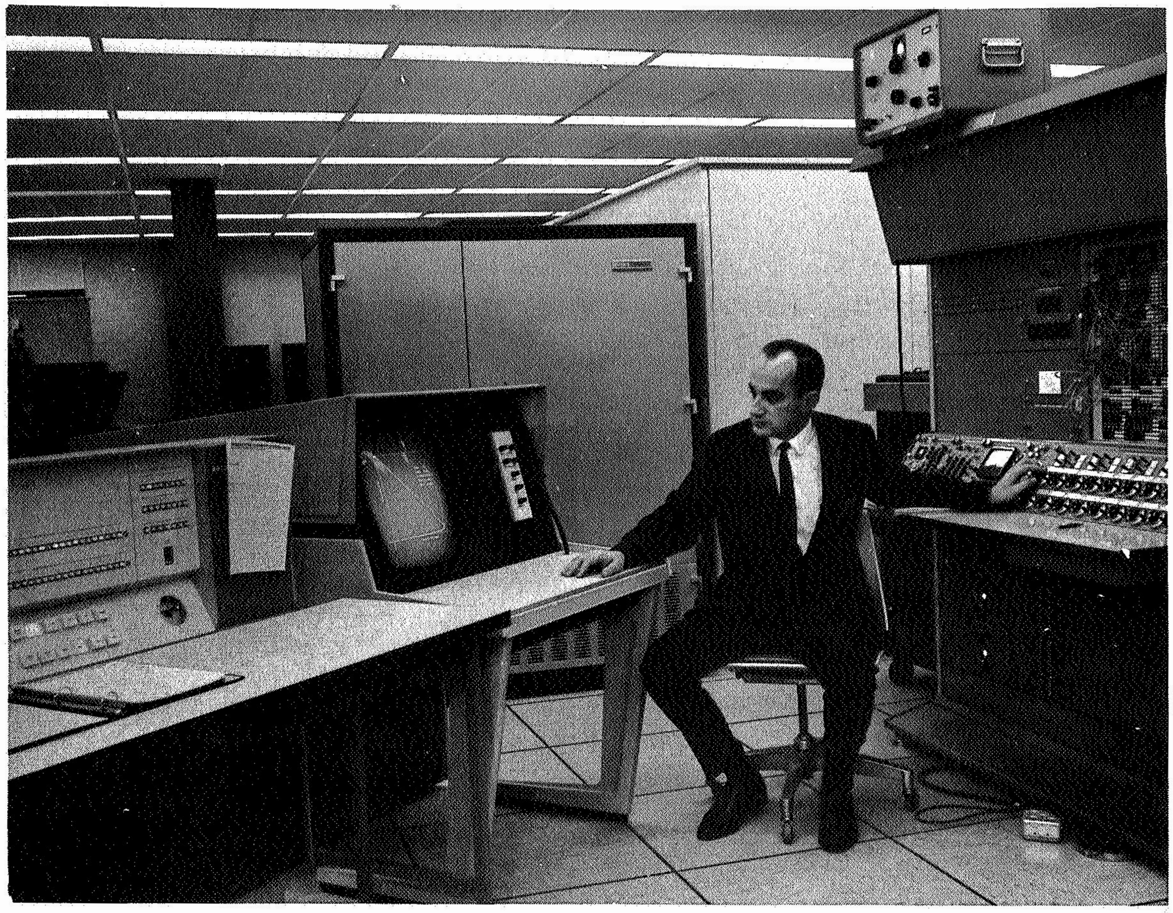

Figure C1. Man Computer Display Simulation System

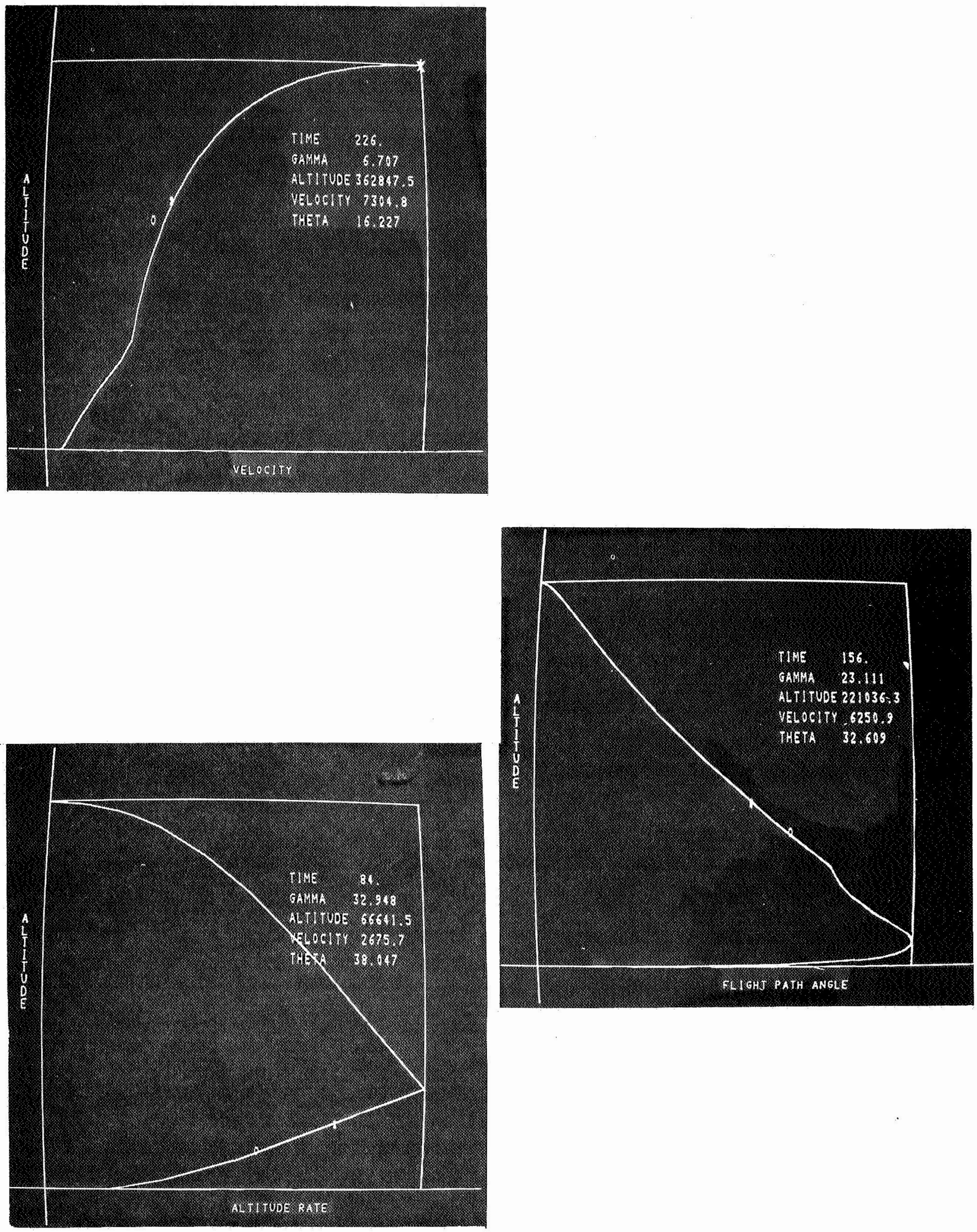

Figure C2. Displays for Manual Nominal Guidance Scheme

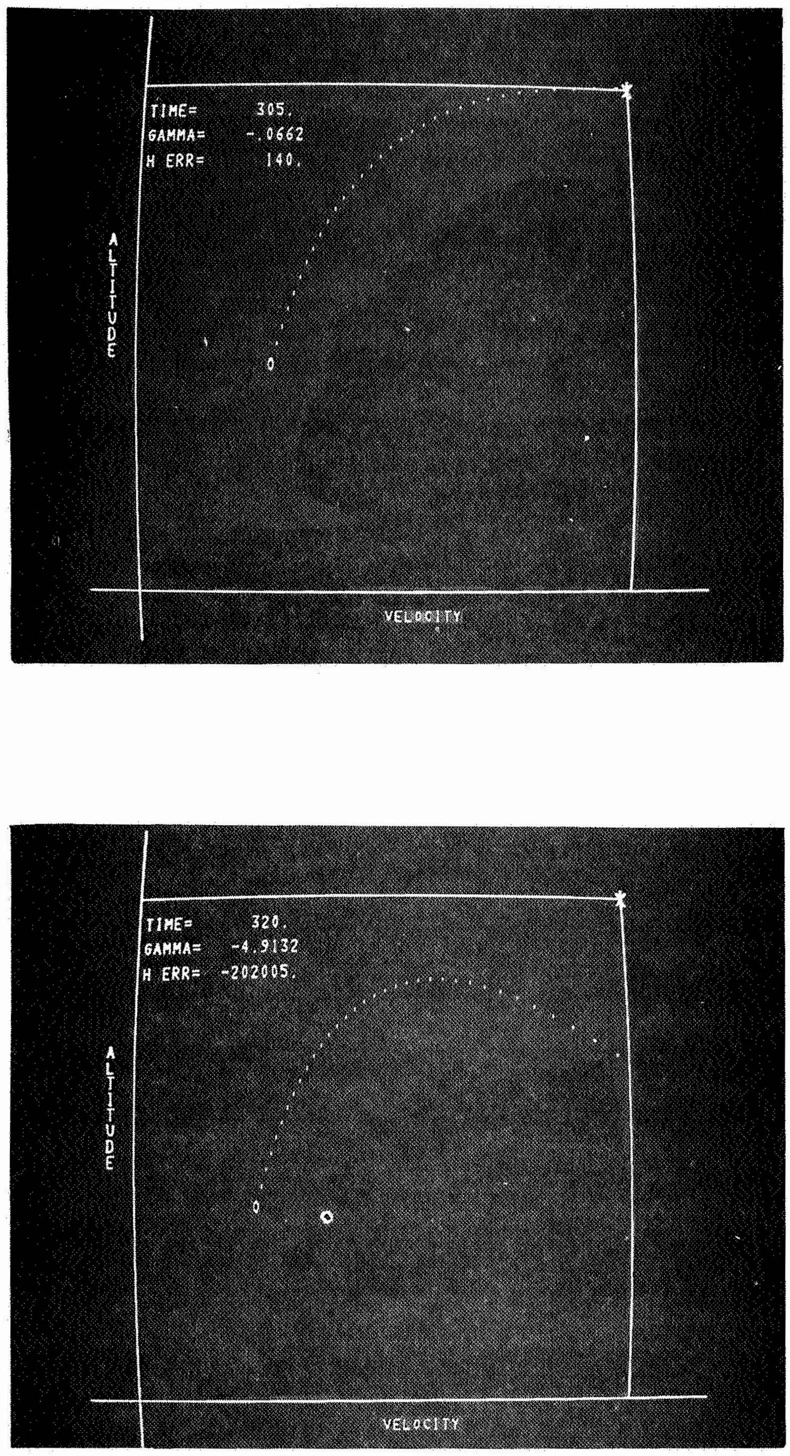

Figure C3. Displays for Manual Predictive Model Guidance Scheme