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NASA TN D-6725

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APOLLO EXPERIENCE REPORT -  
MISSION PLANNING FOR APOLLO ENTRY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972



1. Report No. NASA TN D-6725	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle APOLLO EXPERIENCE REPORT MISSION PLANNING FOR APOLLO ENTRY		5. Report Date March 1972	6. Performing Organization Code
		8. Performing Organization Report No. MSC-S-305	
7. Author(s) Claude A. Graves and Jon C. Harpold, MSC		10. Work Unit No. 076-00-00-00-72	11. Contract or Grant No.
9. Performing Organization Name and Address Manned Spacecraft Center Houston, Texas 77058		13. Type of Report and Period Covered Technical Note	
		14. Sponsoring Agency Code	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		15. Supplementary Notes The MSC Director waived the use of the International System of Units (SI) for this Apollo Experience Report, because, in his judgment, use of SI Units would impair the usefulness of the report or result in excessive cost.	
16. Abstract The problems encountered and the experience gained in the entry mission plans, flight software, trajectory-monitoring procedures, and backup trajectory-control techniques of the Apollo Program should provide a foundation upon which future spacecraft programs can be developed. Descriptions of these entry activities are presented in this report. Also, to provide additional background information needed for discussion of the Apollo entry experience, descriptions of the entry targeting for the Apollo 11 mission and the postflight analysis of the Apollo 10 mission are presented.			
17. Key Words (Suggested by Author(s)) Apollo                      Entry Trajectory Range Profile              Lift-to-Drag Ratio Roll Altitude              Entry Monitoring		18. Distribution Statement	
19. Security Classif. (of this report) None	20. Security Classif. (of this page) None	21. No. of Pages 27	22. Price* \$3.00



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# APOLLO EXPERIENCE REPORT

## MISSION PLANNING FOR APOLLO ENTRY

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### SUMMARY

The Apollo entry mission plans, flight software, trajectory-monitoring procedures, and backup trajectory-control techniques were developed satisfactorily. The problems encountered and the experience gained during Apollo entry activities provide an insight into the types of entry problems, and this insight can benefit future spacecraft programs. Mission requirements for the mission entry phase must be established accurately and realistically early in the program if unsatisfactory compromises between mission plans and system performance are to be minimized. The guidance logic must be simple to minimize the resources required for guidance development and to minimize flight-crew monitoring procedures. Monitoring of the guidance performance should be considered in developing the guidance logic and displays. The guidance logic must be compatible with a backup or alternate trajectory-control procedure.

The targeting of the entry speed, flight-path angle, and range must be maintained at a safe margin from trajectory-constraint boundaries. This safe margin can result in a compromise between mission objectives and entry targeting, particularly for unmanned test flights. The entry-guidance logic must be insensitive to known variations in the command module trim lift-to-drag ratio and in the knowledge of this ratio. This insensitivity was accomplished for the Apollo Program by the incorporation of erasable memory locations to "tell" the logic the expected value of the lift-to-drag ratio and by the conservation of ranging potential early in the entry. The interaction between entry guidance system performance and attitude control system performance must be recognized before requirements for these two systems can be established.

The entry specialists should be an integral part of the flight-crew training, flight-controller training, and flight-control teams. The special skills of the entry specialists can be used to increase the probability of mission success and the flight-crew safety. Finally, positive aerodynamic control of the entry trajectory should be maintained throughout entry.

## INTRODUCTION

The purpose of the Apollo entry maneuver is to dissipate the energy of a spacecraft traveling at high speed through the atmosphere of the earth so that the flight crew, their equipment, and their cargo are returned safely to a preselected location on the surface of the earth. This purpose must be accomplished while stresses on both the spacecraft and the flight crew are maintained within acceptable limits.

The experience gained in developing the Apollo entry mission plans, flight software, trajectory-monitoring procedures, and backup trajectory-control techniques should provide an insight into the problems encountered during the entry phase so that these problems can be avoided in future spacecraft programs. To provide the background information needed for a discussion of the Apollo entry experience, descriptions of the entry targeting for the Apollo 11 mission and of the postflight analysis of the Apollo 10 mission are presented. The entry targeting includes analysis of the interaction between targeting and monitoring of the guidance system operation. A postflight analysis of the entry guidance system operation and a comparison between planned and actual trajectories are presented. Loss of data prevented a detailed postflight analysis of the Apollo 11 entry; therefore, the Apollo 10 postflight analysis is presented. Descriptions of the Apollo entry vehicle, the entry corridor, and the entry-trajectory-control modes also are included. A detailed description of the Apollo entry guidance is contained in references 1 and 2, and the entry monitoring system is described in reference 3. Aspects of the entry phase of mission planning are discussed in references 4 to 6.

## SYMBOLS

$C_{16}, C_{17}$	constant gain
$C_D$	aerodynamic drag coefficient
$C_L$	aerodynamic lift coefficient
$D$	total aerodynamic acceleration, ft/sec <sup>2</sup>
$D_L$	$D$ at skipout or minimum $D$ if skipout is not required, ft/sec <sup>2</sup>
$D_{ref}$	reference value of $D$ , ft/sec <sup>2</sup>
$F_1$	control gain, $f[D/(D \text{ at perigee})]$
$g$	load factor, ft/sec <sup>2</sup>

$K_1, K_2$	optimum constant gains
$K_3$	scale factor to increase trajectory-control response
L/D	command module trim lift-to-drag ratio
$(L/D)_C$	commanded L/D in the osculating plane
$(L/D)_{ref1}$	reference L/D for the up-control guidance logic
$(L/D)_{ref2}$	reference L/D for the second-entry phase
$(L/D)_V$	L/D in the osculating plane
M	Mach number
R	range-to-the-target, n. mi.
$R_p$	predicted second-entry-phase range based on $(L/D)_{ref2}$ , n. mi.
$R_{ref}$	second-entry-phase reference range based on $(L/D)_{ref2}$ , n. mi.
Roll <sub>C</sub>	roll-attitude command, deg
$\dot{r}$	altitude rate, ft/sec
$\dot{r}_{ref}$	reference value of $\dot{r}$ , ft/sec
V	velocity, ft/sec
V, g	EMS velocity and load-factor trace
$V_i$	inertial velocity, ft/sec
$V_L$	velocity at $D_L$ , ft/sec
$V_{ref}$	reference velocity, ft/sec
V, $\gamma$	velocity and flight-path angle
$\alpha$	trim angle of attack, deg
$\gamma$	flight-path angle relative to the local horizontal, deg

# APOLLO ENTRY VEHICLE

The entry vehicle for the Apollo missions is the command module (CM), which has a symmetric body with an offset center of gravity (c.g.). This offset c.g. causes the CM to trim aerodynamically at an angle of attack with a resulting lift force as illustrated in figure 1. The magnitude of the lift force is not controllable; therefore, trajectory control is provided by modulating the direction of the lift-force vector. The direction is modulated by rolling the CM, and hence the lift-force vector, about the relative-wind-velocity vector. The trim aerodynamic coefficients of the Apollo 11 CM are presented in table I.

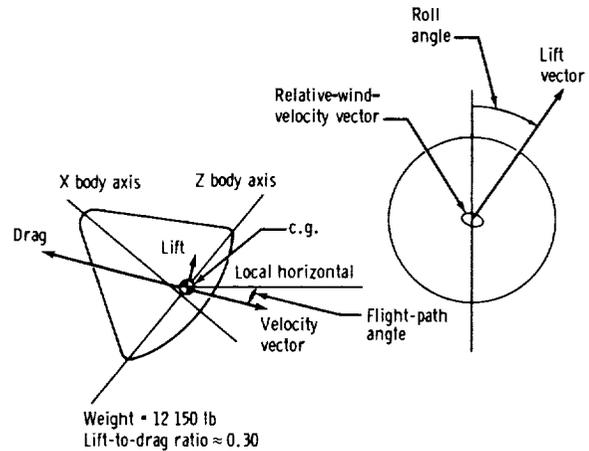


Figure 1. - Apollo command module characteristics.

TABLE I. - TRIM AERODYNAMIC COEFFICIENTS FOR THE APOLLO 11 COMMAND MODULE

M	$\alpha$ , deg	$C_L$	$C_D$	L/D
0.4	167.14	0.24465	0.85300	0.28682
.7	164.38	.26325	.98542	.26714
.9	161.70	.32074	1.10652	.30110
1.1	154.87	.49373	1.1697	.42208
1.2	155.13	.47853	1.1560	.41395
1.35	154.01	.56282	1.2788	.44013
1.65	153.22	.55002	1.2657	.43455
2.0	153.14	.53247	1.2721	.41858
2.4	153.62	.50740	1.2412	.40881
3.0	154.14	.47883	1.2167	.39353
4.0	156.12	.44147	1.2148	.36340
10.0	156.79	.42856	1.2246	.34996
$\geq 29.5$	160.06	.38773	1.2891	.30076

## ENTRY CORRIDOR

The entry corridor is defined as the set of space trajectories for which aerodynamic capture within the atmosphere of the earth can be achieved and for which entry-trajectory control can be accomplished without exceeding either flight-crew or CM stress limits. Therefore, definition of the corridor limits includes four basic considerations: aerodynamic capture within the atmosphere, the aerodynamic load factor, aerodynamic heating, and landing-point control.

If the CM enters the atmosphere at an angle that is too shallow, the trajectory cannot be controlled and the CM will skip out of the atmosphere at high speeds that will result in unacceptable range and flight time. If the CM enters the atmosphere at an angle that is too steep, the aerodynamic-load-factor magnitudes will be unacceptable. The region within these two limits defines the extreme boundaries of the entry corridor. However, the maximum entry-ranging capability and the aerodynamic heating limits within these boundaries must be considered. For the Apollo missions, the maximum entry-range requirement (that is, the great-circle distance between entry into the atmosphere and landing) is 2500 nautical miles. This ranging capability provides flexibility for landing-point control in order to avoid possible bad weather conditions in the planned recovery area.

The entry corridor can be defined by limits for any combination of parameters that are sufficient to define free-flight trajectories. The Apollo entry corridor is defined by flight-path-angle limits as a function of CM speed at the entry interface. This interface is defined as an altitude of 400 000 feet above the surface of the earth. Overshoot boundaries of the entry corridor, based upon 2500- and 1285-nautical-mile entry ranges, are presented in figure 2. These overshoot boundaries define the shallowest flight-path angle for which these minimum ranges can be achieved. These two boundaries are based upon a lift-vector-down attitude until aerodynamic capture is achieved, followed by ranging with the entry guidance system. Two undershoot boundaries also are presented in figure 2. One boundary is based upon a maximum aerodynamic load factor of 12g, and the other is based upon a maximum range of 2500 nautical miles. The 12g undershoot boundary defines the steepest flight-path angle for which the maximum load factor will not exceed 12g. This boundary is based upon the CM being at 15° from a lift-vector-up attitude until the peakload factor is passed. The 15° attitude is consistent with the Apollo entry-guidance logic, which, for cross-range control, permits a 15° attitude excursion from a lift-vector-up attitude before achieving the peakload factor. The 2500-nautical-mile-range undershoot

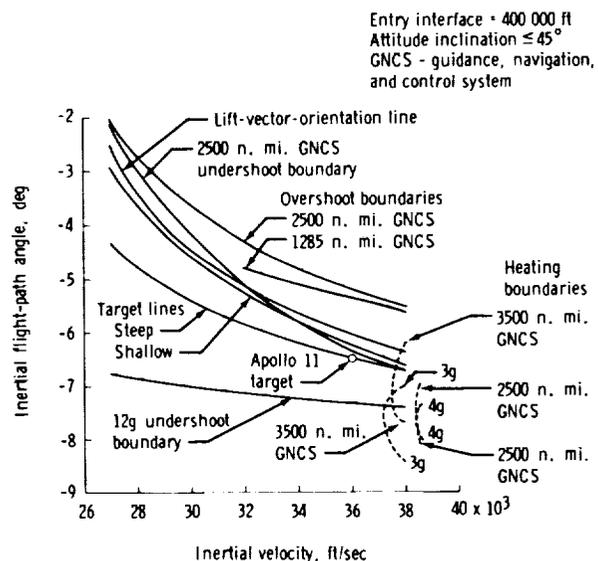


Figure 2. - Apollo 11 entry corridor.

boundary defines the steepest flight-path angle for which a 2500-nautical-mile range can be achieved by using the entry guidance system for trajectory control.

The aerodynamic heating boundaries for guided entries and for entries controlled to a constant-load factor are also presented in figure 2. These boundaries are based on a maximum temperature of 600° F at the bondline between the heat shield and the heat-shield substructure. Guided-entry heating boundaries are presented for 2500- and 3500-nautical-mile entry ranges, and the constant-load-factor entry heating boundaries are presented for entries controlled to the 3g and 4g levels. No heating limits exist for the 5g trajectories.

All boundaries of the entry corridor presented in figure 2 are conservative because the boundaries are defined for the worst combination of atmospheric density, lift-to-drag ratio  $L/D$ , trajectory inclination, and entry latitude within the 45° inclination limit for Apollo entry trajectories. For example, the 2500-nautical-mile-range under-shoot boundary is based on the minimum  $L/D$  for an Apollo mission, and the heating boundary is based on the maximum  $L/D$ .

For information purposes only, the lift-vector-orientation (LVO) line is shown in figure 2. This line defines the shallowest entry-flight-path angle for which the entry guidance will command a lift-vector-up CM attitude at initial entry into the atmosphere. For shallower entries, the entry guidance will command a lift-vector-down CM attitude until aerodynamic capture by the atmosphere is achieved.

## ENTRY TRAJECTORY-CONTROL MODES

Three basic modes exist for controlling the entry trajectory. The primary control mode uses the entry guidance by use of the guidance, navigation, and control system (GNCS). In addition, two backup control modes exist, both of which are based on manual roll-attitude control of the CM through use of the CM stabilization and control system. One backup mode involves the use of the entry monitoring system (EMS) as the primary flight-crew display, and the other mode involves the use of a g-meter and an attitude reference as the basic displays. In addition to providing information for backup trajectory control, the EMS is the primary source of information for monitoring the entry trajectory for flight safety. Additional monitoring is provided by observing the displays of the GNCS computer.

### Entry Guidance

The GNCS consists of a stable platform with three mutually orthogonal pulse-integrating pendulous accelerometers, a digital command module computer (CMC), and an attitude control system. The CMC provides CM navigation based upon the output of the accelerometers combined with the initial state-vector data provided to the CMC before entry. The initial state vector is based upon the Manned Space Flight Network (MSFN) tracking of the transearth trajectory. The CM attitude commands are determined by the CMC, which processes the navigation and landing-point target data through the entry-guidance logic. In addition, the digital autopilot (DAP) portion of the CMC provides the on/off logic for the attitude-control thrusters, which provide the impulse for CM attitude control.

The entry-guidance logic, developed by the Massachusetts Institute of Technology Instrumentation Laboratory, has seven phases that are used to guide the CM to the landing point, as shown in figure 3. The basic accomplishments of this guidance logic are to arrest the descent rate, thereby minimizing the peak-aerodynamic-load factor, and then to loft the trajectory to achieve the desired range. The lofting is necessary because of the relatively low command module L/D. The degree of lofting is a function of the entry range.

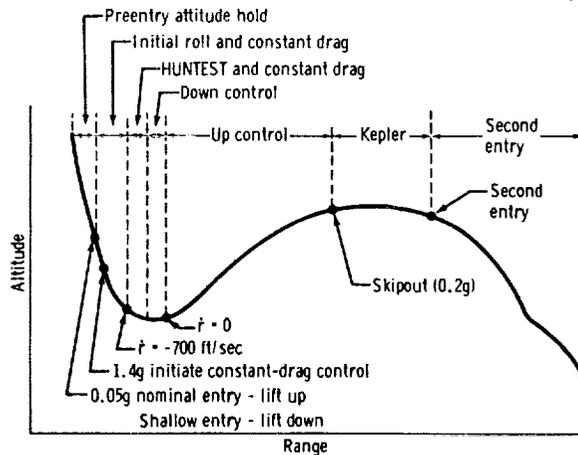


Figure 3. - Entry-guidance phases.

Preentry phase. - Before the CM reaches the entry interface, the CMC receives the necessary initialization quantities from the ground-based computer in the Mission Control Center at the NASA Manned Spacecraft Center. During the preentry phase, no aerodynamic forces and no trajectory control exist. Therefore, the CM is maintained in a three-axis attitude-hold mode that orients the spacecraft to an aerodynamic trim attitude in preparation for penetration into the atmosphere.

Initial roll and constant-drag phases. - The initial roll phase of the entry guidance is initiated when an aerodynamic deceleration of 0.05g is first sensed by the GNCS accelerometers. When this deceleration is sensed, the three-axis attitude-hold mode is discontinued, and rate damping is initiated about the pitch and yaw axes. The roll attitude is controlled in response to the guidance command. The guidance logic determines an initial LVO to ensure a safe entry and aerodynamic capture within the atmosphere of the earth. This LVO for high-speed entries is determined from the navigated velocity and altitude rate when the GNCS accelerometers first sense 0.05g. A lift-vector-up attitude is commanded if the flight-path angle is steeper than the LVO line in figure 2. Otherwise, a lift-vector-down attitude is commanded to ensure capture. This initial LVO is maintained until a predetermined load factor (1.4g for lunar-return entries) is sensed. At this point, constant-aerodynamic-load-factor (constant drag) control is initiated. This control mode is maintained until an altitude descent rate of 700 ft/sec is reached. When this rate is reached, the guidance transfers to the HUNTEST (hunting and testing) and constant-drag phases.

HUNTEST and constant-drag phases. - The purpose of the HUNTEST phase is to determine the basic characteristics of the remainder of the entry trajectory and to dissipate any excessive amount of energy that the CM may have. In the first pass through the HUNTEST logic, the velocity at the perigee point (altitude rate equal to zero) and the range traveled from the present state vector to perigee are predicted analytically. This phase of the entry trajectory (from the present state to the perigee point), the down-control phase, is based on a lift-vector-up attitude. Then, the skipout velocity and the flight-path angle are predicted based on a predetermined value of L/D in the osculating plane  $(L/D)_V$  of 0.15. These predictions form the basis for analytical computation of the range traveled from the perigee point to the skipout (Kepler phase).

The second-entry range is determined by linear perturbation about the predicted second-entry state vector. For this prediction, the second-entry  $(L/D)_V$  is assumed to be approximately one-half the CM trim  $L/D$ . Therefore, a basic entry trajectory is predicted, and the entry range for each phase is determined.

When the predicted skipout velocity is computed, it is compared with the circular orbital velocity. If the predicted skipout velocity is greater than the circular orbital velocity, an overshoot trajectory is assumed, and the constant-drag phase is entered to dissipate excess energy. During this phase, the guidance logic generates the roll commands necessary to control the trajectory to a predefined constant-aerodynamic-load-factor level. This sequence is repeated every 2 seconds until the predicted skipout velocity is less than the circular orbital velocity. When this condition is reached, the predicted range from the HUNTEST phase is compared with the range-to-the-target. If the predicted range exceeds the range-to-the-target, the constant-drag phase will be entered again to dissipate the excess energy. This sequence is repeated every 2 seconds until the predicted range is less than the range-to-the-target. Once an undershoot trajectory is predicted, the constant-drag phase is not entered again. Instead, the guidance logic enters a tight loop that adjusts the  $(L/D)_V$  assumed for the phase from the perigee point to skipout (that is, the up-control phase) such that the predicted range matches the range-to-the-target. A solution is accepted when the predicted range and the range-to-the-target differ by less than 25 nautical miles.

If the predicted skipout velocity is less than 18 000 ft/sec, the up-control phase is omitted, and the second-entry phase is entered directly from the HUNTEST phase. If a skipout trajectory (load factor less than 0.2g) is not required or achievable, then the minimum load factor and corresponding velocity are predicted by the HUNTEST logic. The predicted skipout load factor or the predicted minimum load factor is defined as  $D_L$ , and the corresponding velocity is defined as  $V_L$ .

Down-control phase. - The down-control phase is entered after the excess energy of the spacecraft has been dissipated by the constant-drag phase and after the HUNTEST phase has successfully established the basic entry-trajectory-shaping parameters. As mentioned previously, the down-control phase is based upon a lift-vector-up attitude; therefore, the actual spacecraft trim  $L/D$  is used as the reference  $(L/D)_V$ . An analytical reference trajectory can be computed for the down-control phase using the reference  $(L/D)_V$ , knowledge of the present state vector, and the predicted velocity at perigee. This computation is accomplished with velocity as the independent variable and with acceleration and altitude rate as the dependent variables. Then, the roll commands are computed as shown in equations (1) and (2) to control the down-control trajectory.

$$(L/D)_C = \frac{L}{D} + C_{16}(D - D_{ref}) - C_{17}(\dot{r} - \dot{r}_{ref}) \quad (1)$$

$$\text{Roll}_C = \cos^{-1} \left[ \frac{(L/D)_C}{L/D} \right] \quad (2)$$

Up-control phase. - During the HUNTEST phase, the values of  $V_L$  and  $D_L$  were computed analytically, based upon a constant  $(L/D)_V$  (equal to 0.15) and upon the predicted velocity at the end of the down-control phase. This computation is sufficient to define a reference trajectory throughout the up-control phase, which begins at the perigee point. This reference trajectory is computed analytically during the up-control phase, with aerodynamic acceleration as the independent variable and with velocity and altitude rate as the dependent variables. Then, during the up-control phase, the CM roll-attitude commands are as computed in the following equation and in equation (2).

$$(L/D)_C = (L/D)_{ref1} + K_1 F_1 \left[ K_2 F_1 (\dot{r} - \dot{r}_{ref}) + (V - V_{ref}) \right] \quad (3)$$

Kepler phase. - The Kepler phase in the guidance logic is assumed to begin when the aerodynamic load factor decreases to 0.2g. During this phase, trajectory control is not possible because the aerodynamic forces are small; therefore, no roll-attitude commands are computed after the load factor decreases below 0.2g. The CM is placed in a three-axis attitude-hold mode when the aerodynamic load factor decreases to 0.05g. This attitude-control mode is maintained until the load factor increases to 0.05g again. When the load factor reaches 0.05g, the pitch- and yaw-rate damping mode is initiated again.

Second-entry phase. - After the Kepler phase, when the aerodynamic load factor increases to  $6.5 \text{ ft/sec}^2$ , the second-entry phase is entered. The second-entry-phase guidance is based upon linear perturbations about a stored reference trajectory. The independent variable is velocity, and the dependent variables are acceleration and altitude rate. This reference trajectory is used to predict the range potential from the present state to the landing. The roll-attitude commands are generated to drive the range potential to the range-to-the-target as the drogue-parachute-deployment altitude is reached. The range potential during the second entry is computed as follows.

$$R_p = R_{ref} + \frac{\partial R}{\partial D} (D - D_{ref}) + \frac{\partial R}{\partial \dot{D}} (\dot{r} - \dot{r}_{ref}) \quad (4)$$

Then, the  $L/D$  command and the roll-attitude command are computed by using the following equation and equation (2).

$$(L/D)_C = (L/D)_{ref2} + \frac{K_3 (R - R_p)}{\frac{\partial R}{\partial (L/D)}} \quad (5)$$

During the second-entry phase, the g-limiter logic overrides the roll-angle commands if the predicted load factor exceeds 10g. The g-limiter logic predicts the limiting altitude rate at each flight condition that will result in a 10g peakload factor, based

upon a lift-vector-up attitude. If the magnitude of the navigated altitude rate exceeds this limit, a lift-vector-up attitude is commanded to minimize the aerodynamic load factor.

Lateral logic. - Trajectory control is accomplished by rolling the CM about the relative-wind-velocity vector. This rotation results in a coupling between the in-plane trajectory control and the lateral trajectory control. The in-plane ranging requirements determine the magnitude of the spacecraft roll-attitude commands, and the lateral ranging requirements control the direction of the roll-attitude command. The predicted lateral-range error is compared to the predicted lateral ranging capability of the spacecraft. When the lateral-range error exceeds the predicted capability, a reversal of the roll direction is commanded. The predicted lateral capability is conservative to ensure adequate lateral control in the presence of dispersions. However, this procedure normally results in approximately four roll reversals. When the bank-angle command is either a lift-vector-up or a lift-vector-down attitude, a 15° roll-attitude command is generated to reduce the lateral-range error. This 15° roll attitude has a small effect on the down-range maneuver capability but produces a significant part of the total lateral ranging capability.

### Entry Monitoring System

The EMS is the primary display used by the flight crew to monitor the entry trajectory flown by the GNCS and to provide manual backup ranging capability. The EMS functions and hardware are independent of the GNCS and consist of a single body-mounted accelerometer and a panel of displays from which the flight crew can monitor the trajectory. The panel consists of a velocity/load-factor display, a range-to-go display, a 0.05g indicator, and a roll-attitude indicator. These components are labeled 1, 2, 3, and 4, respectively, in figure 4.

The primary display on the EMS is a velocity/load-factor trace superimposed on a pattern of flight constraints. The pattern of flight constraints is mounted on a scroll assembly that moves the scroll pattern horizontally by the display window using stepper motors and integrating circuits. The scroll pattern is driven in proportion to the spacecraft velocity, which is obtained by integrating the acceleration sensed by the body-mounted accelerometer. Simultaneously, a stylus moves vertically in direct proportion to the sensed aerodynamic load factor or acceleration, inscribing a load-factor trace on the moving pattern of flight constraints.

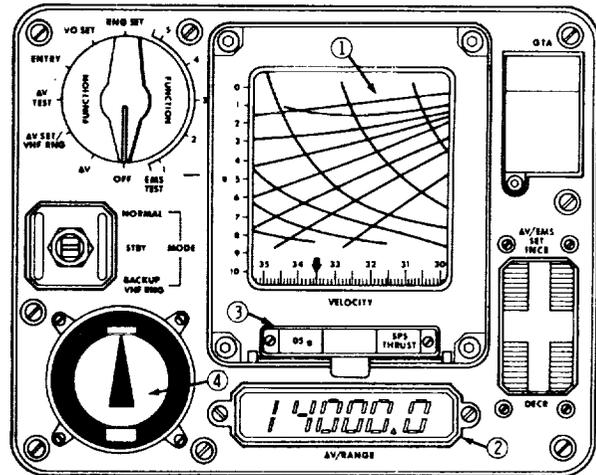
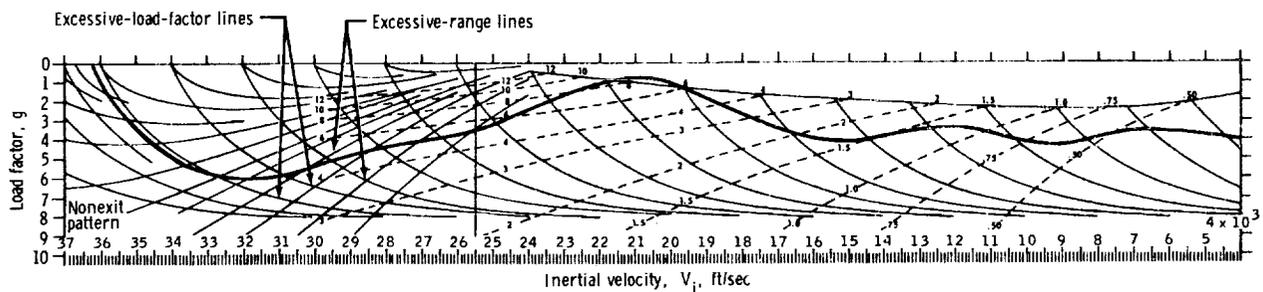


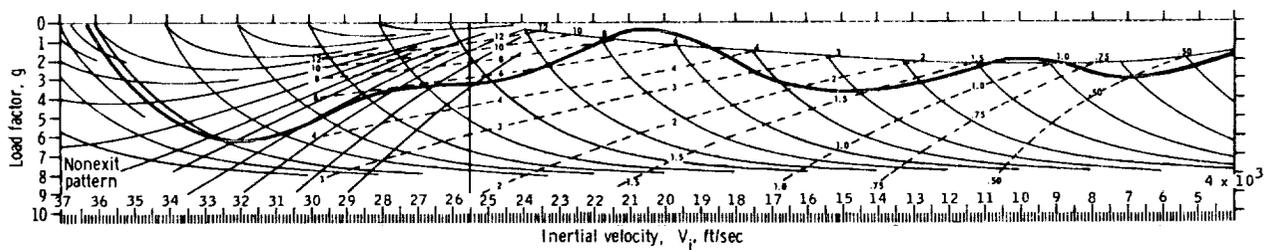
Figure 4. - Entry monitoring system control panel.

From the EMS flight trace, the load factor, velocity, and slope of the velocity/load-factor profile can be determined. This determination is equivalent to defining the in-plane CM state vector. This state-vector information, combined with knowledge of the CM lifting capability and projected roll-attitude profile, is sufficient to define a complete entry trajectory. Therefore, at any point in the velocity/load-factor phase plane, the limiting slope values of the EMS trace can be defined to predict the condition for which an excessive load factor, excessive range, or skipout from the atmosphere (load factor less than 0.2g) will occur.

The flight constraints consist of a series of excessive-g lines and excessive-range (skipout) lines (fig. 5). The excessive-g lines (g-onset lines) are the limiting slopes of the velocity/load-factor trace for which a peakload factor of 10g will occur. This limit is based upon an initial lift-vector-down attitude, followed by a roll to a lift-vector-up attitude after a time delay for flight-crew response. Therefore, a lift-vector-up attitude is necessary to prevent an excessive load factor if the slope of the g-onset lines is exceeded.



(a) 1350-nautical-mile range and  $-6.48^\circ$  entry flight-path angle.



(b) 1600-nautical-mile range and  $-6.48^\circ$  entry flight-path angle.

Figure 5. - Typical EMS ranging trajectories for EMS lunar nonexit range limit pattern.

The excessive-range lines (g-offset lines) are the limiting slope of the velocity/load-factor trace for which excessive range will occur. This limit is based upon an initial lift-vector-up attitude, followed by a roll to a lift-vector-down attitude after a time delay for flight-crew response. Therefore, a lift-vector-down attitude is required to prevent excessive range if the slope of the velocity/load-factor trace exceeds the

slope of the g-offset lines, of which there are two sets. One set is based upon prevention of entry ranges in excess of 3500 nautical miles, and the other is based upon prevention of a skipout of the atmosphere (load factor less than 0.2g). With proper GNCS performance and trajectory control, the 3500-nautical-mile maximum range lines permit guided entry ranges up to 2500 nautical miles without violation of the g-offset lines.

Therefore, two EMS patterns were developed. The exit pattern prevents ranges in excess of 3500 nautical miles and uses the g-onset lines combined with the 3500-nautical-mile g-offset lines. The nonexit pattern prevents skipout from the atmosphere and uses the g-onset lines combined with the nonexit g-offset lines. If either set of flight constraints on the EMS scroll is violated and if the GNCS is not already controlling the CM to an attitude that will correct the situation, the flight crew assumes a GNCS failure and manually controls the CM roll attitude to correct the trajectory deviation.

The dashed lines below a 30 000-ft/sec velocity are range-potential lines that indicate to the flight crew the ranging capability of the spacecraft. The range-potential lines are based on maintaining the current g-level throughout the remainder of the entry. These lines, in conjunction with the range-to-go display, provide the flight crew with sufficient information to permit manual range control to the planned landing site in case of a GNCS failure. No cross-range display and, therefore, no provisions for closed-loop cross-range control are provided. The range-to-go display, which is located directly below the velocity/load-factor display, is obtained by integrating the velocity used in the velocity/load-factor display.

### Backup Trajectory-Control Modes

Two backup trajectory-control modes are used for the Apollo entry. Both these modes use manual CM attitude control and are based upon constant-aerodynamic-load-factor (constant-g) trajectories. The mode normally used in event of a GNCS failure uses the EMS as the flight-crew display. The basic control technique, using the EMS, is to control the entry trajectory to a load factor of 4g until the CM velocity is reduced below the circular orbital velocity. During the subcircular orbital velocity portion of the entry, the EMS range counter and range-potential lines are used by the flight crew to control the down-range landing point. The basic technique for range control is to gain ranging potential after the CM orbital velocity becomes subcircular by maintaining a lift-vector-up attitude until the EMS velocity and load-factor  $V, g$  trace shows that the CM has more ranging potential than is required to reach the target. The excess ranging potential then is dissipated gradually so that the range-to-go and the range potential coincide when the 100-nautical-mile range-potential line is crossed. The EMS traces for manually controlled trajectories to 1350- and 1600-nautical-mile targets are shown in figure 5.

In the event of a GNCS and EMS failure, the entry is controlled to a constant-g trajectory with manual attitude control by using the g-meter and backup attitude reference as the primary displays. The theoretical lifting force and the CM attitude required to maintain equilibrium flight, and therefore approximately a constant-g flight, at any velocity is shown in figure 6. These data are based on the assumption that an

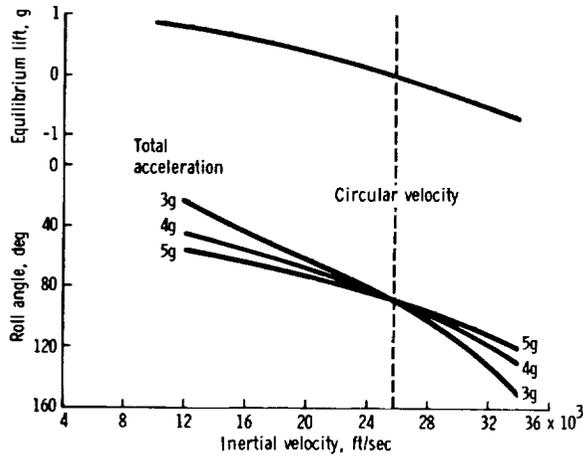


Figure 6. - Lift and associated roll angle required to hold an entry vehicle in near-equilibrium (constant-g) flight ( $L/D = 0.30$ ).

equilibrium state has been achieved; however, even for nonequilibrium conditions, these data give the flight crew an insight into the bank-angle profiles required to maintain a particular g-level.

## ENTRY TARGETING

Two types of targeting are used for the Apollo entry: velocity and flight-path angle  $V, \gamma$  targets at the entry interface and entry range. The  $V, \gamma$  targets are selected to ensure aerodynamic capture by the atmosphere of the earth while entry-ranging capability and acceptable aerodynamic heating conditions are maintained. The target entry range is chosen to be compatible with GNCS performance and to enhance the entry monitoring and backup control capabilities.

The entry-ranging capability is not used for control of the landing position relative to the surface of the earth. That is, the landing latitude is essentially at the lunar antipode at the time the CM enters the sphere of influence of the earth. This restriction occurs because the transearth trajectory must pass over the lunar antipode once the gravitational potential of the earth becomes the predominant force field, and the relatively short entry ranges result in the landing point always being located near the antipode. The landing longitude is controlled by varying the transearth injection time and by varying the transearth transit time to permit the earth to rotate to a favorable position relative to the transearth and entry trajectories. Therefore, the primary use of the variable entry-ranging capability is to make relatively small adjustments to the planned landing point during the mission to avoid bad weather conditions that may develop in the landing area.

## Velocity and Flight-Path-Angle Targeting

The  $V, \gamma$  targets for the Apollo 11 mission are shown in figure 2 as two target lines that present the target flight-path angle as a function of the entry velocity. The targets in figure 2 include the entry-velocity regime that extends from the relatively low-velocity entries caused by early aborts during translunar injection (TLI) to the high-velocity entries resulting from lunar-return trajectories.

At a lunar-return velocity of approximately 36 000 ft/sec, the shallow target line is biased above the 2500-nautical-mile-range undershoot boundary. This bias is such that this maximum range can be achieved even for a  $3\sigma$ -steep trajectory resulting from the primary transearth trajectory-control mode. This control mode uses MSFN navigation and midcourse correction maneuvers trimmed by using the small attitude control thrusters of the service module (SM). The 2500-nautical-mile-range line is based upon

the GNCS ranging capability combined with the effects of the worst-case combination of L/D, atmospheric density, trajectory inclination, and entry latitude. Targeting the entry in this manner ensures the 2500-nautical-mile-ranging capability while providing an adequate margin from the overshoot boundary. At lower velocities, this target line is placed sufficiently steep within the entry corridor to ensure capture when using the primary trajectory-control mode for TLI aborts and is placed sufficiently shallow within the corridor to provide a reasonable entry maneuver capability.

At lunar-return speeds, the steep target line is biased from the 1285-nautical-mile-range overshoot boundary by the  $3\sigma$  dispersion resulting from the backup mode of the transearth trajectory control. This control mode uses onboard navigation, based upon sextant sightings with midcourse correction maneuvers executed by the large service propulsion system engine. At the lower speeds, this target line is biased from the overshoot boundary by an amount consistent with the backup mode for trajectory control after TLI aborts.

An 1800-nautical-mile entry range can be achieved for a  $3\sigma$ -steep flight-path angle relative to the steep target line, provided the primary method of transearth trajectory control is used. This maximum range includes allowances for the worst-case combination of L/D, atmospheric density, latitude, and inclination. The nominal entry range for the Apollo 11 entry was 1285 nautical miles. Therefore, the Apollo 11 mission was targeted to the steep target line. During the mission, the Apollo 11 entry range had to be increased to 1492 nautical miles to avoid bad weather conditions. Because this longer range was also compatible with the steep target line, this  $V, \gamma$  targeting was maintained. If the entry range had been increased to a value longer than 1800 nautical miles, a shift to the shallow target line would have been necessary to ensure entry-ranging capability.

The nominal Apollo 11  $V, \gamma$  target is presented in figure 2. The entry velocity is not close to the aerodynamic heating boundaries; therefore, the heating boundaries were of secondary importance in the entry targeting. Short transearth flight times (that is, less than 1.5 days, compared with a nominal transit time of 3 days) result in entry speeds that approach the aerodynamic heating limits. Because of SM propellant limitation, these short return times cannot be achieved for a normal transearth injection and are therefore excluded from normal targeting.

## Entry Range Targeting

Three factors must be considered when selecting the target entry range. These factors are the performance of the primary entry guidance system, the entry-monitoring capability, and the backup trajectory-control modes.

The performance of the entry guidance is shown in figure 7 as a function of the down-range and cross-range target location relative to the entry-maneuver capability or footprint. The maximum open-loop footprint for an L/D of 0.29 and an L/D of 0.25 at a Mach number greater than 29.5 for the Apollo 11 entry speed and flight-path-angle targets of 39 194 ft/sec and  $-6.5^\circ$ , respectively, are shown in figure 7. Also, target locations for which the entry guidance can steer to the target, that is, the GNCS footprint, are indicated in figure 7. The GNCS footprint is divided into three areas.

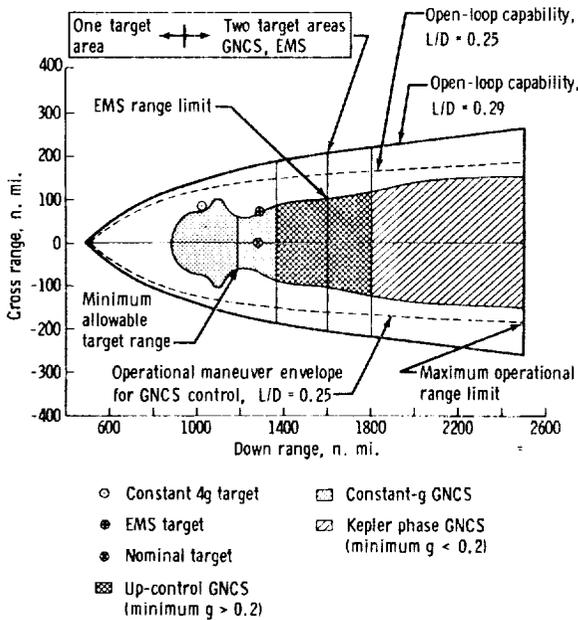


Figure 7. - Entry-guidance capability.

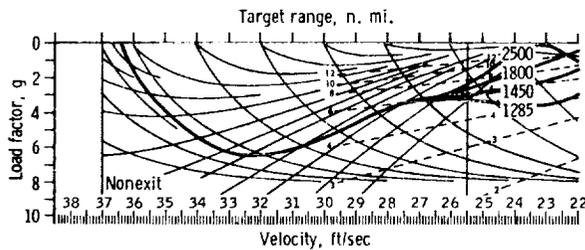


Figure 8. - Typical EMS entry traces.

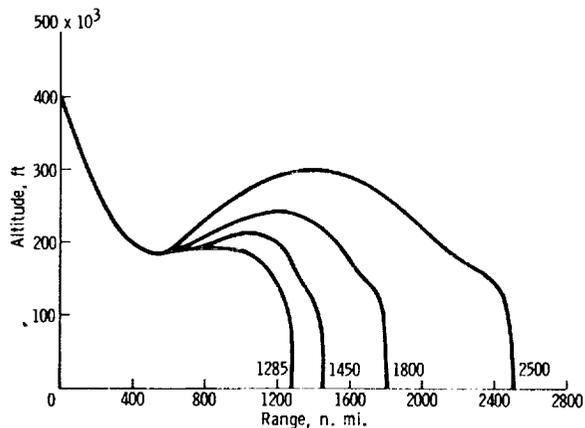


Figure 9. - Typical entry altitude/range profiles.

The first applies to long-range entry targets for which a skipout-type trajectory (that is, minimum load factor less than  $0.2g$ ) is required. Another area applies to short-range targets for which the guidance cycles directly from the constant-drag control mode to the second-entry phase. The resulting trajectory does not enter the up-control guidance logic, and very little trajectory lofting is required to reach the target. The third area applies to entry ranges that require use of the up-control guidance for trajectory lofting to reach the target, but that do not require a skipout-type trajectory; that is, no Kepler phase is required. The EMS traces for these three types of entry trajectories are shown in figure 8, and the altitude/range profiles are shown in figure 9. As shown in figure 8, monitoring with the EMS nonexit pattern is not difficult for ranges as long as 1800 nautical miles, but monitoring for longer ranges becomes more difficult and requires a change to the EMS exit pattern. With a GNCS failure, the EMS exit pattern permits entry ranges as long as 3500 nautical miles, and the EMS nonexit pattern permits shorter maximum ranges. Therefore, the use of the shorter ranges and of the EMS nonexit pattern reduces the maximum range potential with a GNCS failure. This pattern use, coupled with the fact that nonexit trajectories provide a degree of trajectory control throughout entry and eliminate the need for controlling to a critical skipout-type maneuver, led to the elimination of skipout-type trajectories from consideration for nominal targeting.

The basic GNCS areas defined in figure 7 are unaffected by variation in  $L/D$ , atmospheric density, and entry flight-path angle; however, the positions of the boundaries shift as a function of these parameters. For example, in figure 10, the boundary for the up-control/no-up-control regions is shown. This boundary is shown by plotting the entry flight-path angle as a function of the entry range. Both the nominal boundary and the extreme boundaries caused by variations in entry trajectory inclination, latitude,  $L/D$ , and atmospheric density are

shown in figure 10. Therefore, within these boundaries, the sequencing of the entry-guidance logic cannot be predicted. Because GNCS sequencing is monitored during entry to evaluate the GNCS operation, this region was eliminated from consideration for nominal targeting. The midcourse correction logic does not require course correction if the flight-path angle is within  $0.1^\circ$  on the steep side and  $0.2^\circ$  on the shallow side of the target flight-path angle. Therefore, entry ranges between 1305 and 1410 nautical miles were eliminated from consideration for nominal trajectory targeting. For guided entries, entry ranges shorter than approximately 1200 nautical miles result in a maximum load factor in excess of 7g during the second-entry phase. Therefore, ranges shorter than 1200 nautical miles were eliminated from consideration for nominal targeting.

The target points for the backup modes and the GNCS should be as close as possible to minimize recovery logistics. Therefore, the EMS and constant-g ranging potential must be evaluated. Man-in-the-loop simulations of backup control, using the EMS ranging, indicates that the maximum range for this backup control mode should be approximately 1600 nautical miles. The trajectory lofting required for longer ranges results in a difficult control task. Furthermore, a significant improvement in EMS ranging capability occurs as the entry range is decreased to less than 1600 nautical miles.

The ranging capability using the constant-g backup mode is shown in figure 11. The entry range for constant-g entries on the steep target line varies from approximately 950 to 1250 nautical miles as the g-level varies from 3g to 5g. Man-in-the-loop simulations show that controlling to a 4g level for flight-path angles on the steep target line is an easier task than controlling to either the 3g or the 5g level. It is difficult to control the transition from the peakload factor of 6.7g to the 3g level. However, once the trajectory is stabilized at the 3g level, trajectory control becomes an easy task. The 5g level is difficult to control because of the tendency to overcontrol, and the results are a highly oscillatory trajectory. Therefore, the 4g level, which results in a 1070-nautical-mile range, was selected for the constant-g backup control mode. The EMS landing point is offset laterally from the GNCS target, and the constant-g landing point is both offset laterally from and considerably short of the GNCS target (fig. 7). In both cases, the lateral offset is caused by the fact that roll reversals are not used in the manual ranging mode.

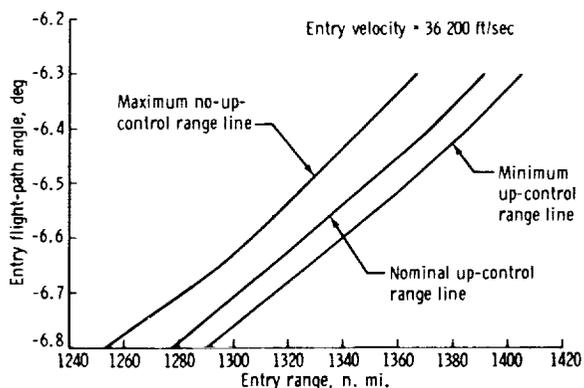


Figure 10. - Up-control breakpoint.

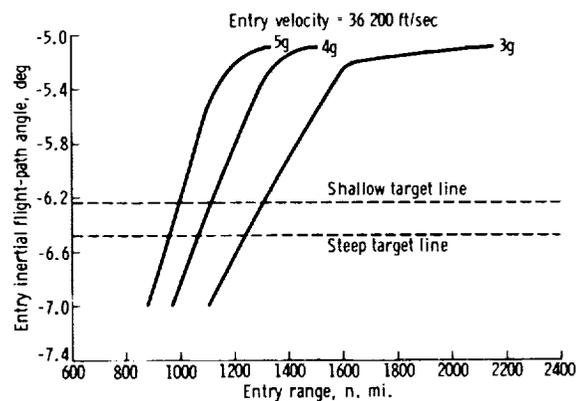


Figure 11. - Constant g ranging capability.

Based upon these ranging considerations, the best compromise for the normal targeting is an entry range between the minimum allowable range of 1200 nautical miles and the maximum no-up-control range of 1305 nautical miles. Therefore, a nominal entry range of 1285 nautical miles was selected for the Apollo 11 mission. This provided the capability of shortening the range by 85 miles to avoid bad weather conditions. Lengthening the range to avoid bad weather conditions resulted in a trade-off among targeting factors, previously discussed in this section, the particular weather problems that may exist, and the recovery force logistics.

The Apollo 11 mission was targeted at transearth injection for a 1285-nautical-mile target range. However, approximately 12 hours before entry, a bad weather system moved into the primary landing area. That close to entry, a propulsive maneuver to change the flight time and longitude of the landing would have used excessive propellant. Therefore, the CM lifting capability was used to overfly the bad weather system. The size of the bad weather system and the capability of the recovery ship to change its position caused a target range of approximately 1500 nautical miles to be chosen. The entry was executed using the GNCS control mode, with the flight crew monitoring for a system failure. The CM landed approximately 1.7 nautical miles from the desired target point. This mission clearly demonstrated the need for entry-maneuver capability with lift-vector modulation.

## POSTFLIGHT ANALYSIS

Because the majority of the entry telemetry data defining GNCS performance during the Apollo 11 entry was lost, the postflight analysis of the Apollo 10 mission results is presented. The Apollo 10 spacecraft entered the atmosphere of the earth on May 26, 1969, with an inertial velocity of 36 309 ft/sec and an inertial flight-path angle of  $-6.61^\circ$ .

The Apollo 10 entry was controlled by the GNCS, with the flight crew monitoring the onboard systems. The CMC was updated before entry with a CM state vector and a target point that resulted in an entry range of 1293 nautical miles. A comparison at the entry interface between the postflight best-estimated state vector and the state vector loaded into the CMC is given in table II. These data are indicative that an accurate state vector was provided by the ground support facilities.

The computer began the guidance commands at 0.05g, initially commanding a lift-vector-up attitude (fig. 12) to minimize the first peakload factor (6.8g). The CMC then commanded a roll to a lift-vector-down attitude to establish a constant-load factor of 4g. The g-level reached a minimum of 2.8g and then increased to 3.4g. This large overshoot of the desired g-level can be attributed to the gains in the constant-drag guidance logic. These gains have been updated for future missions to eliminate this overshoot by providing a better transition between the peakload factor and the constant 4g load factor. During the final-phase guidance, the peakload factor was 4.5g.

The response of the DAP to the roll commands generated by the entry guidance is shown in figure 12; this figure is indicative that the DAP adequately controlled the CM to the desired roll angle for trajectory control. The Apollo 10 altitude and velocity time histories are shown in figure 13.

TABLE II. - STATE-VECTOR COMPARISON AT ENTRY INTERFACE

Parameter	Best-estimated trajectory	Onboard state vector
Time, hr:min:sec . . . . .	191:48:52.16	191:48:52.16
Velocity, ft/sec . . . . .	36 309.257	36 309.548
Flight-path angle, deg . . . . .	-6.616	-6.620
Azimuth, deg . . . . .	71.928	71.932
Longitude, deg E . . . . .	174.244	174.244
Latitude, deg S . . . . .	23.652	23.653
Altitude, ft . . . . .	406 441.29	405 350.3

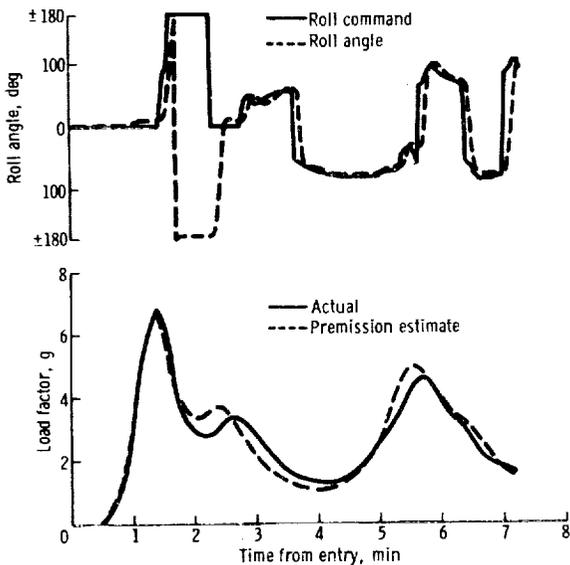


Figure 12. - Apollo 10 roll-angle and load-factor time histories.

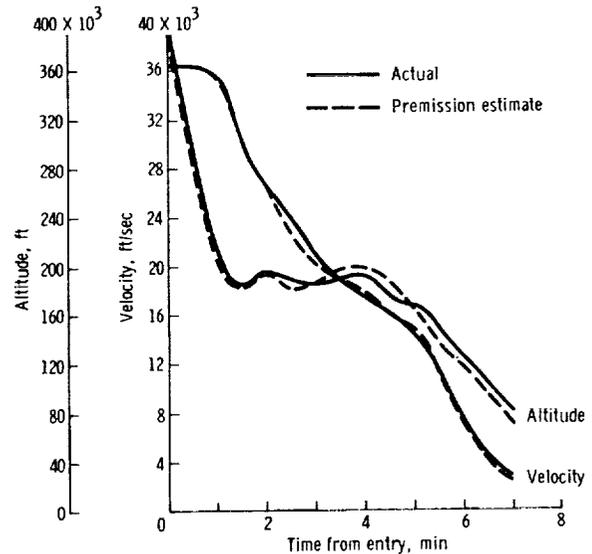


Figure 13. - Apollo 10 velocity and altitude time histories.

A comparison of the preflight, postflight-reconstructed, and inflight-measured L/D is given in figure 14. Both the inflight-measured and the postflight-reconstructed L/D are within the predicted accuracy ( $\pm 0.03$  unit) of the preflight L/D. The inflight-measured L/D was generated from GNCS accelerometer data.

The EMS scroll pattern for the Apollo 10 mission is shown in figure 15. The EMS presented an accurate V,g trace for crew monitoring of the entry and showed that the GNCS trajectory control was satisfactory.

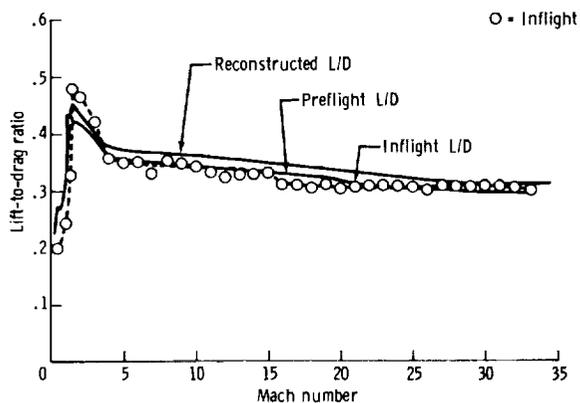


Figure 14.- Comparison of the inflight-measured and the postflight-reconstructed L/D with the preflight L/D.

A comparison of the onboard-navigation state vector at guidance termination and the postflight-reconstructed state vector is given in table III. This reconstructed state vector is based upon the best estimate of the initial state vector and the corrected GNCS accelerometer data during entry. The accelerometer data were corrected for known hardware deviations and were corrected to match drogue-parachute-deployment altitude and velocity. The navigation accuracy at guidance termination was 0.48 nautical mile, and the CM landed 1.3 nautical miles from the desired target point.

All onboard systems worked properly throughout the Apollo 10 entry. Also, the entry trajectory agreed with the preflight estimate of the entry.

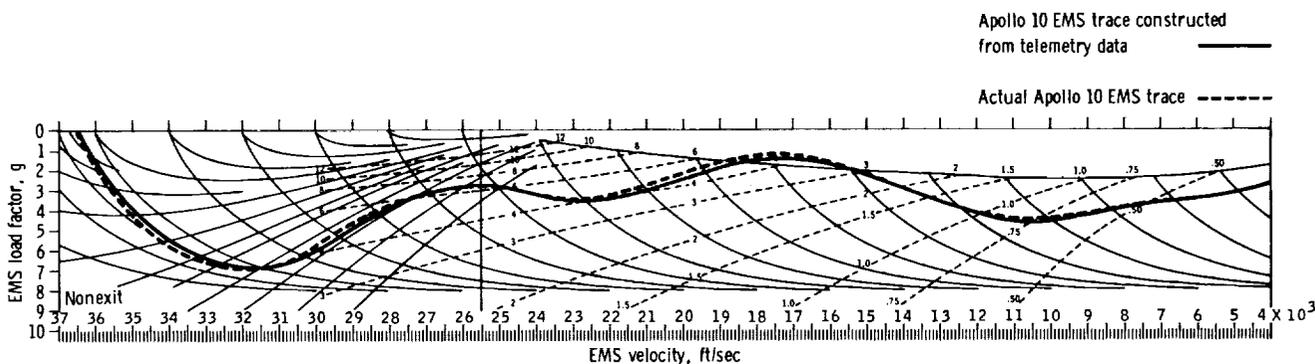


Figure 15.- Entry monitoring system trace for the Apollo 10 mission.

TABLE III.- STATE-VECTOR COMPARISON AT GUIDANCE TERMINATION

Parameter	Best-estimated trajectory	Onboard state vector
Time, hr:min:sec . . . . .	191:56:10.8	191:56:10.8
Velocity, ft/sec . . . . .	2306.3	2306.1
Flight-path angle, deg . . . . .	-16.959	-16.817
Azimuth, deg . . . . .	86.135	86.112
Longitude, deg W . . . . .	164.691	164.699
Latitude, deg S . . . . .	14.994	14.996
Altitude, ft . . . . .	62 389.2	62 130.4

## CONCLUDING REMARKS

During the preparation for the Apollo flights, problems were encountered in developing the entry mission plans, flight software, trajectory-monitoring procedures, and backup trajectory-control techniques. A discussion of these problems and their solutions is presented so that these and similar problems can be avoided in future manned space-flight programs.

The mission requirements for the entry phase must be accurately and realistically established early in the program. Consideration must be given to both the flight operation and hardware aspects of the mission. Once the mission requirements are established, the system requirements such as the lift-to-drag ratio, thermal protection system, guidance hardware, guidance software, and attitude control system requirements can be defined. Unrealistic operational requirements can result in unrealistic system requirements with significant impact on the spacecraft design. This impact can result in subsequent modifications of both the mission plan and the system design such that an undesirable compromise exists between these two factors. For example, the original mission requirements for the Apollo entry included the requirement of an operational entry-ranging capability from 1500 to 5000 nautical miles. This ranging capability was required to ensure that the earth landing point could always be at one of two target points. Subsequently, the maximum ranging requirement was relaxed because the necessary spacecraft lift-to-drag ratio could not be achieved. This relaxing of the ranging requirements resulted in the landing latitude being uncontrolled, with the possibility of earth landing occurring at any latitude between  $40^{\circ}$  N and  $40^{\circ}$  S. Because landing latitude control was no longer required, the real entry-ranging requirement was a 1000-nautical-mile maneuver capability with a maximum range of approximately 2200 nautical miles. This entry range can be achieved without the up-control phase of the entry guidance. However, because the up-control phase of the guidance is the central element of the guidance program, this basic guidance concept was retained. If the more reasonable guidance requirements had been established at the time the guidance development began, a simpler guidance concept without the up-control phase could have been designed. This simpler logic should have resulted in a significant reduction in resources required for guidance software development, verification, and testing.

The guidance logic must be simple. The Apollo entry-guidance logic was unnecessarily complicated because the basic design was based upon unrealistic mission requirements. This complicated logic, coupled with the relatively slow response of the attitude control system, meant that the performance of the logic could not be predicted accurately by the use of analytical or approximate analytical techniques. Therefore, development of the logic required extensive entry simulations throughout the entry corridor to define the performance characteristics of the logic. Furthermore, the effect on systems performance of a change in any part of the guidance logic could not be predicted accurately or extrapolated from the unmodified system performance characteristics. Therefore, complete reevaluation of the logic was required after each logic modification. Furthermore, the more complicated the guidance logic, the more difficult the guidance is to monitor during the mission. The monitoring difficulty complicates the development of the monitoring procedures and increases the time required for flight-crew training, time that often is not available.

Monitoring of the guidance performance should be considered in developing the guidance logic and the guidance displays. The monitoring considerations should not be such a driving factor that unsatisfactory compromises in the logic are made. However, the monitoring aspects should not be ignored to such an extent that the performance of the system cannot be monitored in real time to permit corrective or alternate trajectory-control procedures to be implemented in a timely manner.

The guidance logic should be compatible with a backup or an alternate trajectory-control procedure. That is, once an anomaly is detected in the trajectory control of the primary guidance system, an alternate technique must be available that will allow satisfactory trajectory control to be implemented so that the spacecraft will land near the originally selected target. This alternate-technique approach will reduce the recovery support requirements and permit greater flexibility in selecting landing points to avoid bad weather conditions and satisfy trajectory targeting and monitoring constraints.

The targeting of the entry (that is, the velocity, flight-path angle, and entry-range targeting) must be maintained at a safe margin from trajectory constraint boundaries. A conflict often exists between the constraint boundaries and the mission requirements, particularly for unmanned test flights in which the spacecraft must be tested near the system limits. A reasonable compromise between the achievement of mission objectives and the possible violation of flight constraints must be established. For example, the objective of the AS-202 (Apollo 3) flight could not be achieved without accurate knowledge of the spacecraft aerodynamic characteristics and accurate control of the entry flight-path angle. Therefore, to achieve the mission requirements, a margin existed between the targeting and the flight constraints, which resulted in a target undershot of approximately 200 nautical miles. The mission objectives were met and the spacecraft was recovered; however, a target miss had to be risked to achieve the mission requirements.

The entry-guidance logic must be insensitive to known variations in the lift-to-drag ratio and to knowledge of the true ratio. Insensitivity to known variations in the lift-to-drag ratio was achieved by careful design of the Apollo entry-guidance logic and by incorporation of erasable memory locations to "tell" the logic the expected value of the lift-to-drag ratio. This incorporation allows the lift-to-drag ratio of the spacecraft to vary as the design progresses, without serious impact on the guidance software. Insensitivity to the knowledge of the true lift-to-drag ratio was achieved by conserving ranging potential until late in the trajectory. This insensitivity must be achieved to ensure the capability for satisfactory guidance operation within the uncertainty of the spacecraft lift-to-drag ratio. Coupled with these factors is the recognition of the need for positive control of the spacecraft lift-to-drag ratio in much the same way that spacecraft weight is controlled. The effect of all proposed spacecraft modifications on the lift-to-drag ratio must be considered when the proposed design modifications are evaluated. Furthermore, for the Apollo-type entry vehicle, the flight crew and flight controllers must recognize the importance of the lift-to-drag ratio on trajectory control and the effect of equipment storage on the lift-to-drag ratio. Techniques for real-time control of equipment storage must be implemented.

The interaction between guidance system performance and attitude control system performance must be recognized. Realistic attitude control system response requirements must be established, and guidance-logic design must minimize the need for rapid response.

The entry specialists should be an integral part of the flight-crew training, flight-controller training, and flight-control teams. The entry specialists develop skills and acquire knowledge of the entry problem during the development of the guidance logic, mission plan, monitoring procedures, and backup trajectory-control techniques. These special skills and knowledge are a valuable resource to the flight controller during the real-time decisionmaking process. Furthermore, these same skills provide the entry specialists with a knowledge of the capabilities and limitations of the entry-guidance logic and of the monitoring and backup trajectory-control procedures that are necessary to define a realistic set of simulations required for flight-crew and flight-controller training.

Positive aerodynamic control of the entry trajectory should be maintained throughout entry. Control to a long-range trajectory that requires a skipout from the atmosphere is a critical maneuver that requires precise execution. The consequences of an error in controlling to the skipout make this type of trajectory undesirable.

Manned Spacecraft Center  
National Aeronautics and Space Administration  
Houston, Texas, October 12, 1971  
076-00-00-00-72

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