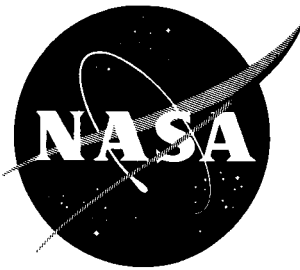


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TECHNICAL NOTE

D-979

GUIDANCE AND CONTROL DURING DIRECT-DESCENT

PARABOLIC REENTRY

By

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON

November 1961

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GUIDANCE AND CONTROL DURING DIRECT-DESCENT

PARABOLIC REENTRY *

By Edwin C. Foudriat and Rodney C. Wingrove

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SUMMARY

The results of studies of four reentry guidance and control techniques for the energy management of vehicles returning to the earth at escape speeds are compared in this paper. The reentry trajectories are constrained to those of direct descent, that is, where the vehicle does not leave that portion of the atmosphere where useful aerodynamic forces are available after its initial entry. The guidance techniques compared are:

- (1) A piloted simulator study using reference trajectory techniques
- (2) An automatic controller using reference trajectory techniques
- (3) A predictor system employing linear prediction (perturbation) techniques
- (4) A repetitive prediction system employing rapid-time computer techniques

The results indicate that none of the procedures provide nearly optimum range capability when maximum down range is required. The repetitive prediction system was shown to obtain excellent control of the initial peak deceleration and, therefore, better minimum range control. The piloted procedure indicates that the pilot with experience and a good display of flight information can capably perform the reentry guidance maneuvers and energy management functions. Actually, the procedure used by the pilot illustrates the manner in which the maximum ranges can be obtained. The other two systems, that is, the automatic reference-trajectory control and the linear prediction technique, indicate that these procedures are applicable to control of reentry from parabolic orbit.

*This report was one of the papers presented at the NASA-Industry Apollo Technical Conference, Washington, D.C., July 18-20, 1961.

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INTRODUCTION

It is desirable that the conclusion of a successful lunar or deep space mission be a reentry from a parabolic orbit to a prescribed landing point on the earth's surface.

From the beginning of the space age intensive study has been conducted on the reentry procedures, range capability, and heating of reentry vehicles (refs. 1 to 3). Reference 4 contains an excellent bibliography of the recent work in the area related to the reentry capability from escape speeds. The area of energy management, that is, the procedure by which the reentry capability is used to attain a desired landing point, has also been studied intensively for orbital reentry conditions (refs. 5 to 11).

With the advent of the lunar and outer space missions, recent studies have been reported on reentry energy management procedures from parabolic reentry conditions (refs. 11 to 14). In addition to these studies, other procedures have been under study.

The purpose of this paper is to review the earlier studies, indicate information obtained from recent programs, and indicate the areas where extension of the range capabilities may be possible.

Four studies are reported on in this paper. The first of these is a piloted simulator study; where the pilot's intelligence and learning capability are used to provide the guidance logic and control commands. Most of the information provided to the pilot may be derived from an inertial reference navigation system. The second program is an automatic control study using a reference trajectory procedure. Here, the control feedbacks are developed for the successful operation of the system and the range capability illustrated. The last two systems discussed in this paper include the use of prediction to obtain control of range. The first of these employs a linear predictor which combines stored trajectories and influence coefficients to determine the final range error (ref. 11). The second uses a rapid-time analog computer to extrapolate the range capability from the present conditions. In this system a pilot is provided this information on a display panel in order to control the vehicle to its desired destination (ref. 12).

Only direct-descent reentry procedures have been discussed in this paper. Although for extreme extensions of range skip out is required, a large range for direct-descent trajectories is available if proper procedures to avoid skip out are employed. These procedures will be discussed and the range available indicated.

SYMBOLS

A	acceleration, ft/sec ²
g	deceleration, g units
h	altitude, ft
K	gain factor
K ₁	gain factor in altitude feedback loop
K ₂	gain factor in acceleration feedback loop
K ₃	gain factor in range feedback loop
L/D	lift-drag ratio
R	range, statute miles
$\bar{u}$	nondimensional velocity
V	velocity, ft/sec
$\delta()$	variation in quantity from the reference
γ_0	initial flight-path angle
ϕ	roll angle, deg
ϵ_R	predicted error in range

Subscripts:

min	minimum value of quantity
max	maximum value of quantity
r	reference trajectory

DEFINITION OF RANGE CAPABILITY FOR

DIRECT-DESCENT TRAJECTORY

The direct-descent trajectory is defined as one for which a vehicle upon entering the earth's atmosphere does not exit or skip out. The restrictions upon the range of such trajectories can best be classified with the help of figure 1. The vehicle trajectory must be controlled outside the atmosphere so that it penetrates at an entry angle steep enough to decelerate but shallow enough to avoid the limit of human tolerance. Once in the atmosphere the minimum range is restricted by the ability of the human occupant to tolerate sustained high-level deceleration. For this paper, this limit has been arbitrarily set at $10g$ in order that the work by the various guidance investigators can be compared. A detailed discussion of the actual tolerance requirements is presented in reference 15. The maximum range is limited by a trajectory which reaches the edge of the usable atmosphere, or about 300,000 feet. These two trajectories then define the down-range capability for the direct-descent reentry. In addition to down-range control it will generally be necessary to change the vehicle's great-circle course. This is designated as cross- or lateral-range capability. Thus, the range capability of any system is the combination of the down and cross ranges available and is a factor of major importance in judging the energy management system.

In order to obtain additional range, it is possible to employ skip-out procedures. Here the maximum range is limited only by the requirement to avoid the Van Allen regions of high-intensity radiation. It should be noted that extreme ranges are available if controlled skip out is used. However it is indicated in reference 4 that the sensitivity of such maneuvers to the velocity and flight path can be extremely large under certain conditions. As noted previously skip-out procedures are not discussed herein.

PILOT SIMULATOR STUDIES

The piloted simulator program was conducted on a fixed-base simulator. The purpose of the study program was to determine the ability of the pilot to fly a reentry vehicle having a low lift-drag ratio, to determine the requirements for instrument display, and to obtain procedures which would permit him to use his intelligence and learning abilities to pilot the vehicle to the desired destination.

The instrument display used for this study is shown in figure 2. The control instrument used to display vehicle attitudes and body rates

is the three-axis "8" ball (this is the instrument in the center of the panel of fig. 2). This single instrument displays yaw, pitch, and roll (the Euler angles) and the body angular rates. The lift forces on the vehicle are indicated by the angle-of-attack and sideslip meters to the left of the "8" ball. The vehicle is capable of trimming from 0° to 40° angle of attack and $\pm 20^\circ$ in sideslip. This angle-of-attack range corresponded to a lift-drag ratio of 0 to 0.58. The vehicle's velocity, altitude, and range to go (distance to the target) are indicated in the column of instruments to the right of the "8" ball. The altitude rate was found to be extremely useful and is indicated on the dial below the "8" ball. An ILS type of instrument which shows down- and cross-range-to-go errors (directly above the "8" ball) is used by the pilot to obtain the desired direction of bank angle and is required for precision maneuvering near the target site. The instrument at the bottom is a memory oscilloscope used in the manner of an x-y plotter. Altitude was plotted on the vertical scale with range to go plotted on the horizontal scale. In addition to plotting the vehicle's past history a reference trajectory curve is traced on the face of the instrument. The pilot is thus able to correlate the past history of the flight with respect to the target and the reference to which he is to fly.

The pilot was provided with a two-axis pencil-type controller and rudder pedals. In addition, trim wheels operated by the left hand were available for pilot control. The damping was provided by auxiliary feedback controls with a minimum damping ratio of at least $\delta = 0.2$. Roll control was provided by proportional reaction control with a maximum acceleration of 5° per second squared and a feedback time constant of 1 second.

The piloting procedure will be described with the aid of figure 3 which shows the vertical and horizontal profile of a short- and a long-range pilot-controlled mission. In both missions the initial phase of the reentry was the same. For the short-range case the pilot remained at approximately the pullout altitude until he reached the reference trajectory. By remaining at the lower altitude the pilot was able to reduce the velocity more rapidly. As the reference was reached the pilot started the descent to the target. Actually, in the case shown in figure 3 the pilot overshot the reference and had to dive more steeply to reach the target.

For the long-range mission the pilot did not remain at the lower altitude but started a pullup which he terminated at about 250,000 feet. The proper pullup procedure is very necessary in order to obtain long ranges and must be done with some care in order to avoid skip out. The procedure was to start the pullup at a velocity between 30,000 and 32,000 ft/sec. For the pullup a rate of climb of 800 ft/sec was established. At an altitude of 230,000 feet the pilot rolled the vehicle over and used all the lift in the negative direction in order to avoid

skip out. When done properly this reduced the rate of climb to zero between 250,000 and 260,000 feet with a velocity between 25,000 and 27,000 ft/sec. At this condition the pilot could be considered at the edge of the atmosphere with near superorbital velocity and with the capability of extremely long range. This has been termed the coasting phase as indicated in figure 3. As can be seen from the figure the pilot initiated the rate of descent when he reached the reference trajectory.

The pilot had no trouble correcting the cross range. When lift was not used vertically the pilot rolled the vehicle to 90° to reduce the cross range. For these runs the roll was initiated at the bottom of the initial pullout as indicated by the cross-range-error reduction. The remainder was eliminated during the coasting and reference trajectory phases.

It should be indicated that the pilot procedure of flying a reference trajectory is similar to the automatic control procedure to be discussed. During the initial portion of the reentry, the pilot did not use the error between the present position and the reference trajectory to direct his control inputs. Instead he used a procedure which when properly executed placed him in a position where he was able to attain the reference trajectory once the initial or superorbital phase was completed. This point has an important bearing on the use of reference trajectory for control as will be indicated subsequently.

Figure 4 shows the range capability of a skilled pilot for three entry angles which include the steeper two-thirds of the reentry corridor. The shaded area indicates the maneuver range for all entry angles studied. The ranges between 2,200 and 3,500 miles are obtained when the pullup maneuver is made so that a velocity of approximately 25,000 ft/sec is reached at the initial point of the coasting phase. As indicated in figure 4, a range extension of 1,500 miles is obtained when the pullup maneuver is made so that initial coasting phase velocities of 27,000 ft/sec are obtained. There is no reason why further down-range extensions should not be possible since for some reentry conditions higher velocities at the beginning of the coasting phase are possible. In addition, further range extension is available by increasing the altitude during the coasting phase as indicated in reference 4.

The results of the pilot studies also indicate that lateral range is a function of initial entry angle γ_0 . Figure 4 indicates that the lateral range available for entries at $\gamma_0 = -6.5^\circ$ is 500 miles greater than that at $\gamma_0 = -5.5^\circ$ and about 300 miles greater than that at $\gamma_0 = -7.5^\circ$. This increase is due to the fact that the $\gamma_0 = -6.5^\circ$ entry is closer to the ballistic entry and therefore less lift is needed either

to keep the vehicle from skipping out or to prevent diving too deep in the atmosphere. This means that during the initial (supercircular) portion more lift is available to obtain larger lateral velocities. Thus, it may be desirable from a control and range-available standpoint to attempt to control the vehicle so that its initial reentry is nearly a ballistic trajectory.

Pilot opinion of the learning, the work load, and the timing required to make successful reentries following this procedure were obtained from this study. The research pilots who participated in the study stated that considerable time was required to attain proficiency in the simulator, basically because they were unfamiliar with the mechanics of reentry. Once this learning period was completed so that the pilots understood the reasoning for the steps in the procedure they found the task only moderately difficult. With sufficient damping the vehicle work loads were considered reasonable, and although good timing was necessary, the experienced pilots felt that with an understanding of each phase, sufficient time was available for anticipating the next control inputs.

STUDY OF THE REFERENCE TRAJECTORY CONTROL PROCEDURE

A second program to be discussed has been studied to determine the usefulness of controlling parabolic reentry by an automatic control system in which stored reference trajectories are used. Such systems have been studied extensively for circular reentries (refs. 5 to 8 and 14). The technique is explained with the help of figure 5. A nominal trajectory (one in which the vehicle enters with the specified conditions and position) is selected and stored in the control system. During the actual flight the measured conditions are compared with those of the reference trajectory and the errors obtained. These errors are passed through constant-gain weighting factors K and the sum of the weighted errors is used to specify the lift-drag ratio L/D to be used to force the actual vehicle conditions to conform to those of the reference trajectory. For the system studied the feedbacks found to be most effective were altitude rate $\dot{h}$, deceleration A , and range R as an outer loop control. For the study these were programed as a function of velocity. Also shown in figure 5 is a switch in the range control loop which provides for closing the range loop at the appropriate velocity. The reason for this switch will be discussed subsequently.

A simplified analysis of feedback control during reentry was conceived to study various feedback conditions using only those variables that strongly affect reentry motion. Reference 13 has presented a method of setting up the approximate reentry motion equations in block diagram form. The Chapman equation (ref. 16) used in this study allows important feedback quantities for range control to be recognized and

its relative ease of mechanization on an analog computer allows a straightforward method in the investigation of reentry control.

The study reported in reference 13 has shown the control range to be a third-order control system. As for any other third-order control system, it was found that two inner-loop control terms were desirable. Damping the trajectory is especially important for those velocities greater than satellite velocity, where the vehicle can either skip back out of the atmosphere or exceed a given deceleration limit.

The fixed-trajectory control studies of reference 13 have been extended here to show the characteristic of feedback control in damping the trajectory above satellite velocity. Also, the manner in which range feedback must be used is demonstrated, and the maximum down and cross ranges available are indicated.

Figure 6 shows the typical entrance-angle limits for a body with $L/D = 0.5$ entering the atmosphere at 400,000 feet at a velocity 40 percent above satellite speed. The overshoot limit is determined by the entrance angle at which the vehicle will just stay within the atmosphere when full negative lift is used. The undershoot limit, which is a function of the maximum deceleration, is determined by the entrance angle at which the vehicle will just reach the given g -value with full positive lift. The scale of this figure is adjusted so that the corridor width corresponding to given entrance-angle limits is a linear extrapolation. The entrance-angle limits for various control laws are shown with respect to the available limits of the vehicle. By controlling L/D as a function of altitude rate of change or deceleration rate of change, all but the upper 10° of the available corridor width can be used.

Although the altitude rate of change would have to be measured from an inertial reference during reentry, the deceleration measurement could be obtained from an accelerometer strapped to the vehicle in such a position that it will not couple with the short-period dynamics. The other control law is control to a trajectory in which deceleration varies as a function of velocity. Although this system obtains almost all the capability available to the vehicle for high design maximum decelerations, when the design maximum deceleration is low (below 6g) the vehicle will tend to skip out of the atmosphere after the initial dive to maximum deceleration. It was found that combining the two concepts shown in figure 6 would use almost all the corridor width available to the vehicle over the complete deceleration range.

The control of range about the design trajectory is next considered with the following control equation:

$$\left. \frac{L}{D} \right|_{-.5}^{.5} = K_1 \dot{h} + K_2 [A - A(\bar{u})] + K_3 [R - R(\bar{u})]$$

where $\bar{u}$ is nondimensional velocity. The terms $K_1 \dot{h} + K_2 [A - A(\bar{u})]$ are for inner-loop control and the term $K_3 [R - R(\bar{u})]$ is for range control. The inner-loop terms are a combination of those already shown to keep the controlled trajectory within limits during the supercircular portion of the trajectory.

Figure 7 shows the maximum range values that can be obtained for range control starting both above and below satellite velocity. As seen in the figure, a high value of range control gain K_3 will allow very little range control above satellite velocity, but with low feedback gain some range control is available. Just below satellite velocity, full range control can be added because the vehicle cannot usually skip back out of the atmosphere.

Two important points are indicated in figure 7. The first point is that it is more important during the supercircular portion to control the vehicle in order to avoid skip out than to control the error in range from the fixed reference. This point, which was indicated in the piloted procedure, is forcefully illustrated in figure 7. The second point is that when proper range control is used the reference trajectory approach gives good range control within a down-range capability of 2,000 miles.

The maximum cross range that could be used during the supercircular entry was determined by flying the vehicle at a trim L/D condition of 0.5, letting the roll angle command the L/D value that was used for control in the previous section. The command roll angle becomes

$$\text{Command roll angle} = \cos^{-1} \frac{\text{Command } L/D}{\text{Trim } L/D = 0.5}$$

The cross range was computed by using the method of reference 17 and letting the roll angle control side force to only one side of the trajectory during the full reentry.

Figure 8 shows the cross range available for this control scheme. As presented, about twice the cross range is available if lateral range control is started at parabolic velocity than if range control is started at satellite velocity since the vehicle has no tendency to skip out when lateral force is used.

Actually the reference trajectory and piloted procedure described in the previous section have a great deal of similarity. In the Chapman equation of reference 16 acceleration is comparable to altitude in the standard equations. Thus, whereas the pilot controlled the supercircular portion using altitude and altitude rate with velocity as an index, the automatic feedback control system used acceleration and altitude rate. Suborbitally both used reference trajectories based upon range.

LINEAR PREDICTION

In addition to the more simplified guidance approaches just described, prediction of critical reentry quantities has been used to improve or augment the control logic of the reference trajectory approach.

The linear prediction technique has been studied for entries with two degrees of freedom from circular orbit (ref. 10). This work has been extended to include some of the problems of reentry from parabolic orbits. Figure 9 shows a block diagram of the linear prediction scheme and how the method works. First, the similarity between it and the reference trajectory technique is quite evident. The stored trajectory variables are compared with the present flight conditions and the errors are obtained. However, instead of using constant weighting function a set of influence coefficients calculated by the adjoint technique (ref. 10) is used to predict the effect of these present errors on the end conditions. This predicted final value in range is then used to control the lift-drag ratio of the vehicle. Thus, where the reference trajectory technique forces the vehicle to fly to a single trajectory, the prediction technique selects one of many trajectories which terminate at the desired destination.

The use of the linear prediction technique is illustrated in figure 10 where the errors in the vehicle variables and the predicted range error are plotted as a function of time for a circular reentry control. The figure indicates that the initial altitude is above the reference trajectory, the initial velocity and flight path are correct, and the vehicle's range error ϵ_R is about 280 miles beyond the target. Therefore, the vehicle is trimmed to a minimum lift until the predicted error goes to zero. At this point the velocity and flight path have large but canceling errors - the velocity is 1,600 ft/sec faster than the reference velocity but the flight path is about 0.4° steeper. When zero range error was predicted the vehicle returned to the nominal lift condition and no further control inputs were required.

The use of prediction has been extended to supercircular reentries. The first control problem is to keep the vehicle from overdeceleration. Figure 11 illustrates the ability of the system to predict the peak decelerations from a nominal 7.6g reentry trajectory. Over the range of interest from 5g to 10g the prediction error was less than 0.2g for the cases studied. In addition, the predictor shows improved accuracy as the time when this acceleration will be obtained is decreased.

It should be pointed out that the prediction of range superorbitally will suffer from a problem similar to that for the reference trajectory; that is, the control of range in the superorbital portion will cause the vehicle to skip out. Studies are being conducted to determine how the superorbital control may be accomplished to avoid skip out.

REPETITIVE PREDICTION BY FAST-TIME COMPUTATION

In addition to the use of linear prediction, a more sophisticated prediction system, a high-speed repetitive computer, has been used to aid the pilot in the reentry energy management problem. Although the basic concepts of this procedure have been summarized in references 12 and 13, a brief description of the prediction method of end-point guidance and control is presented here.

The aerodynamic range capability of the vehicle is predicted from existing conditions along the flight path by solving equations of motion for constant trim conditions (assumed to give maximum maneuver). In this study three constant trim conditions were used:

- (1) $(L/D)_{\max} = 0.5$ and bank angle zero ($\phi = 0^\circ$) for maximum range
- (2) $(L/D)_{\max} = 0$ and $\phi = 0^\circ$ for minimum range
- (3) $(L/D)_{\max} = 0.5$ and $\phi = 45^\circ$ for maximum cross range

This area of aerodynamic range is solved repetitively, as fast as possible, for changing flight conditions by an airborne computer. The assumed maximum maneuver capability is thus known continuously as the vehicle conditions vary.

The prediction method of endpoint guidance and control was simulated by using an electronic analog computer, fixed cockpit, and pilot to close the guidance loop. The guidance display used in this simulation is shown in figure 12. The "footprint" or range envelope is a transparent overlay on the face of a 5-inch oscilloscope. The destination is a moving dot on the scope presented in relation to the predicted maximum range

capabilities of the vehicle. The oscilloscope display appears to the pilot as though he were looking at the nondimensionalized maneuver capability of the vehicle. The desirable procedure is for the pilot to control so that the destination is in the center of the maneuver capability; that is, the pilot should fly the destination dot to the center of the scope. Then the pilot has maximum maneuver capability about the target site to take care of unpredicted errors (wind, drifts, etc.). For the conditions shown in figure 12 the procedure would be for the pilot to establish a bank angle of about 40° with a value of L/D of 0.5 and thus overcorrect to force the destination dot toward the center of the display.

In the simulation two restrictions were placed upon the vehicle trajectory, a maximum deceleration limit of $10g$ and a maximum skip-out altitude of 300,000 feet. The repetitive prediction was capable of predicting these boundary values which were displayed to the pilot as bars on the scope. For reentries at the shallow entry angles the upper bar would appear near the lower boundary of the scope indicating to the pilot to use negative lift to remain in the atmosphere. At the steep entry angles the lower bar would appear at the top of the scope indicating that maximum positive lift was required in order to avoid severe decelerations.

The pilots considered this system entirely satisfactory. The pilot's function needed here was to close the control loop between the bank and trim indicators and navigation display. The pilots had no difficulty coping with emergency or abort reentry conditions far removed from parabolic entry conditions. This ability of the guidance system to predict range, deceleration, and skip-out limits for any entry condition makes it an almost universal control method.

A point of interest should be made about the equations used by this repetitive prediction technique. The procedure investigated was conducted by using the Chapman approximate equation (ref. 16) for the solution in the fast-time computer. Other than the simplification of the computation one factor involving the change from geometric to effective density altitude is clearly pointed out by use of the approximate equations. First, the use of density altitude provides a compensation for nonstandard atmosphere conditions. In addition, the instability in the inertial reference system affects the control procedure less if density altitude is used. Actually, this procedure is applicable to all systems and it is felt that the use of density altitude will be advantageous.

COMPARISON OF DOWN-RANGE CAPABILITY

As indicated previously, the range capability is probably a major factor in assessing the quality of a reentry guidance system. Figure 13

shows a summary of the down-range capability for the repetitive prediction, the reference trajectory, and the pilot-controlled systems. (The linear prediction procedure is left off because range data have not been obtained on the reentry from parabolic orbits.) In the control of minimum range the use of the prediction system indicates a definite superiority. This is due to the fact that the predictor gives the lift-drag ratio at which to trim the vehicle in order to reach peak deceleration, and the pilot can easily control the dive into the atmosphere to obtain and hold this value, thereby obtaining shorter ranges.

L For the maximum range the piloted system shows a definite superiority
1 in obtaining ranges in excess of those obtained so far by the
7 other systems. This is due to the fact that the automatic system was
5 forced to fly a trajectory not designed to obtain optimum long ranges
2 and the predictor system was confined to the prediction of maximum range by a procedure in which L/D is fixed. However, a varied L/D program, similar to that developed in the piloted procedure where high coasting phase velocities are obtained, is required for maximum range when skip out is to be avoided.

Although the research to date has indicated that the pilot is capable of using his experience and judgment in order to obtain longer ranges than are obtained by the other systems, this conclusion should be tempered in light of possible future developments. First, there is no reason theoretically why the reference and prediction schemes cannot take advantage of similar procedures. Additional study will be required to assess the system complexities which may result from their use. In addition, none of the systems has approached the ranges predicted in reference 4. Therefore, further study will be required on all systems including the piloted technique in order that a more nearly optimum percent of the total range capability may be obtained.

CONCLUSIONS

The following conclusions have been obtained from the present studies made on reentry guidance and energy management procedures:

1. The procedures studied have not provided nearly the optimum direct-descent range that is available. Further study will be necessary in order to assess the additional complexities required in each system in order to obtain a more nearly optimum range.

2. The repetitive prediction technique provides for excellent control of the initial peak decelerations and a more nearly universal reentry procedure, in that abort conditions are easily handled.

3. The piloted study has indicated that the human operator with experience and a good display of flight information can capably perform the reentry guidance maneuvers required.

4. The reference-trajectory and linear-prediction control techniques appear applicable to the problem and will require more study to assess their true value.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., July 18, 1961.

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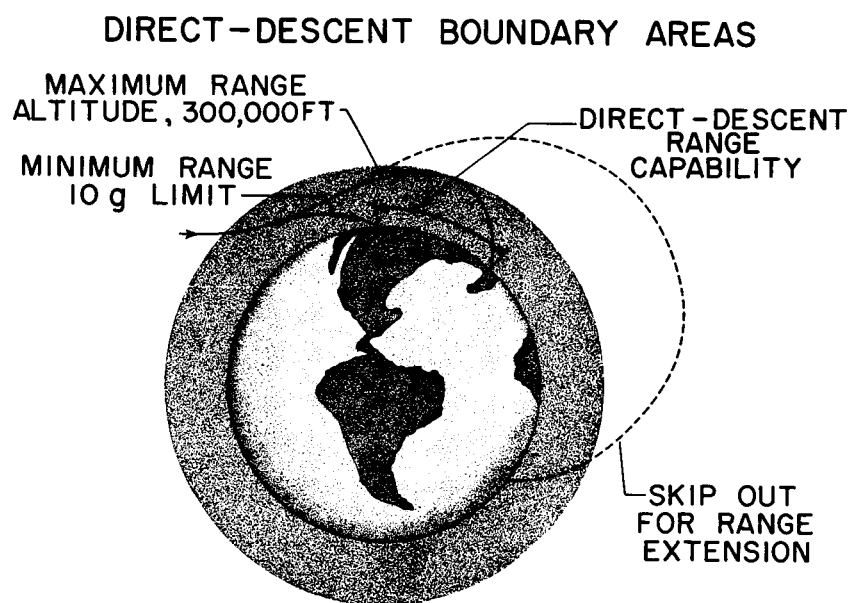


Figure 1

INSTRUMENT PANEL USED IN PILOTED GUIDANCE SYSTEM

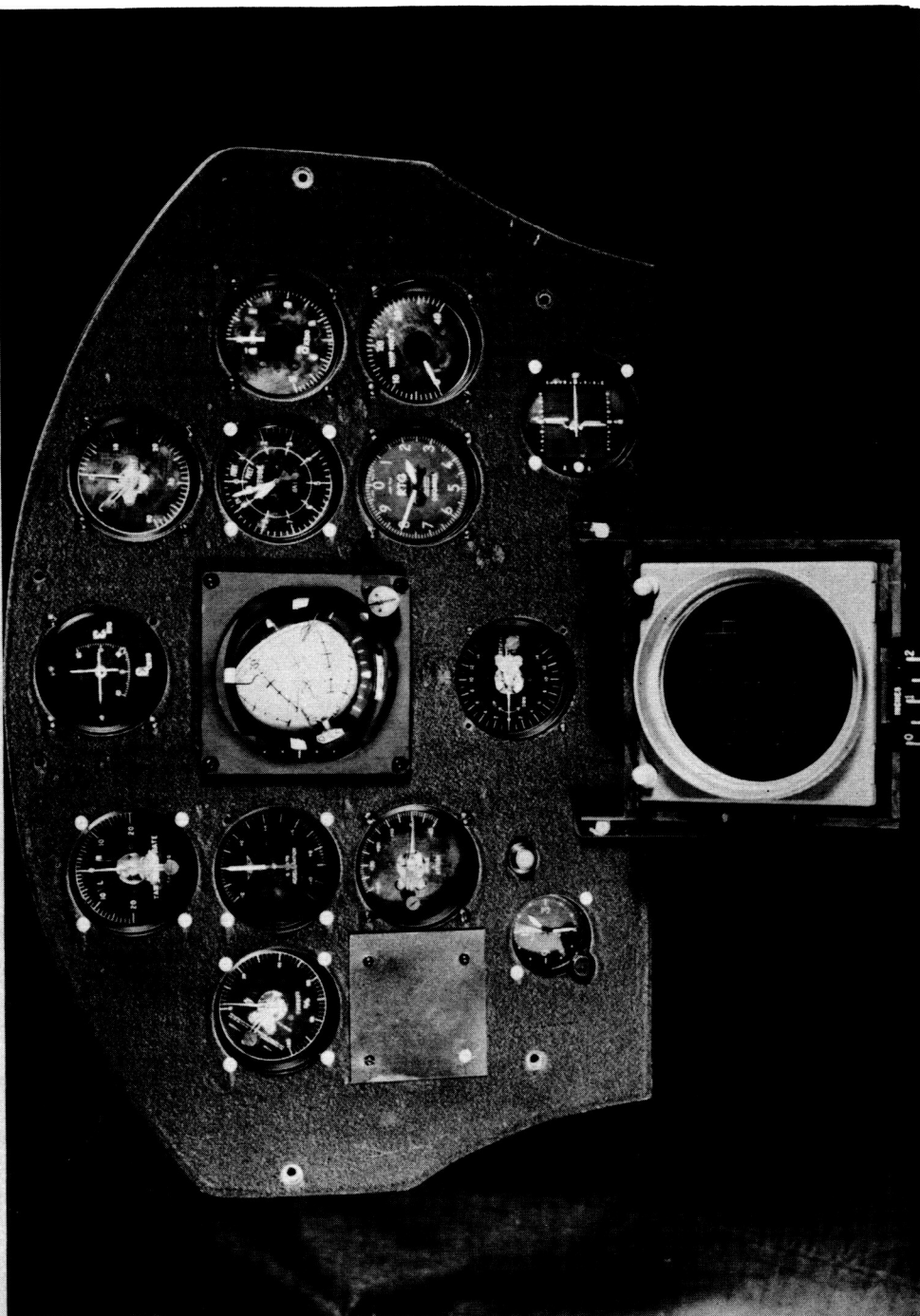


Figure 2

L-61-4422

PILOT-CONTROLLED REENTRIES

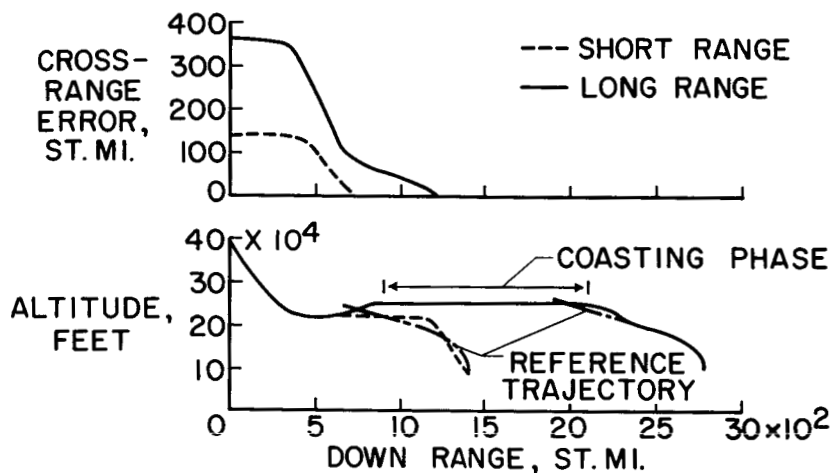


Figure 3

PILOT-CONTROLLED RANGE CAPABILITY

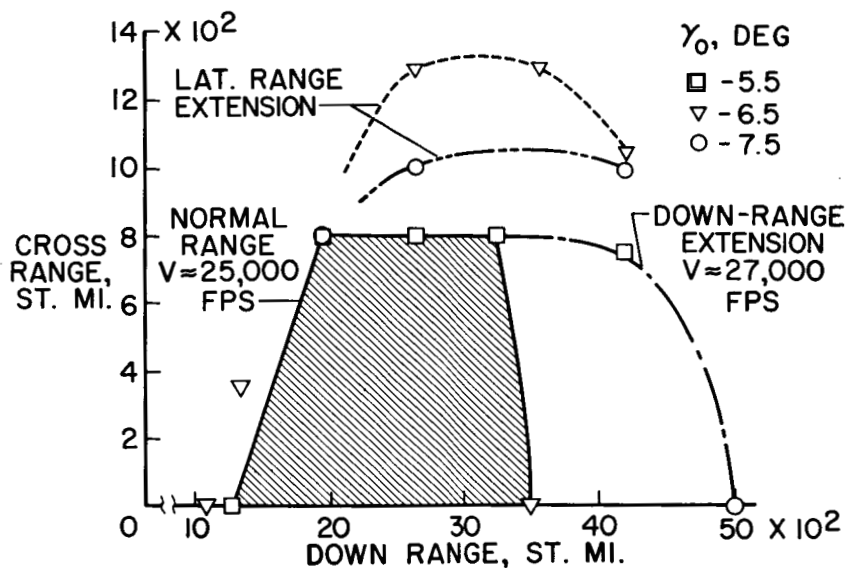


Figure 4

REFERENCE TRAJECTORY DOWN-RANGE CONTROL SYSTEM

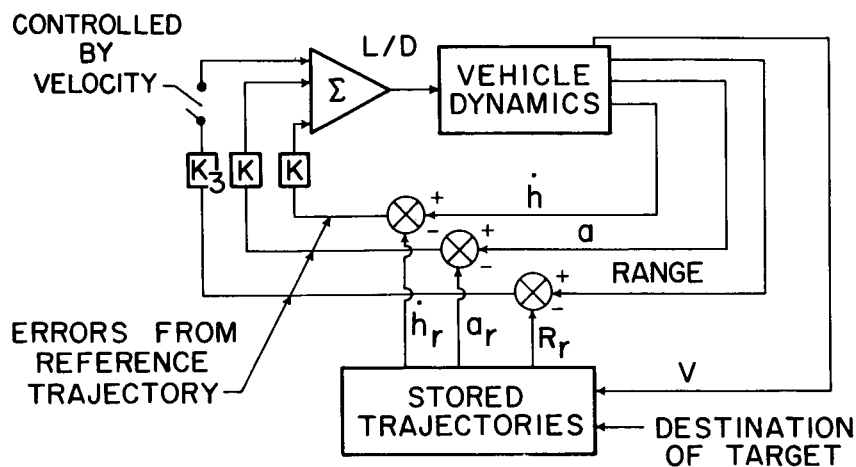


Figure 5

CORRIDOR WIDTH FOR TRAJECTORY DAMPING

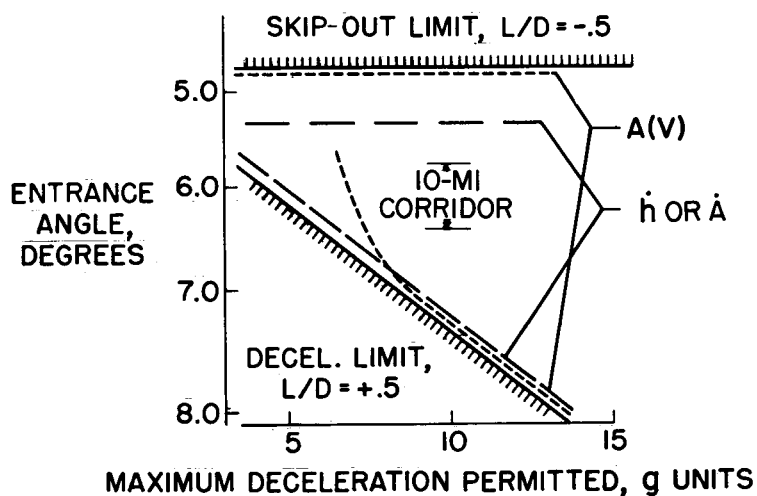


Figure 6

DOWN-RANGE CAPABILITY FOR CONTROL TO A FIXED TRAJECTORY

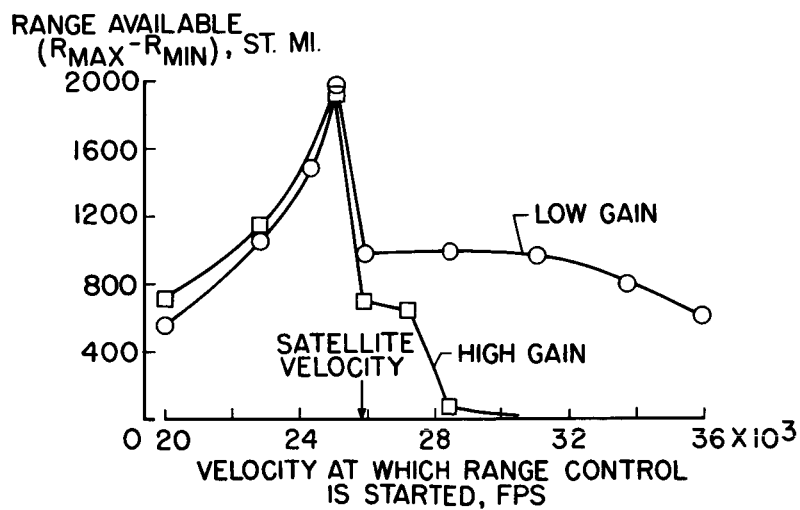


Figure 7

LATERAL RANGE CAPABILITY FOR TRAJECTORY CONTROL

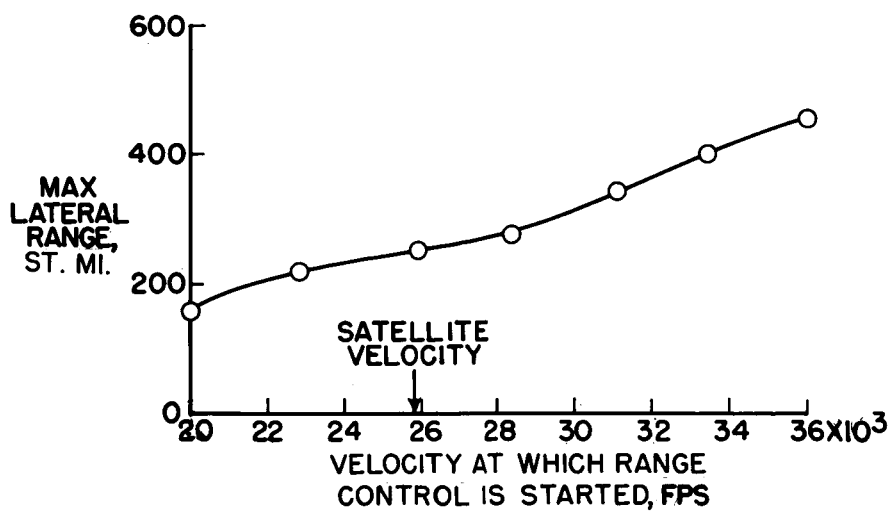


Figure 8

BLOCK DIAGRAM OF LINEAR PREDICTOR CONTROL SYSTEM

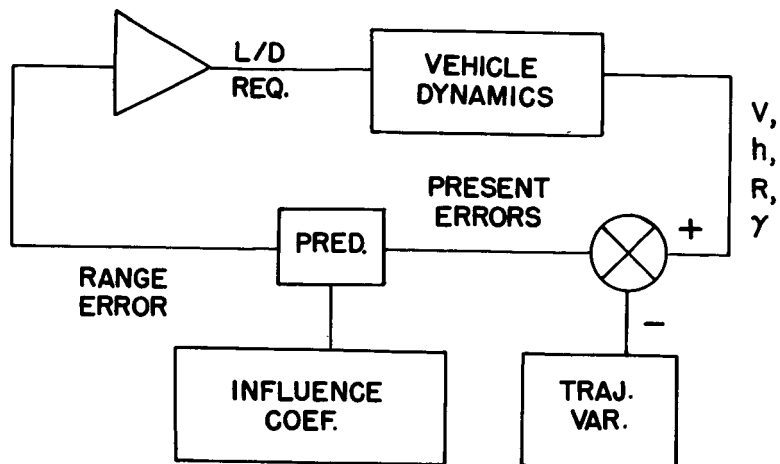


Figure 9

EXAMPLE OF LINEAR PREDICTION OF RANGE

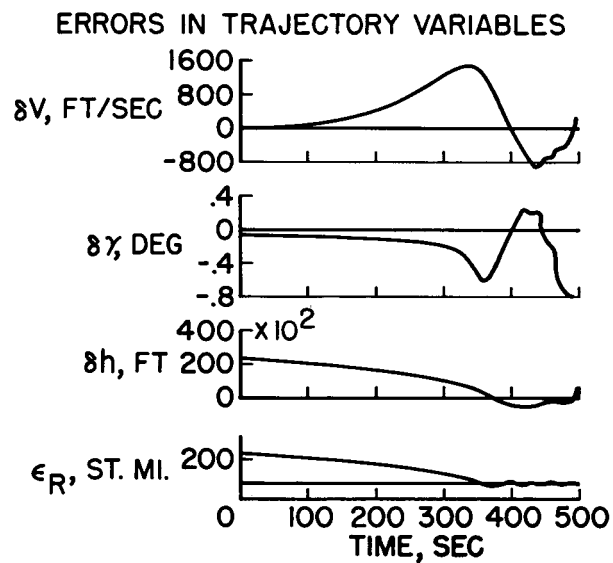


Figure 10

PREDICTOR DECELERATION ACCURACY

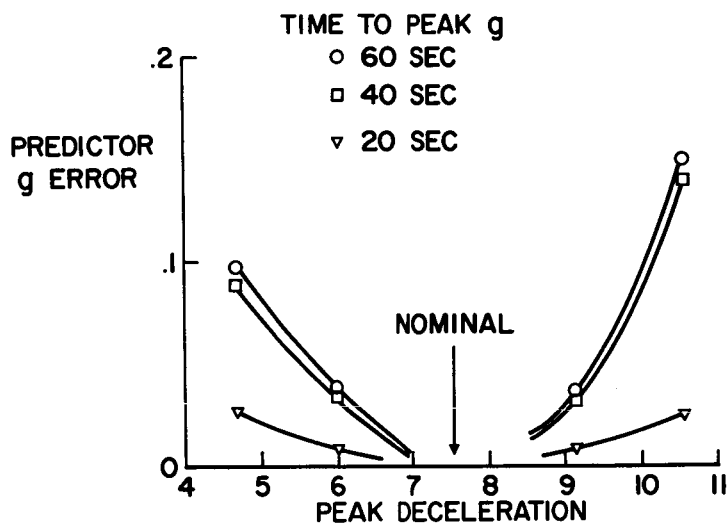


Figure 11

GUIDANCE DISPLAY

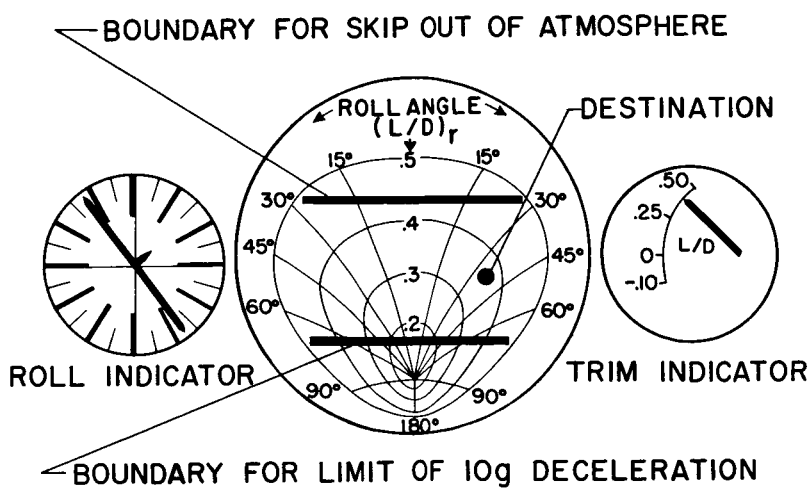


Figure 12

COMPARISON OF RANGE CAPABILITY FOR GUIDANCE SYSTEMS STUDIED

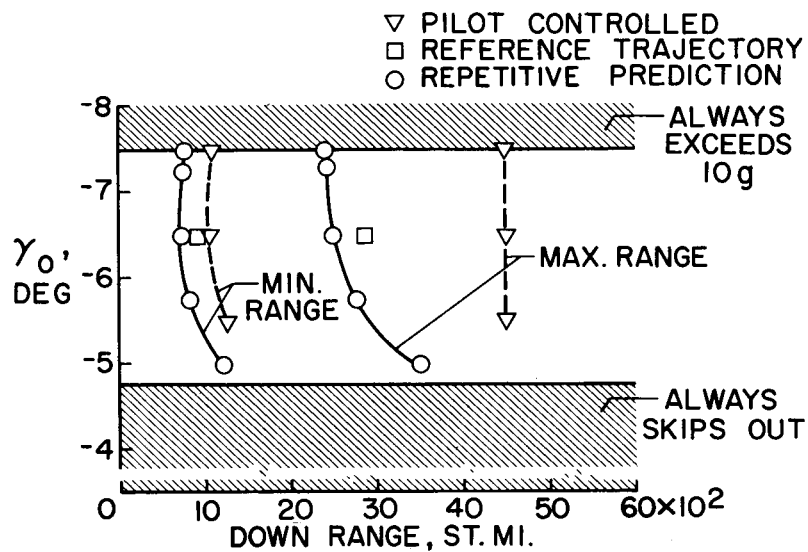


Figure 13