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065-6064

CONTRACT REQUIREMENTS	CONTRACT ITEM	MODEL	CONTRACT NO.	DATE
Exhibit E, Para.5.1	13	LEM	NAS 9-1100	14 Jan. '63

TYPE II

Primary No. 694

REPORT

065-6064

NO. LED-500-4

DATE: 31 March 1965

ABORT GUIDANCE SYSTEM  
REDEFINITION STUDIES (U)

CODE 26512

**UNCLASSIFIED**  
 To authority of 68-101-1012  
 Changed by J. Spitzer Date 11/13/72  
 Classified Document Master Control Station, NASA  
 Scientific and Technical Information Facility

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DATE	REV. BY	REVISIONS & ADDED PAGES	REMARKS

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TABLE OF CONTENTS

	<u>PAGE</u>
Glossary of Symbols . . . . .	iii
List of Figures . . . . .	vi
List of Tables . . . . .	vii
Section	
I - Summary . . . . .	1
II - Introduction . . . . .	2
A. Objectives . . . . .	2
B. Scope . . . . .	2
C. Requirements . . . . .	2
III - Guidance Law Studies . . . . .	4
A. Introduction . . . . .	4
B. Thrust Velocity Guidance . . . . .	4
Description . . . . .	4
Analysis Performed . . . . .	7
C. Delta Guidance . . . . .	14
Description . . . . .	14
Analysis Performed . . . . .	18
D. Steering Techniques . . . . .	24
1. Open-Loop Steering . . . . .	25
a) In-Plane Steering . . . . .	25
b) Out-of-Plane Steering . . . . .	26
2. Closed-Loop Steering . . . . .	27
IV - Performance Evaluation . . . . .	28
A. Evaluation Program . . . . .	28
B. Nominal Trajectories . . . . .	28
C. Performance Results . . . . .	29
Abort From Descent (No Beacon) . . . . .	29
Abort From Descent With Ascent Engine Only (No Beacon)	30
Aborts From Descent (Beacon Aided, Descent/Ascent	
Engines) . . . . .	31
Ascent From The Lunar Surface . . . . .	32
Aborts From Ascent . . . . .	32
V - Conclusions . . . . .	46
VI - References . . . . .	48
Appendix A - Delta Guidance Results . . . . .	A-1
Appendix B - Thrust Velocity Guidance Results . . . . .	B-1



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GLOSSARY OF SYMBOLS

<u>SYMBOL</u>	<u>DEFINITION</u>
AGS	Abort Guidance System
PGNCS	Primary Guidance, Navigation and Control System
$\Delta V$	Integrated Thrust Acceleration, fps.
hp	Pericynthion Altitude, feet
$\Delta V_T$	Total $\Delta V$ used, fps
$\Delta V_{MC}$	$\Delta V$ used for midcourse correction, fps
$\delta hp$	Change in pericynthion altitude, feet
$\delta \Delta V_T$	Change in total $\Delta V$ used, fps.
$\delta \Delta V_{MC}$	Change in $\Delta V$ used for midcourse correction, fps.
$\sigma$	Standard deviation
$V_g$	Velocity-to-be-gained, fps.
$\dot{V}_g$	Rate of change of velocity-to-be-gained, ft./sec. <sup>2</sup>
$\Delta f_x, \Delta f_z$	Delta functions, fps. (for Thrust Velocity Guidance)
tab	Time of abort initiation, sec.
$C_x, C_z$	Constants (for Thrust Velocity Guidance)
$t_{ol}$	Open-loop steering time (measured), secs.
$t_{nom}$	Nominal open-loop time for abort at $t = tab$ , secs.
td	Time along powered descent, secs.
$E ( )$	Error in a quantity
$V_r$	Velocity required, fps.
$x, y, z, \dot{x}, \dot{y}, \dot{z}$	Measure vehicle inertial position and velocity in ft and fps, respectively.
$X_o, Y_o, Z_o, \dot{X}_o, \dot{Y}_o, \dot{Z}_o$	Expansion point required inertial position and required velocity in ft. and fps., respectively. (For Delta Guidance).

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<u>SYMBOL</u>	<u>DEFINITION</u>
$T_0$	Expansion point time, secs.
$T$	Measured trajectory time, secs.
$K$ 's	Coefficients of the Taylor series expansion (For Delta Guidance)
$A_T$	Thrust Acceleration, ft/sec. <sup>2</sup>
$g$	Gravitational acceleration ft/sec <sup>2</sup>
$\mu$	Lunar gravitational constant, ft <sup>2</sup> /sec <sup>3</sup>
$\omega_B$	Commanded turning rate vector in body coordinates
$\underline{X}_B$	Unit vector in measured direction of X-body axis
$\underline{X}_{BC}$	Unit vector in desired direction of X-body axis
$C$	Body direction cosines
$K_i$	Steering-loop constants (gains)
$C_{ijc}$	Commanded direction cosines
LEM	Lunar Excursion Module
CSM	Command and Service Modules
$\Delta\theta$	Pitch misalignment (rotation about Y-body axis)
$\Delta\psi$	Roll misalignment (rotation about X-body axis)
$\Delta\phi$	Yaw misalignment (rotation about Z-body axis)
$\Delta\dot{\theta}$	Pitch gyro drift rate
$\Delta\dot{\psi}$	Roll gyro drift rate
$\Delta\dot{\phi}$	Yaw gyro drift rate
$R_T$	Thrust error (ascent engine)

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<u>SYMBOL</u>	<u>DEFINITION</u>
$\epsilon_X$	X- Accelerometer bias
$\epsilon_Y$	Y- Accelerometer bias
$\epsilon_Z$	Z- Accelerometer bias
$k_x$	X-Accelerometer scale factor
$k_y$	Y- Accelerometer scale factor
$k_z$	Z- Accelerometer scale factor
$\gamma_{BO}$	Burnout flight path angle, degrees.
$\sigma_I$	Central angle traversed by the LEM, degrees
Subscripts	
x,y,z,	Indicates inertial components
p	Denotes primary guidance system
A	Denotes abort guidance system

LIST OF FIGURES

<u>FIGURE</u>	<u>TITLE</u>	<u>PAGE</u>
III-1	Inertial Coordinate System .....	5
III-2	Delta Functions For Ascent Engine Only and Ascent/Descent Combination. Burnout Flight Path Angle ( $\gamma_{BO}$ ) = $0^\circ$ .....	10
III-3	Descent/Ascent Combination Delta Functions .....	11
III-4	Delta Functions For Aborts From Powered Descent .....	12
III-5	Delta Functions For Aborts From Powered Ascent and From The Lunar Surface .....	13



LIST OF TABLES

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
III-1	Determination of Thrust Error Coefficients and Errors in $\Delta V$ Components for Approximate Values .....	9
III-2	Expansion Point Coordinates and Expansion Coefficients - Abort From Powered Descent (Direct Transfer) .....	21
III-3	Expansion Point Coordinates and Expansion Coefficients - Abort From Lunar Surface and Powered Ascent (Direct Transfer) .....	22
III-4	Expansion Point Coordinates and Expansion Coefficients - Abort From Powered Descent Lunar Surface, Powered Ascent (Parking Orbit) .....	23
IV-1	Delta Guidance Performance - Abort From Descent .....	34
IV-2	Thrust Velocity Guidance - Abort From Descent .....	35
IV-3	Per Cent Contribution of AGS Errors to Change in Pericynthion Altitude and Total $\Delta V$ - Delta Guidance .....	36
IV-4	Per Cent Contribution of AGS Errors to Change in Pericynthion Altitude and Total $\Delta V$ - Thrust Velocity Guidance .....	37
IV-5	Delta Guidance Performance - Abort From Powered Descent With Ascent Engine Only .....	38
IV-6	Thrust Velocity Guidance Performance - Abort From Powered Descent With Ascent Engine Only .....	39
IV-7	Delta Guidance Performance - Abort From Beacon-aided Descent (Descent/Ascent Engine Combination)...	40
IV-8	Thrust Velocity Guidance Performance - Abort From Beacon-aided Descent (Descent/Ascent Engine Combination) .....	41
IV-9	Delta Guidance - Ascent From The Lunar Surface .....	42

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
IV-10	Thrust Velocity Guidance - Ascent From The Lunar Surface .....	43
IV-11	Delta Guidance - Abort From Ascent .....	44
IV-12	Thrust Velocity Guidance - Abort From Ascent .....	45

APPENDIX A - DELTA GUIDANCE RESULTS

A-1	Characteristics of Nominal Trajectories.....	A-2
A-2	Maximum PGNC Errors .....	A-3
A-3	3σ PGNC Initial Condition Errors and 3σ AGS Errors .....	A-4
A-4	Δhp Due to Off - Nominal Descents - No AGS Errors, 10σ PGNC Errors .....	A-5
A-5	Δhp Due to Off - Nominal Descents - No AGS Errors, Max.σ PGNC Errors .....	A-6
A-6	ΔΔVT Due to Off - Nominal Descents - No AGS Errors, 10σ PGNC Errors .....	A-7
A-7	ΔΔVT Due to Off - Nominal Descents - No AGS Errors, Max.σ PGNC Errors .....	A-8
A-8	ΔΔVMC Due to Off - Nominal Descents - No AGS Errors, 10σ PGNC Errors .....	A-9
A-9	ΔΔVMC Due to Off - Nominal Descents - No AGS Errors, Max.σ PGNC Errors .....	A-10
A-10	Δhp Due to AGS Errors (3σ Values) - 10σ PGNC Errors .....	A-11
A-11	Δhp Due to AGS Errors (3σ Values) - Max.σ PGNC Errors .....	A-12
A-12	ΔΔVT Due to AGS Errors (3σ Values) - 10σ PGNC Errors .....	A-13
A-13	ΔΔVT Due to AGS Errors (3σ Values) - Max.σ PGNC Errors .....	A-14

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
A-14	$\delta \Delta V_{MC}$ Due to AGS Errors (3 $\sigma$ Values) - 10 $\sigma$ PGNCS Errors .....	A-15
A-15	$\delta \Delta V_{MC}$ Due to AGS Errors (3 $\sigma$ Values) - Max. $\sigma$ PGNCS Errors .....	A-16
A-16	$\delta$ hp Per Cent Contribution For AGS Errors (3 $\sigma$ ) Using Nominal Descent .....	A-17
A-17	$\delta \Delta V_T$ Per Cent Contribution For AGS Errors (3 $\sigma$ ) Using Nominal Descent .....	A-18
A-18	Nominal Abort From Powered Descent - Ascent Engine Only .....	A-19
A-19	$\delta \Delta V_T$ Due to Off - Nominal Descents - No AGS Errors, Ascent Engine Only, 10 $\sigma$ PGNCS Errors .....	A-20
A-20	$\delta \Delta V_{MC}$ Due to Off - Nominal Descents - No AGS Errors, Ascent Engine Only, 10 $\sigma$ PGNCS Errors .....	A-21
A-21	$\delta$ hp Due to Off - Nominal Descents - No AGS Errors - Ascent Engine Only, 10 $\sigma$ PGNCS Errors .....	A-22
A-22	Abort From The Lunar Surface - Nominal In - Plane .....	A-23
A-23	Abort From The Lunar Surface - In Plane Effects of 3 $\sigma$ AGS Errors .....	A-24
A-24	Abort From the Lunar Surface - Nominal 0.5 Degrees Out-Of-Plane .....	A-25
A-25	Abort From The Lunar Surface - 0.5 Degrees Out-Of-Plane Effects of 3 $\sigma$ AGS Errors .....	A-26
A-26	Abort From Powered Ascent - Nominal .....	A-27
A-27	Abort From Powered Ascent - Effects of 3 $\sigma$ AGS Errors .....	A-28
A-28	Aborts From Beacon-aided Descent - Nominal Trajectory Characteristics .....	A-29
A-29	$\delta$ hp Due to Off - Nominal Beacon, Initial Condition Errors and 10 $\sigma$ PGNCS Errors - Abort From Beacon-aided Descent .....	A-30

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
A-30	$\delta \Delta V_T$ Due to Off - Nominal Beacon, Initial Condition Errors and $10\sigma$ PGNC Errors - Abort From Beacon-aided Descent .....	A-31
A-31	$\delta \Delta V_{MC}$ Due to Off - Nominal Beacon, Initial Condition Errors and $10\sigma$ PGNC Errors - Abort From Beacon-aided Descent .....	A-32
 <u>APPENDIX B - THRUST VELOCITY GUIDANCE RESULTS</u> 		
B-1	Characteristics of Nominal Trajectories .....	B-2
B-2	$\delta$ hp Due to Off - Nominal Descents - No AGS Errors, $10\sigma$ PGNC Errors .....	B-3
B-3	$\delta \Delta V_{MC}$ Due to Off - Nominal Descents - No AGS Errors, $10\sigma$ PGNC Errors .....	B-4
B-4	$\delta \Delta V_T$ Due to Off - Nominal Descents - No AGS Errors, $10\sigma$ PGNC Errors .....	B-5
B-5	$\delta$ hp Due to Off - Nominal Descents - No AGS Errors, Max. $\sigma$ PGNC Errors .....	B-6
B-6	$\delta \Delta V_{MC}$ Due to Off - Nominal Descents - No AGS Errors, Max. $\sigma$ PGNC Errors .....	B-7
B-7	$\delta \Delta V_T$ Due to Off - Nominal Descents - No AGS Errors, Max. $\sigma$ PGNC Errors .....	B-8
B-8	$\delta$ hp Per Cent Contribution For AGS Errors ( $3\sigma$ ) Using Nominal Descent .....	B-9
B-9	$\delta \Delta V_T$ Per Cent Contribution For AGS Errors ( $3\sigma$ ) Using Nominal Descent .....	B-10
B-10	$\delta$ hp Due to AGS Errors ( $3\sigma$ ) - $10\sigma$ PGNC Errors .....	B-11
B-11	$\delta \Delta V_{MC}$ Due to AGS Errors ( $3\sigma$ ) - $10\sigma$ PGNC Errors .....	B-12
B-12	$\delta \Delta V_T$ Due to AGS Errors ( $3\sigma$ ) - $10\sigma$ PGNC Errors .....	B-13

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
B-13	$\delta$ hp Due to AGS errors (36) - Max.6 PGNCS Errors .....	B-14
B-14	$\delta \Delta V_{MC}$ Due to AGS Errors (36) - Max.6 PGNCS Errors .....	B-15
B-15	$\delta \Delta V_T$ Due to AGS Errors (36) - Max.6 PGNCS Errors .....	B-16
B-16	Characteristics of Trajectories Using Ascent Engine Only - No AGS or PGNCS Errors .....	B-17
B-17	$\delta$ hp Due to Off - Nominal Descents Using Ascent Engine Only - No AGS Errors, 106 PGNCS Errors .....	B-18
B-18	$\delta \Delta V_{MC}$ Due to Off - Nominal Descents Using Ascent Engine Only - No AGS Errors, 105 PGNCS Errors .....	B-19
B-19	$\delta \Delta V_T$ Due to Off - Nominal Descents Using Ascent Engine only - No AGS Errors, 106 PGNCS Errors .....	B-20
B-20	Characteristics of Nominal Aborts From Lunar Surface .....	B-21
B-21	Effect of AGS Errors (35) On Abort From The Lunar Surface .....	B-22
B-22	Per Cent Contribution of AGS Errors To $\delta$ hp In-Plane Abort From the Lunar Surface .....	B-23
B-23	Per Cent Contribution of AGS Error to $\delta \Delta V_T$ In-Plane Abort From The Lunar Surface .....	B-24
B-24	Characteristics of Nominal Trajectories Abort From Powered Ascent .....	B-25
B-25	Effects of AGS Errors (36) - Aborts From Powered Ascent .....	B-26
B-26	Aborts From Beacon-aided Descent - Nominal Trajectory Characteristics .....	B-27
B-27	$\delta$ hp Due to Off - Nominal Beacon, Initial Condition Errors and 105 PGNCS Errors - Abort From Beacon- aided Descent.....	B-28

<u>TABLE</u>	<u>TITLE</u>	<u>PAGE</u>
B-28	$\delta \Delta V_{MC}$ Due to Off - Nominal Beacon, Initial Condition Errors and $10\sigma$ PGNC S Errors - Abort From Beacon-aided Descent .....	B-29
B-29	$\delta \Delta V_T$ Due to Off - Nominal Beacon, Initial Condition Errors and $10\sigma$ PGNC S Errors - Abort From Beacon-aided Descent.....	B-30

I. Summary

A study was performed to determine the ability of delta guidance and of thrust velocity guidance to perform aborts from powered descent, from the lunar surface and from powered ascent. This report presents the development of each guidance law plus performance results. Based on the performance results, it was concluded that both delta guidance and thrust velocity guidance can adequately perform abort maneuvers. However, it was found that delta guidance offers greater flexibility and accuracy than thrust velocity guidance.

## II. INTRODUCTION

GAEC has redefined the AGS in compliance with the directive contained in the NASA letter EG-32-2-64-377, dated 30 July 1964. The redefinition of the AGS was aimed at obtaining greater flexibility in the abort guidance system than that provided by the "T<sub>1</sub> Compensation" guidance law. It is the purpose of this report to present the results of the guidance law studies conducted during the redefinition effort. The analyses performed for this report were accomplished during a three month period commencing 1 September 1964 and ending 1 December 1964.

### A. OBJECTIVES

The primary objective of the AGS redefinition study was to determine the impact on the AGS computer design of more sophisticated guidance techniques than had been considered previously (Reference II-1). These improved guidance techniques were considered in order to obtain increased flexibility of abort operations, and to take advantage of possible improvements in sensor performance levels beyond those presently specified.

### B. SCOPE

Various perturbative and explicit guidance schemes were studied to determine the tradeoffs between computer hardware penalties versus increased flexibility and performance. The perturbative guidance system performance studies were conducted by GAEC while the explicit guidance performance studies as well as the hardware impact studies for all the guidance schemes were conducted by Space Technology Laboratories, Inc. (STL) under P.O. 2-24485-C. The results of the explicit guidance performance studies and computer hardware studies are summarized in STL report 4250-6003-R0000 (Reference II- ) and will not be discussed here. This report will concern itself primarily with the GAEC perturbative guidance studies. These perturbative studies are extensions of previous GAEC analyses which are summarized in References II-3 through II-10.

### C. REQUIREMENTS

The guidance law requirements as outlined in References II-11 and II-12 can be categorized as primary and secondary requirements. The primary requirements are those that must be satisfied by any guidance law that is to be considered for inclusion in the AGS. The secondary requirements are desirable characteristics which can give the AGS greater flexibility and capability, but which are not considered mandatory in performing the basic AGS function. The requirements are tabulated below.

#### Primary Requirements

1. Provide the capability to abort from beacon-aided or non-beacon-aided powered descent, from the lunar surface, and from powered ascent.



2. Allow a choice of burnout conditions which will result in either a nominal intercept trajectory or a parking orbit.
3. Provide the capability to perform aborts with the descent engine alone (when there is sufficient  $\Delta V$  available), with the descent-ascent engines in combination, or with the ascent engine alone.
4. Provide an orbit after the first thrusting phase whose minimum altitude is at least 30,000 feet.
5. The total  $\Delta V$  used for ascent, midcourse correction and rendezvous in the presence of three sigma total AGS sensor errors and ascent engine thrust variation shall not exceed 98% of the  $\Delta V$  budget allocated for these phases over the entire range of initial conditions specified. For an ascent from the lunar surface, a maximum out-of-plane condition of  $0.5^\circ$  must be accommodated.

Secondary Requirements

1. Provide the capability to perform aborts from coasting descent.
2. Provide the capability to perform self-contained midcourse corrections.
3. Provide the capability to determine the time and thrust vectoring requirements to inject from a phasing orbit into an ascent transfer orbit that intercepts the CSM at a point selected by the astronaut.

The analyses performed for this study were done using an IBM 7094 computer program specifically developed for this analysis. The authors wish to acknowledge the invaluable programming effort of M. J. Steigman.

### III. GUIDANCE LAW STUDIES

#### A. INTRODUCTION

The perturbative guidance laws studied by GAEC for the AGS function included thrust velocity,  $Q$ , and delta guidance. Thrust velocity is the last complex of the guidance laws and was considered the minimum acceptable system.

Thrust velocity guidance consists essentially of determining the thrust velocity removed during the descent and replacing it during the ascent. An empirically derived correction function is added to the thrust velocity components to compensate for differences between the descent and ascent trajectories. Navigation data is not required for the thrust velocity guidance scheme.

The  $Q$  guidance technique utilizes the past history of velocity-to-be-gained by integrating equations relating the rate of change of velocity-to-be-gained ( $V_g$ ) to thrust acceleration throughout all phases of powered flight. Further consideration of this guidance technique was dropped after preliminary studies indicated that it was not suitable for the abort guidance function. The primary problem was the difficulty of achieving the capability to burn out into either a direct intercept orbit or a parking orbit. Providing this capability would impose a requirement to keep track of two velocities-to-be-gained throughout the powered descent, with increased requirements for computer storage and time. Since preliminary estimates indicated that  $Q$  guidance would have an accuracy comparable to delta guidance, it was concluded that the additional complexity introduced by  $Q$  guidance was not warranted. Therefore, no further discussion of  $Q$  guidance is to be presented in this report.

The delta guidance law utilizes a Taylor series expansion about a nominal cut-off point for the computation of the velocity required by the LEM to intercept the CSM. It is a somewhat more sophisticated perturbation technique in that the guidance loop is closed through a navigation system and, therefore, has greater inherent capability to handle off-nominal conditions at the time of abort.

The following paragraphs present detailed descriptions of the thrust velocity and delta guidance techniques, plus a summary of the analyses that were required to synthesize the respective guidance techniques. The results from performance analyses of these two guidance techniques, as determined by digital computer simulations, are presented in Section IV.

#### B. THRUST VELOCITY GUIDANCE

##### Description

Thrust velocity is defined as the integrated thrust accelera-

tion vector referenced to an inertial frame. Thrust velocity guidance is based on the theory that the thrust velocity removed during the powered descent phase of the LEM mission must be replaced during an abort ascent. In order to account for differences in the descent and ascent trajectories, and for the variable phasing between the LEM and CSM, delta functions are added to the components of thrust velocity accumulated during the powered descent to obtain the initial conditions for the abort thrust velocity-to-be-gained computations.

The components of thrust velocity-to-be-gained for abort are computed at the abort initiation time as follows,

$$\begin{aligned}
 V_{gx}(t_{ab}) &= -\Delta V_x(t_{ab}) + \Delta f_x(t_{ab}) \\
 V_{gy}(t_{ab}) &= -\Delta V_y(t_{ab}) \\
 V_{gz}(t_{ab}) &= -\Delta V_z(t_{ab}) + \Delta f_z(t_{ab})
 \end{aligned}
 \tag{III-1}$$

where,

- $V_{gx}, V_{gy}, V_{gz}$  = Inertial components of thrust velocity-to-be-gained
- $\Delta V_x, \Delta V_y, \Delta V_z$  = Inertial components of integrated thrust acceleration
- $\Delta f_x, \Delta f_z$  = Preprogrammed delta functions
- $t_{ab}$  = Time of abort initiation

The inertial components of integrated thrust acceleration are obtained through the use of body mounted integrating accelerometers, and a body to inertial axis coordinate conversion. The inertial coordinate system is shown in Figure III-1.

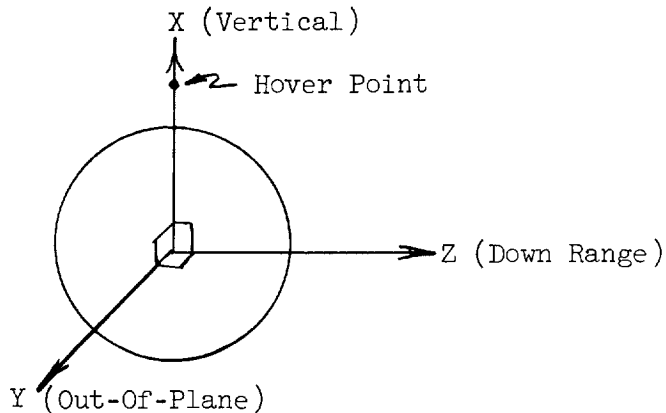


Figure III - 1

When an abort is initiated, the delta functions of equations III-1 are computed. The abort starts with an open loop pitch program that utilizes a  $\Delta V$  step profile, as discussed under steering techniques (Section II-D of this report). The thrust velocity-to-be-gained is continuously updated by the accelerometer data during this open loop phase even though the information is not being used for steering. Upon completion of the open loop phase, a closed loop guidance phase ensues in which the remaining thrust velocity-to-be-gained vector is nulled.

In order to compensate for off-nominal ascent engine thrust, a correction term proportional to the off-nominal ascent time is added to equations III-1.

$$\left. \begin{aligned} V_{gx}(t) &= -\Delta V_x(t) + \Delta f_x(t_{ab}) + C_x(t_{ol} - t_{nom}) \\ V_{gy}(t) &= -\Delta V_y(t) \\ V_{gz}(t) &= -\Delta V_z(t) + \Delta f_z(t) + C_z(t_{ol} - t_{nom}) \end{aligned} \right\} \text{(III-2)}$$

where,

- $C_x, C_z$  = Constants
- $t_{ol}$  = Measured open loop time
- $t_{nom}$  = Nominal open loop time for abort at  $t = t_{ab}$

In the implementation of the guidance law, a new set of delta functions is defined:

$$\left. \begin{aligned} \Delta F_x(t) &= \Delta f_x(t) - C_x * t_{nom}(t) \\ \Delta F_z(t) &= \Delta f_z(t) - C_z * t_{nom}(t) \end{aligned} \right\} \text{(III-3)}$$

Using these new delta functions in equations III-2, the equations for thrust velocity-to-be-gained during the closed loop guidance phase become:

$$\left. \begin{aligned} V_{gx}(t) &= -\Delta V_x(t) + \Delta F_x(t_{ab}) + C_x * t_{ol} \\ V_{gy}(t) &= -\Delta V_y(t) \\ V_{gz}(t) &= -\Delta V_z(t) + \Delta F_z(t_{ab}) + C_z * t_{ol} \end{aligned} \right\} \text{(III-4)}$$

The above discussion applies to aborts from descent as well as to aborts from the lunar surface and from ascent. However, for aborts from the lunar surface and from ascent the delta functions are functions of launch time measured from some arbitrary reference, rather than functions of abort initiation time. In the present analysis, launch time is referenced to the time when the central angle from the CSM to the LEM local vertical is 20 degrees. Components of  $\Delta V$  are accumulated from the start of ascent. For aborts from the primary ascent trajectory the starting point on the open loop pitch profile depends on the  $\Delta V$  accumulated prior to the abort initiation.

Analysis Performed

a. Determination of delta-functions and thrust error coefficients

The delta functions were determined empirically using the generalized three dimensional point mass digital computer program described in reference III-1. The guidance subroutine of the program included the primary descent guidance law and the thrust velocity abort guidance law. The descent guidance law generated a descent trajectory, and an abort was performed at a prescribed time using the thrust velocity guidance law.

The delta functions were evaluated at each abort time using an iterative procedure, as follows: Using the state vectors of the LEM and CSM at the end of the open loop phase, and with the constraint of a horizontal burnout flight path angle, the impulsive  $\Delta V$  required for a second conjunction intercept (central angle greater than 180 degrees) is computed. If no second conjunction intercept is possible, a  $\Delta V$  is computed which will put the LEM into an orbit that has an apocynthion altitude equal to the CSM orbital altitude. The computed  $\Delta V$  is converted into components of thrust velocity-to-be-gained which are nulled using the closed loop guidance law described previously. At thrust termination, the LEM will not have the desired trajectory because a finite thrust was used rather than the computed impulsive thrust. At this time, a new impulsive  $\Delta V$ , based on the present positions and velocities of the LEM and CSM is computed. This impulsive  $\Delta V$  is converted into thrust velocity-to-be-gained components which are added to those computed initially. The initial conditions at the start of the closed loop phase are restored, and the updated thrust velocity-to-be-gained vector is flown as described above. The iteration is continued in this manner until the additional  $\Delta V$  for the next iteration is less than one ft/sec, at which time the iteration process stops. Since the components of thrust velocity-to-be-gained are zero, the delta functions become:

$$\left. \begin{aligned} \Delta f_x &= \Delta V_x \\ \Delta f_z &= \Delta V_z \end{aligned} \right\} \quad \text{(III-5)}$$

where  $\Delta V_x$  and  $\Delta V_z$  are the components of thrust velocity accumulated during descent and abort ascent.

The thrust error coefficients,  $C_x$  and  $C_z$  are also determined empirically. A trajectory is flown with an off-nominal thrust, and, by using the iterative technique described previously, the exact values of thrust velocity-to-be-gained at the start of the closed loop phase are determined. Knowing the nominal and actual open loop times and the delta functions, the coefficients can be computed from the burnout conditions, using equations III-2

$$\begin{aligned}
 C_x &= \frac{\Delta V_x - \Delta f_x}{t_{ol} - t_{nom}} \\
 C_z &= \frac{\Delta V_z - \Delta f_z}{t_{ol} - t_{nom}}
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} C_x \\ C_z \end{aligned}} \right\} \text{(III-6)}$$

Some typical values are shown in Table III-1. In order to reduce the computer storage requirements for  $C_x$  and  $C_z$ , they were maintained constant for all aborts. It was found that using these constant values did not degrade the guidance law performance. For this study, the following representative values were used :

$$\begin{aligned}
 C_x &= 3.0 \text{ ft/sec}^2 \\
 C_z &= .25 \text{ ft/sec}^2
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} C_x \\ C_z \end{aligned}} \right\} \text{(III-7)}$$

Table III-1 also shows the error in thrust velocity components due to these non-exact thrust error coefficients.

Using the chosen values for  $C_x$  and  $C_z$ , the delta functions can be determined from equations III-3,

$$\begin{aligned}
 \Delta F_x &= \Delta f_x - C_x t_{nom} \\
 \Delta F_z &= \Delta f_z - C_z t_{nom}
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} \Delta F_x \\ \Delta F_z \end{aligned}} \right\} \text{(III-8)}$$

The delta functions were determined for both aborts with the ascent engine only and with the descent/ascent engine combination. When the descent engine was used, a constant thrust-to-weight ratio was commanded (0.357 for aborts prior to 280 seconds, and 0.50 for aborts after 280 seconds along the powered descent). The resulting delta functions are shown in Figure III-2.

b. Linearization of delta functions

In order to reduce the computer storage requirements, the delta functions shown in Figure III-2 have been linearized. The burnout flight path angle was determined, as a function of descent

TABLE (III-1)

DETERMINATION OF THRUST ERROR COEFFICIENTS  
AND  
ERRORS IN  $\Delta V$  COMPONENTS FOR APPROXIMATE VALUES

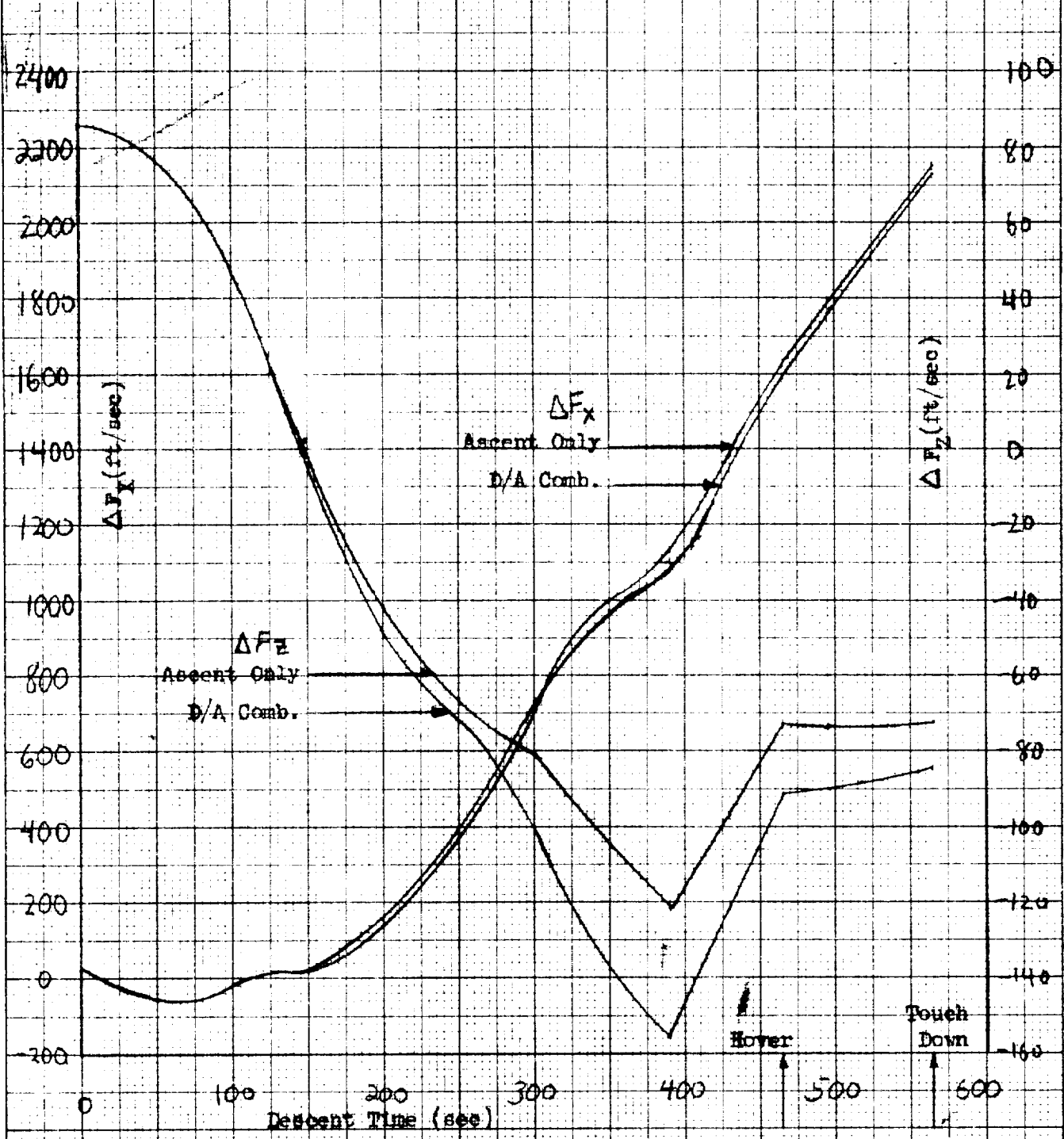
Thrust error varies linearly from 0 to 10% of nominal over burn time.

Time of Abort $t_d$ (Secs.)		250	350	390	390*
Exact $C_x$		3.44	3.66	2.87	3.4
Exact $C_z$		-.12	.27	.22	.50
$C_x = 3.0$	$\mathcal{E} (\Delta v_x)$ (ft/sec)	2.2	6.3	1.7	3.9
	$\mathcal{E} (\Delta v_z)$ (ft/sec)	1.9	.2	.4	2.0
$C_z = .25$					

\* Thrust = 3605 lbs. (+ 3%)

Figure (III-2)

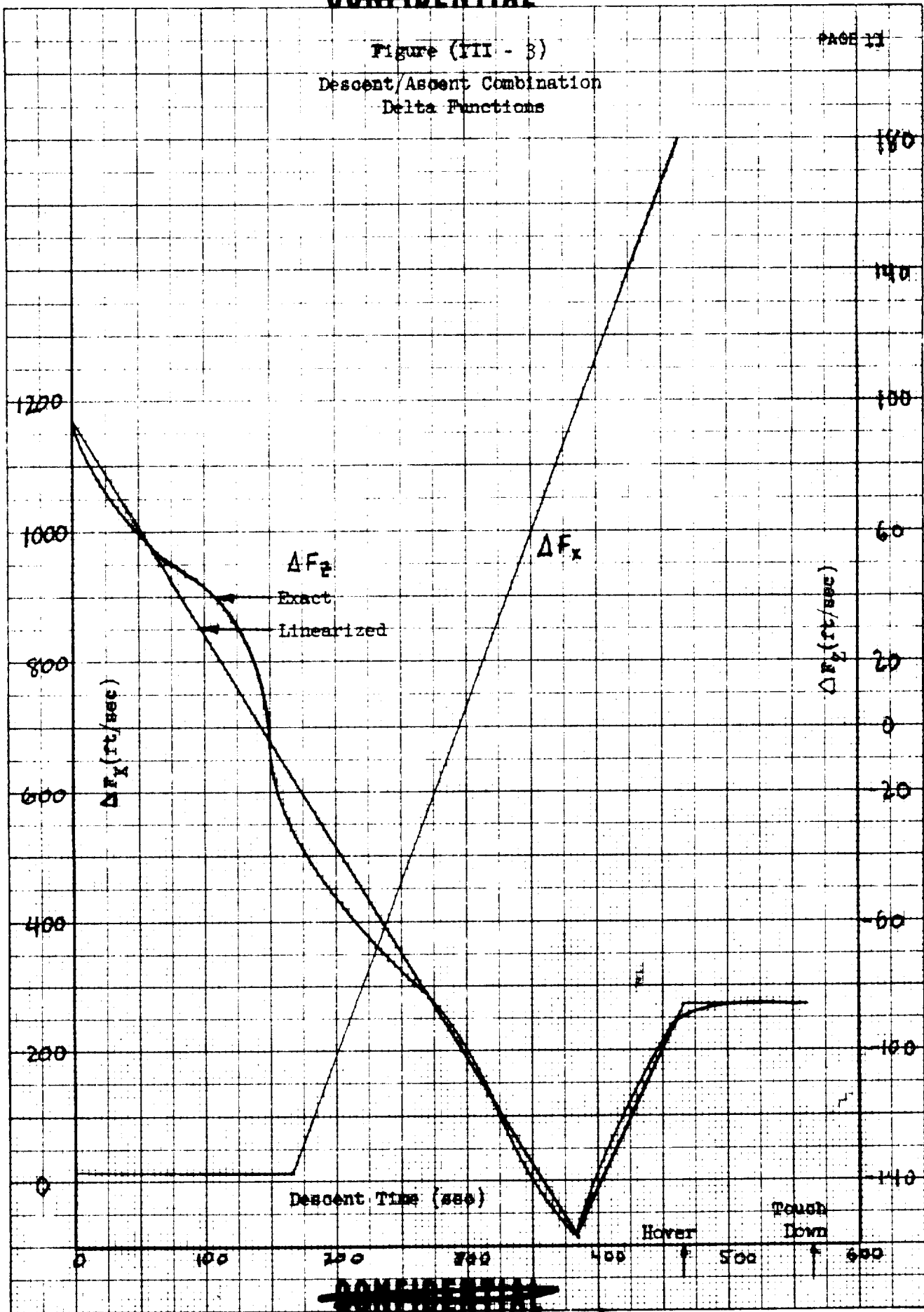
Delta Functions for Ascent Engine Only and Ascent/Descent Combination. Burnout Flight Path Angle ( $\gamma_{BO}$ ) =  $6^\circ$



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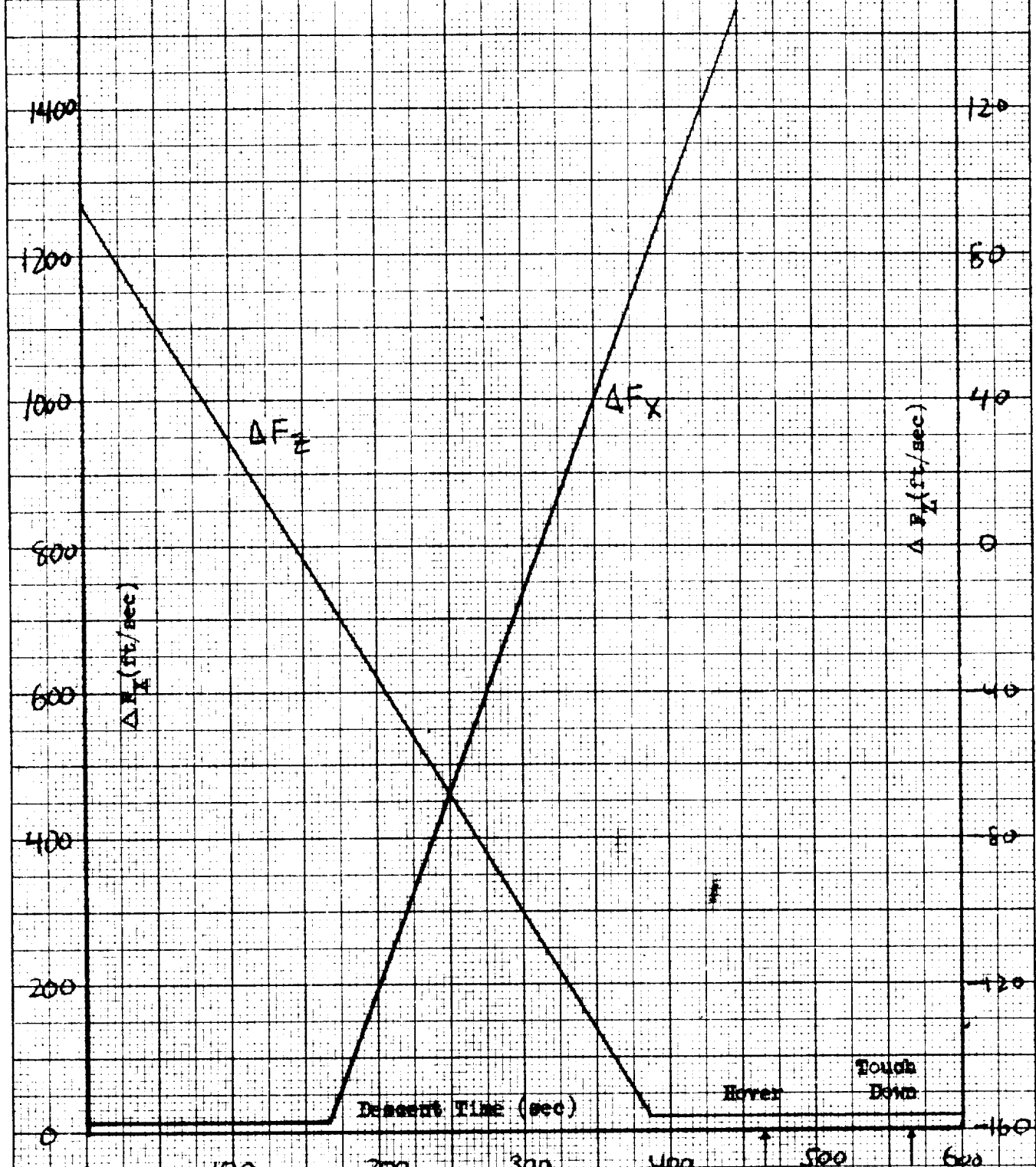
Figure (III - 3)  
Descent/Ascent Combination  
Delta Functions



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Figure (III - 4)

Delta Functions For Aborts From Powered Descent

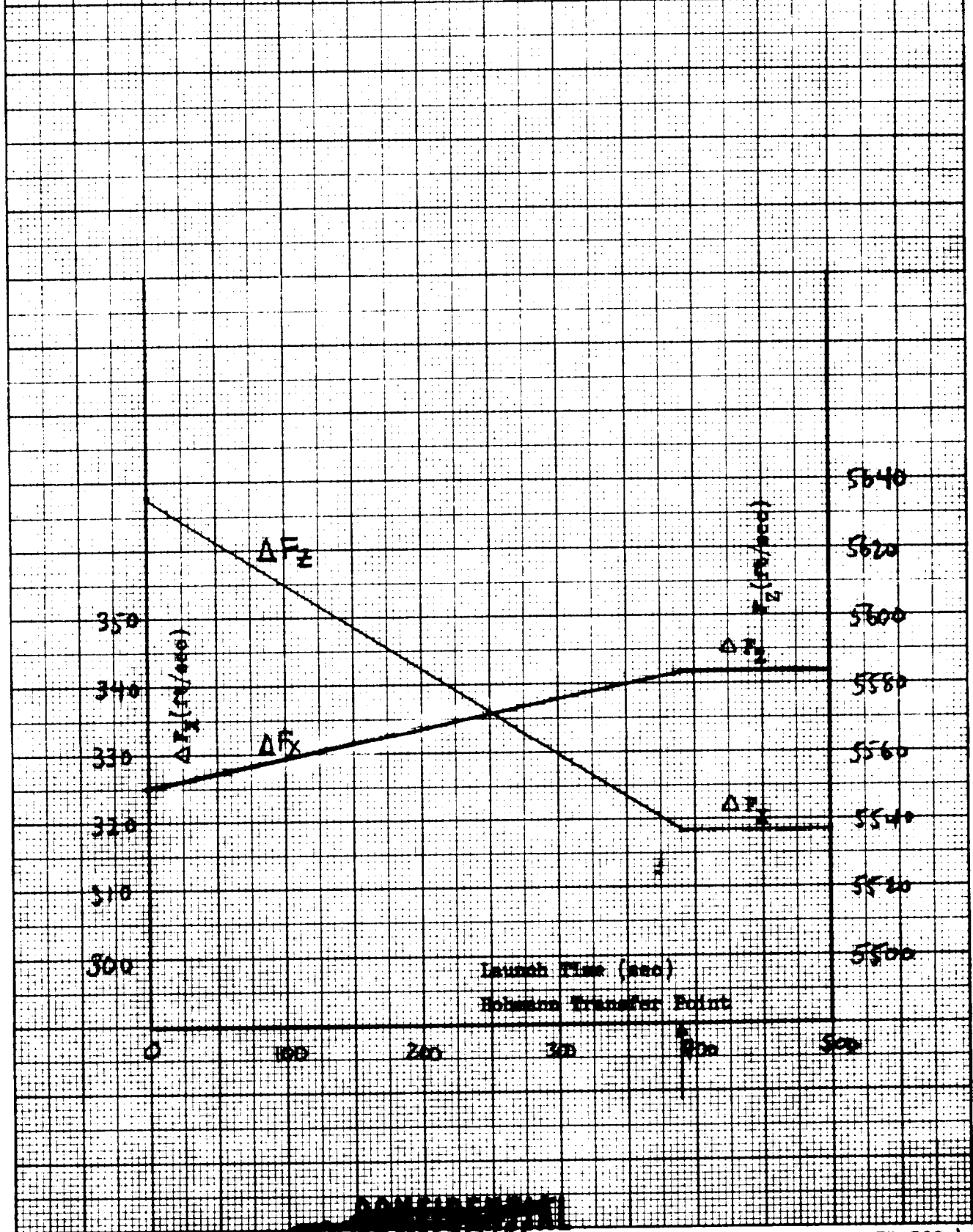


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Figure (III - 5)

Delta Functions For Aborts From Powered Ascent  
And From The Lunar Surface



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time, such that  $\Delta F_x$  was made linear as shown in Figure III-3. The maximum burnout flight path angle that was needed to achieve this linear curve was 1.4 degrees at a descent time of 390 seconds. Using the new flight path angle constraint,  $\Delta F_z$  (see Figure III-3) was determined for each abort point, using the iterative method described previously. This  $\Delta F_z$  was approximated by a series of straight lines, as shown in Figure III-3. The break in  $\Delta F_z$  at a descent time of 390 seconds is due to a change from intercept to phasing orbits. Since the delta functions for ascent engine only aborts are almost the same as for descent/ascent engine combination aborts (see Figure III-2), the same set was used for both engine configurations.

By allowing the apocynthion altitude of the phasing orbit be less than 80 nautical miles,  $\Delta F_z$  can be made constant after 390 seconds of descent time. The final form of the delta functions is shown in Figure III-4.

- a. Delta functions for aborts from primary ascent and from the lunar surface.

The delta functions for aborts from primary ascent and from the lunar surface were determined in the same manner as those for aborts from powered descent. They were found to be linear functions of launch time and, hence, the horizontal burnout flight path angle constraint did not have to be relaxed. These delta functions are shown in Figure III-5.

### C. DELTA GUIDANCE

#### Description:

The primary functions of any guidance law are to determine the required velocity needed to intercept the target and to generate thrust vectoring commands so that the vehicle achieves the required velocity. For Delta guidance, the required velocity is expressed in terms of a Taylor series expansion about a nominal burnout point. Throughout the powered flight, this series is evaluated approximately every two (2) seconds and compared to the measured vehicle velocity to determine the velocity-to-be-gained by the vehicle in order to intercept the target. When the velocity-to-be-gained is zero, the thrust is terminated and the vehicle coasts to an intercept with the target.

The velocity required to intercept the CSM is a continuous function of LEM position and time. Therefore, it can be expressed as a Taylor series expansion about a nominal position and time. The general form of the required velocity equations is as follows:

$$V_{rx} = \dot{x}_o + K_{xx}\Delta X + K_{xy}\Delta Y + K_{xz}\Delta Z + K_{xt}\Delta T + K_{xxx}\Delta X^2 + K_{xyy}\Delta Y^2 + K_{xzz}\Delta Z^2 + \dots$$

$$V_{ry} = \dot{y}_o + K_{yx}\Delta X + K_{yy}\Delta Y + K_{yz}\Delta Z + K_{yt}\Delta T + K_{yxx}\Delta X^2 + K_{yyy}\Delta Y^2 + K_{yzz}\Delta Z^2 + \dots$$

$$V_{rz} = \dot{z}_o + K_{zx}\Delta X + K_{zy}\Delta Y + K_{zz}\Delta Z + K_{zt}\Delta T + K_{zxx}\Delta X^2 + K_{zyy}\Delta Y^2 + K_{zzz}\Delta Z^2 + \dots$$

(III-9)

where:

$$\Delta X = (x - x_o)$$

$$\Delta Y = (y - y_o)$$

$$\Delta Z = (z - z_o)$$

$$\Delta T = (t - t_o)$$



(III-10)

x,y,z = measured vehicle inertial position

x<sub>o</sub>,y<sub>o</sub>,z<sub>o</sub>,ẋ<sub>o</sub>,ẏ<sub>o</sub>,ż<sub>o</sub> = expansion point required inertial position and required velocity, respectively.

T<sub>o</sub> = expansion point time

T = measured trajectory time

V<sub>rx</sub>, V<sub>ry</sub>, V<sub>rz</sub> = required velocity in inertial coordinates

K<sub>xx</sub>, K<sub>xy</sub>, K<sub>xz</sub>,

K<sub>xt</sub>, K<sub>yx</sub>, K<sub>yy</sub>,... = the coefficients of the Taylor series expansion

The coordinate system used here is the same as that used for the Thrust Velocity analyses (Figure III-1).

One or more of the coefficients (K's) used in Equations (III-9) may be zero depending on the phase of the mission from which the abort occurs. One constraint must be applied to the form of the coasting abort trajectory in order to fully define the required velocity and evaluate the Taylor series coefficients. In this study, the constraint used was a horizontal flight path at injection. This constraint was chosen since it gives indirect control over the pericyynthion of the orbit (nominal pericynthion occurs at the burnout altitude) and also results in a required velocity that varies slowly with position and time. This latter characteristic results in a series with good accuracy over a broad range of positions and times with a minimum number of coefficients.

The major problem involved in the implementation of delta guidance is to minimize the number of expansion points and expansion coefficients that have to be stored in the AGS computer. By using the trajectory constraint of a horizontal flight path at injection it was found that only three expansion points and their corresponding sets of expansion coefficients were needed to cover the spectrum of required aborts. The portion of the mission covered by each of the three sets is as follows:

a) Abort from powered descent between  $t = 0$  and  $t = 350$  seconds which result in a direct intercept orbit. Direct intercept orbits are not possible after  $t = 350$  seconds with the horizontal flight path constraint. The series, in this case requires position and time terms, plus some second order terms.

b) Abort from powered descent, from the lunar surface, or from primary ascent which result in a parking orbit. The parking orbit is defined as an orbit which has an insertion velocity equal to the velocity required for a circular orbit plus 20 fps. The series expansion for this case, contains only linear position terms.

c) Abort from the lunar surface or from powered ascents which result in direct intercept trajectories. In this case only linear terms in position and time are required.

After the required velocity has been determined the velocity-to-be-gained is computed as follows:

$$\left. \begin{aligned} V_{gx} &= V_{rx} - \dot{x} \\ V_{gy} &= V_{ry} - \dot{y} \\ V_{gz} &= V_{rz} - \dot{z} \end{aligned} \right\} \text{(III-11)}$$

The components of velocity-to-be-gained ( $V_{gx}$ ,  $V_{gy}$ ,  $V_{gz}$ ) are used to steer the vehicle in a direction such that the velocity-to-be-gained goes to zero. This direction is defined by the desired direction cosines:

$$\left. \begin{aligned} C_{11} &= \frac{V_{gx}}{V_g} \\ C_{21} &= \frac{V_{gy}}{V_g} \\ C_{31} &= \frac{V_{gz}}{V_g} \end{aligned} \right\} \text{(III-12)}$$

When the velocity-to-be-gained is zero, the required velocity and measured vehicle velocity are equal, thrust is terminated, and the LEM coasts to an intercept with the CSM (or goes into a parking orbit). The total steering for the vehicle consists of the closed loop phase just described, preceded by an open-loop phase which places the LEM in the region where the Taylor series expansion is valid. The open-loop steering phase consists of a vertical rise and a step profile pitch maneuver. The steering techniques used are the same as those for Thrust Velocity guidance, and are discussed fully in Section III-D.

Since the guidance equations use vehicle position and velocity data, a navigation loop is required. The navigation equations solved are as follows:

$$\begin{aligned} \ddot{X} &= A_{tx} + g_x \\ \ddot{Y} &= A_{ty} + g_y \\ \ddot{Z} &= A_{tz} + g_z \end{aligned} \quad \left. \vphantom{\begin{aligned} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{aligned}} \right\} \quad (III-13)$$

where:

$\ddot{X}, \ddot{Y}, \ddot{Z}$  = inertial components of vehicle acceleration

$A_{tx}, A_{ty}, A_{tz}$  = inertial components of thrust acceleration

$g_x, g_y, g_z$  = inertial components of gravitational acceleration defined by the following set of equations:

$$\begin{aligned} g_x &= -\frac{\mu}{R^3} X \\ g_y &= -\frac{\mu}{R^3} Y \\ g_z &= -\frac{\mu}{R^3} Z \\ R &= \sqrt{X^2 + Y^2 + Z^2} \end{aligned} \quad \left. \vphantom{\begin{aligned} g_x \\ g_y \\ g_z \\ R \end{aligned}} \right\} \quad (III-14)$$

where:

$\mu$  = lunar gravitational constant

$X, Y, Z$  = inertial components of vehicle position

$$\left. \begin{aligned} \dot{X} &= \int \ddot{X} dt + \dot{X}(0) \\ \dot{Y} &= \int \ddot{Y} dt + \dot{Y}(0) \\ \dot{Z} &= \int \ddot{Z} dt + \dot{Z}(0) \end{aligned} \right\} \text{(III-15)}$$

$$\left. \begin{aligned} X &= \int \dot{X} dt + X(0) \\ Y &= \int \dot{Y} dt + Y(0) \\ Z &= \int \dot{Z} dt + Z(0) \end{aligned} \right\} \text{(III-16)}$$

where:

$\dot{X}, \dot{Y}, \dot{Z}$  = inertial components of velocity

$\dot{X}(0), \dot{Y}(0), \dot{Z}(0)$

$X(0), Y(0), Z(0)$  = initial conditions of velocity and position, respectively

Analysis Performed

The primary analysis effort in developing the delta guidance law was to determine the coefficients of the Taylor series expansions for the three abort cases. The first case studied was the abort from powered descent which attains a direct intercept orbit. For various abort times along the powered descent, the nominal burnout positions and times resulting from the open loop steering profile were determined. Thirty-five (35) nominal burnout points were obtained to cover the range of aborts from  $t = 0$  to  $t = 350$  seconds. For each of these points the required velocity to intercept the USM was computed by a digital computer program using the constraint of horizontal injection. Based upon the values of the components of required velocity, an expansion point was chosen which was midway along the required velocity space. This trajectory was equivalent to an abort from 200 seconds along the powered descent. The time and position perturbations from this nominal expansion point were determined for the 35 burnout points chosen. By substituting the required velocity and the corresponding perturbations into the Taylor series for each burnout point, 35 equations were obtained for each series expansion. This over-determined set of equations was solved in a least squares sense to obtain the series coefficients. Based upon the residuals of the curve fit (i.e., the difference between the actual value of required velocity and the value calculated by means of the Taylor series expansion) it was found that the following expressions were sufficient to perform all of the aborts from powered descent.



$$\left. \begin{aligned}
 V_{rx} &= \dot{X}_{01} + K_{xx1} \Delta X + K_{xz1} \Delta Z + K_{xt1} \Delta T + K_{zzz1} (\Delta Z)^2 + K_{xtt1} (\Delta T)^2 \\
 V_{ry} &= \dot{Y}_{01} + K_{yy1} \Delta Y + K_{yyx1} \Delta Y \Delta X + K_{yyz1} \Delta Y \Delta Z + K_{yyt1} \Delta Y \Delta T \\
 V_{rz} &= \dot{Z}_{01} + K_{zx1} \Delta X + K_{zz1} \Delta Z + K_{zt1} \Delta T + K_{zzz1} (\Delta Z)^2 + K_{ztt1} (\Delta T)^2
 \end{aligned} \right\} \text{(III-17)}$$

It was also determined that equation (III-17) was valid for the following volume of space and time:

- $\Delta X = +22,169$  to  $-92,635$  ft;  $\Delta Y = +50,000$  to  $-50,000$  ft;
- $\Delta Z = +190,679$  to  $-1,939,631$  ft;  $\Delta T = +247$  to  $-484$  seconds

with a maximum error of 2.86 fps in  $V_{rx}$ , - 2.17 fps in  $V_{ry}$ , and 0.33 fps in  $V_{rz}$ . The numerical values used for the coefficients and the expansion point values are given in Table (III-2).

The next case studied was that of aborts from the lunar surface or from powered ascent that aim for a direct intercept. These aborts were performed at various times between the point where the initial phase of the CSM lags the LEM by 20° (corresponding to  $T = 0$  seconds) up to the nominal Hohmann transfer phasing (corresponding to  $T = 389$  seconds). The procedure followed was the same as that used for aborts from powered descent to determine the nominal burnout points, the corresponding required velocities, and the series expansion point. In this case, only 15 points were used since it was expected that only the first order coefficients would be required due to the smaller volume of possible burnout points as compared to aborts from descent. Based on the curve fit residuals it was found that the following expansions were sufficient for computing the required velocity:

$$\left. \begin{aligned}
 V_{rx} &= \dot{X}_{03} + K_{xx3} \Delta X + K_{xz3} \Delta Z + K_{xt3} \Delta T \\
 V_{ry} &= \dot{Y}_{03} + K_{yy3} \Delta Y + K_{yyx3} \Delta Y \Delta X + K_{yyz3} \Delta Y \Delta Z + K_{yyt3} \Delta Y \Delta T \\
 V_{rz} &= \dot{Z}_{03} + K_{zx3} \Delta X + K_{zz3} \Delta Z + K_{zt3} \Delta T
 \end{aligned} \right\} \text{(III-18)}$$

It was found that equation III-18 was valid for the following volume of space and time:

- $\Delta X = +30,000$  to  $-30,000$  ft;  $\Delta Y = +60,000$  to  $-60,000$  ft.
- $\Delta Z = +60,761$  to  $-60,761$  ft;  $\Delta T = +187$  to  $-198$  seconds

with a maximum error of 0.27 fps. in  $V_{rx}$ , -0.61 fps. in  $V_{ry}$ , and

3.16 fps. in  $V_{rz}$ . The numerical values of the coefficients and the nominal expansion point values are listed in Table III-3.

For the case of aborts from powered descent, the lunar surface, and powered ascent into a parking orbit, the coefficients were derived for a parking orbit of circular plus 20 feet per second velocity. No out of plane coefficients were derived in this case because the required out of plane velocity is zero. Since the required velocity for insertion into a parking orbit is not a function of time, no time terms are required in the velocity expansions. The technique of obtaining the coefficients is the same as for the other cases, except that only twelve burnout points and corresponding required velocities are used. This reduced number of points is satisfactory due to the fact that only the first order position coefficients are required.

Based on the foregoing discussion, the following set of equations was used to determine the required velocity:

$$\left. \begin{aligned} V_{rx} &= \dot{X}_o + K_{xx2} \Delta X + K_{xz2} \Delta Z \\ V_{rz} &= \dot{Z}_o + K_{zx2} \Delta X + K_{zz2} \Delta Z \end{aligned} \right\} \text{(III-19)}$$

Equations III-19 was determined to be valid for the following volume of space:

$$\Delta X = +42,619 \text{ to } -39,536 \text{ ft}; \Delta Z = +26,079 \text{ to } -75,532 \text{ ft.}$$

Time along descent > 350 sec; Time for launch = 389 to 600 sec. with a maximum error in  $V_{rx} = -0.11$  fps, and in  $V_{rz} = -0.12$  fps. The numerical values of the coefficients and the nominal expansion point coordinates are listed in Table III-4.

All of the studies described were performed using an IBM 7094 computer. Two separate programs were developed to determine the required velocity and to perform the least squares curve fit.

After the coefficients were developed for the delta guidance expansions a closed loop simulation and error analysis was performed. This is discussed fully in a following section.

TABLE III-2

EXPANSION POINT COORDINATES AND EXPANSION COEFFICIENTS

ABORT FROM POWERED DESCENT (DIRECT TRANSFER)

Expansion Point

$X_0 = 5.758301 \times 10^6 \text{ ft}; Y_0 = 0; Z_0 = 9.319878 \times 10^5 \text{ ft};$

$T_0 = 517.99 \text{ seconds}$

$\dot{X}_0 = -8.9394 \times 10^2 \text{ fps}; \dot{Y}_0 = 0; \dot{Z}_0 = 5.52319 \times 10^3 \text{ fps}$

Expansion Coefficients

$\underline{V_{rx}}$	$K_{xx} \text{ fps/ft}$	$K_{xz} \text{ fps/ft}$	$K_{xt} \text{ fps/sec}$	$K_{xzz} \text{ fps/fps}^2$	$K_{xtt} \text{ fps/sec}^2$
	$+6.90544 \times 10^{-5}$	$-9.57891 \times 10^{-4}$	$+7.26036 \times 10^{-2}$	$+1.35146 \times 10^{-11}$	$+1.12047 \times 10^{-4}$

$\underline{V_{ry}}$	$K_{yy} \text{ fps/ft}$	$K_{yyx} \text{ fps/ft}^2$	$K_{yyz} \text{ fps/ft}^2$	$K_{yyt} \text{ fps/ft-sec}$
	$-3.06545 \times 10^{-5}$	$-6.02954 \times 10^{-10}$	$+6.83133 \times 10^{-10}$	$-2.38789 \times 10^{-6}$

$\underline{V_{rz}}$	$K_{zx} \text{ fps/ft}$	$K_{zz} \text{ fps/ft}$	$K_{zt} \text{ fps/sec}$	$K_{zzz} \text{ fps/ft}^2$	$K_{ztt} \text{ fps/sec}^2$
	$-8.24826 \times 10^{-4}$	$-2.42252 \times 10^{-4}$	$-2.27197 \times 10^{-1}$	$-1.55180 \times 10^{-10}$	$+2.03778 \times 10^{-6}$

TABLE III-3

EXPANSION POINT COORDINATES AND EXPANSION COEFFICIENTS

ABOVE FROM LUNAR SURFACE AND POWERED ASCENT (DIRECT TRANSFER)

Expansion Point

$X_0 = 5.666072 \times 10^6 \text{ ft}; Z_0 = 9.75044 \times 10^5 \text{ ft}; T_0 = 612.904 \text{ seconds}$

$\dot{X}_0 = -9.5721 \times 10^2 \text{ fps}; \dot{Y}_0 = 0; \dot{Z}_0 = 5.56243 \times 10^3 \text{ fps}$

Expansion Coefficients

$\underline{V_{rx}}$	$K_{xx} \text{ fps/ft}$	$K_{xz} \text{ fps/ft}$	$K_{xt} \text{ fps/sec}$
	$+3.18596 \times 10^{-4}$	$-9.25381 \times 10^{-4}$	$+4.43291 \times 10^{-2}$

$\underline{V_{ry}}$	$K_{yy} \text{ fps/ft}$	$K_{yyx} \text{ fps/ft}^2$	$K_{yyz} \text{ fps/ft}^2$	$K_{yyt} \text{ fps/ft-sec}$
	$-7.73768 \times 10^{-5}$	$+9.47371 \times 10^{-9}$	$+4.50387 \times 10^{-9}$	$-5.49789 \times 10^{-7}$

$\underline{V_{rz}}$	$K_{zx} \text{ fps/ft}$	$K_{zz} \text{ fps/ft}$	$K_{zt} \text{ fps/sec}$
	$-6.64075 \times 10^{-4}$	$-8.58322 \times 10^{-5}$	$-2.09014 \times 10^{-1}$

TABLE III-4

EXPANSION POINT COORDINATES AND EXPANSION COEFFICIENTS

ABOUT FROM POWERED DESCENT, LUNAR SURFACE, POWERED ASCENT (PARKING ORBIT)

Expansion Point

$X_0 = 5.718618 \times 10^6 \text{ ft}; Z_0 = 1.0965882 \times 10^6 \text{ ft.}$

$\dot{X}_0 = -1.02977 \times 10^3 \text{ fps}; \dot{Z}_0 = 5.37014 \times 10^3 \text{ fps.}$

Expansion Coefficients

$\frac{V}{r_x}$	$K_{xx} \text{ fps/ft}$	$K_{xz} \text{ fps/ft}$
	$+2.76292 \times 10^{-4}$	$-9.10234 \times 10^{-4}$

$\frac{V}{r_z}$	$K_{zx} \text{ fps/ft}$	$K_{zz} \text{ fps/ft}$
	$-4.17091 \times 10^{-4}$	$-2.59368 \times 10^{-4}$

D. STEERING TECHNIQUES

The purpose of the abort steering law is to null the components of velocity-to-be-gained, and also to achieve efficiently a safe burnout altitude. Ascent abort steering first provides an open loop phase which is designed to achieve a safe burnout point near the nominal burnout point for which the perturbative guidance equations are derived. This is followed by a closed loop phase which nulls the velocity-to-be-gained. The same open and closed loop steering law equations were used for Thrust-Velocity and for Delta guidance.

The basic concept used for both the open and closed-loop steering equations was to develop a rate proportional to the vector cross-product of the measured vehicle X-Body axis direction and the commanded direction of the X-Body axis.

$$\underline{\omega}_{CB} = (\underline{X}_B) \times (\underline{X}_{BC}) \tag{III-20}$$

where

$\underline{\omega}_{CB}$  = commanded turning rate vector in body coordinates.

$\underline{X}_B$  = unit vector in measured direction of X-Body axis

$\underline{X}_{BC}$  = unit vector in desired direction of X-Body axis

Since  $\underline{X}_B$  and  $\underline{X}_{BC}$  are unit vectors, equation (III-20) reduces to:

$$\underline{\omega}_{CB} = \left| \underline{X}_B \right| \left| \underline{X}_{BC} \right| \sin \theta = \sin \theta \tag{III-21}$$

where

$\theta$  = the angle between the measured and commanded position vectors.

The components of the commanded turning rate, expressed in terms of direction cosine yield the steering equations.

$$\begin{aligned} \omega_{YB} &= -K_1 \left\{ \begin{matrix} C_{11C} C_{13} + C_{23} C_{21C} + C_{31C} C_{33} \end{matrix} \right\} \\ \omega_{ZB} &= K_2 \left\{ \begin{matrix} C_{11C} C_{12} + C_{21C} C_{22} + C_{31C} C_{32} \end{matrix} \right\} \\ \omega_{XB} &= -K_3 C_{23} \end{aligned} \tag{III-22}$$

where

$\omega_{YB}, \omega_{ZB}, \omega_{XB}$  = the components of the steering signal in body coordinates

$C_{ij}$  = body direction cosines.  $i = 1, 2, 3, \dots j = 1, 2, 3.$

$K_i$  = steering-loop constants (gains).  $i = 1, 2, 3.$

$C_{ijC}$  = commanded direction cosines.  $i = 1, 2, 3. j = 1, 2, 3.$

1. Open-Loop Steering

The open-loop pitch profile developed here was used for both Thrust Velocity and Delta guidance. The open-loop steering function consists of in-plane and out-of-plane steering. These two facets of the steering problem are discussed separately in the following paragraphs.

a) In - Plane Steering

The open-loop profile developed for in-plane steering was a step pitch attitude vs.  $\Delta V$  program. It consists of the following operations:

- 1) Rise vertically until  $\Delta V = \Delta V_1$ .
- 2) Pitch over to an angle  $\theta_1$ , and maintain this angle until  $\Delta V = \Delta V_2$ .
- 3) Pitch over to an angle  $\theta_2$ , and maintain this angle until  $\Delta V = \Delta V_3$ .
- 4) When  $\Delta V = \Delta V_3$ , start closed-loop operation.

The  $\Delta V$ 's used as termination points for the open-loop profile were computed as follows:

For abort from powered descent,

$$\Delta V_1 = \begin{cases} Z_{11} t_{ab} + Z_{12} t_{ab}^2 & t_{ab} < t_h \\ Z_{11} t_h + Z_{12} t_h^2 & t_{ab} \geq t_h \end{cases} \quad \text{(III-23)}$$

$$\Delta V_2 = \begin{cases} 0 & t_{ab} \leq t_{21} \\ Z_{21} (t_{ab} - t_{21}) & t_{21} < t_{ab} < t_{22} \\ Z_{21} (t_{22} - t_{21}) & t_{ab} \geq t_{22} \end{cases} \quad \text{(III-24)}$$

$$\Delta V_3 = \begin{cases} 0 & t_{ab} \leq t_{31} \\ Z_{31} (t_{ab} - t_{31}) & t_{31} < t_{ab} < t_{32} \\ Z_{31} (t_{32} - t_{31}) & t_{ab} \geq t_{32} \end{cases} \quad \text{(III-25)}$$

For abort from the lunar surface or powered ascent.

$$\Delta V_1 = Z_{11} t_h + Z_{12} t_h^2 \quad \text{(III-26)}$$

$$\Delta V_2 = Z_{21} (t_{22} - t_{21}) \quad \text{(III-27)}$$

$$\Delta V_3 = Z_{31} (t_{32} - t_{31}) \quad \text{(III-28)}$$

where:  $Z_{11}, Z_{12}, Z_{21}, Z_{31}, t_{11}, t_{21}, t_{22}, t_{31}, t_{32}$  are constants  
 $t_{ab}$  = time of abort

For the above open-loop pitch profile the following direction cosines are commanded:

1.) For  $\Delta V < (\Delta V_{\text{abort}} + \Delta V_1)$

$$C_{11C} = 1$$

$$C_{21C} = 0$$

$$C_{31C} = 0$$

2.)  $(\Delta V_{\text{abort}} + \Delta V_1) \leq \Delta V < (\Delta V_{\text{abort}} + \Delta V_1 + \Delta V_2)$

$$C_{11C} = K_1 = \cos \theta_1$$

$$C_{21C} = 0$$

$$C_{31C} = K_2 = -\sin \theta_1$$

3.)  $(\Delta V_{\text{abort}} + \Delta V_1 + \Delta V_2) \leq \Delta V < (\Delta V_{\text{abort}} + \Delta V_1 + \Delta V_2 + \Delta V_3)$

$$C_{11C} = K_3 = \cos \theta_2$$

$$C_{21C} = 0$$

$$C_{31C} = K_4 = -\sin \theta_2$$

4.)  $\Delta V \geq (\Delta V_{\text{abort}} + \Delta V_1 + \Delta V_2 + \Delta V_3)$

Use closed-loop operation as defined in the paragraphs on closed-loop steering.

b) Out-of-Plane Steering

In order to minimize the out-of-plane  $\Delta V$  required for the abort maneuver, it is desirable to steer the IIM into the CSM plane during the ascent. For aborts from powered descent it is necessary to measure the out-of-plane velocity and displacement. This necessitates an inertial reference unit, and for this reason the out-of-plane steering technique is not applicable to thrust velocity guidance.

The following direction cosines are used for out-of-plane aborts from powered descent when using delta guidance.

$$C_{21C} = \begin{cases} (\omega_1 Y_0 + \omega_2 \dot{Y}_0) & \text{for } \Delta V < 2950 \\ (\omega_3 Y_0 + \omega_4 \dot{Y}_0) & \text{for } \Delta V > 2950 \end{cases} \quad \text{(III-29)}$$



where:  $\omega_1, \omega_2, \omega_3, \omega_4 = \text{constants}$   
 $Y_0, \dot{Y}_0 = \text{initial out-of-plane position and velocity, respectively.}$

In the case of aborts from the lunar surface it is possible to determine the out-of-plane position of the vehicle prior to launch, and to insert this position into the AGS as an initial condition. For this reason, the following direction cosines are applicable to both thrust velocity and delta guidance.

$$C_{21C} = \begin{cases} -\omega_5 \Delta Y & \text{for } \Delta V < 2950 \\ \omega_5 \Delta Y & \text{for } \Delta V > 2950 \end{cases} \quad \text{(III-30)}$$

where:  $\omega_5 = \text{constant}$   
 $\Delta Y = \text{initial out-of-plane position.}$

2. Closed-Loop Steering

For the closed-loop portion of the trajectory when  $\Delta V \geq \text{abort} + \Delta V_1 + \Delta V_2 + \Delta V_3$ , the commanded direction cosines are determined by the velocity-to-be-gained as follows:

$$\begin{aligned} C_{11C} &= \frac{V_{gx}}{V_g} \\ C_{21C} &= \frac{V_{gy}}{V_g} \\ C_{31C} &= \frac{V_{gz}}{V_g} \end{aligned} \quad \left. \vphantom{\begin{aligned} C_{11C} \\ C_{21C} \\ C_{31C} \end{aligned}} \right\} \text{(III-31)}$$

where

$$V_g = \sqrt{V_{gx}^2 + V_{gy}^2 + V_{gz}^2}$$

$V_{gx}, V_{gy}, V_{gz} = \text{components of velocity-to-be-gained (in the case of thrust velocity guidance these would be components of thrust velocity-to-be-gained).}$

$C_{11C}, C_{21C}$  and  $C_{31C}$  are held constant when  $V_{gz} \leq V_{crit}$  (a constant). When  $V_{gz} = 0$ , thrust cut-off is commanded. The reason for holding the direction cosines constant during the final phase is to prevent large body rates from being commanded as  $V_g$  approaches zero.

IV. PERFORMANCE EVALUATIONA. EVALUATION PROGRAM

The Delta and Thrust-Velocity guidance laws were evaluated with the use of a digital simulation program. The salient features of the program are as follows:

1. Closed loop simulation.
2. 3 degree-of-freedom point mass.
3. Body rate limitation = 10 deg/sec.
4. Contains an IMU error model (see Reference IV-1), Landing Radar Update, Rendezvous Radar update (beacon landing), ACS inertial component error model.
5. Determines the  $3\sigma$  deviation of the minimum altitude of the orbit achieved after the first burn. (AGS burnout covariance matrix propagated to the point of minimum altitude.)
6. Capable of determining the impulsive  $\Delta V$  required for a direct intercept. Midcourse correction is performed at burnout, and is based on minimum  $\Delta V$  for midcourse plus rendezvous.
7. Capable of determining the impulsive  $\Delta V$  required for parking orbits. Transfer into an intercept orbit is performed after 20 minutes of coasting, and is based on a minimum  $\Delta V$  for injection plus rendezvous.
8.  $180^\circ \pm 20^\circ$  central angle coasting trajectories are excluded to minimize out-of-plane  $\Delta V$  correction.
9. Capable of determining  $3\sigma$  deviations in total  $\Delta V$  and midcourse  $\Delta V$  due to ACS sensor errors and thrust magnitude variations.

B. NOMINAL TRAJECTORIES

The nominal trajectories assumed for the purposes of the Redefinition Study are identical to those described in Reference IV-2. The trajectories (nominally flown by the PGNS, Reference IV-1) are briefly described below.

The LEM and GSM are initially in an 80 n. mi. circular orbit. At 192.4 degrees before the hover point, the insertion maneuver is initiated. The completion of this maneuver by LEM results in a Hohmann orbit which has a pericyynthion altitude of 50,000 feet.

The pericyynthion occurs at a central angle of 12 degrees prior to the hover point. At this time the optimum fuel portion (Phase 1) of the powered descent is initiated. Approximately 349 seconds later Phase 1 terminates and the visibility phase (Phase 2) is initiated. Phase 2, which is completed at the hover point, lasts approximately 115 seconds. Landing radar updating of the PCWCS starts at 25,000 feet. This point nominally occurs 220 seconds after the start of powered descent. The hover to touchdown maneuver lasts 564 seconds and terminates at touchdown on the lunar surface.

The nominal powered ascent trajectory starts from a launch position that is displaced  $\frac{1}{2}$  degree from the CSM orbit plane. Ascent is initiated when the phase of the CSM lags the landing point by 3.85 degrees. Burnout occurs at 50,000 feet above the mean lunar surface, at which point the LEM out-of-plane displacement with respect to the CSM orbit plane is 0.732 degrees. The central angle from burnout to CSM intercept is 160 degrees.

Rendezvous is initiated when the LEM is 5 n. mi. from the CSM, and terminates when the LEM is 0.25 n. mi. from the CSM with a relative velocity of about 3.0 feet per second.

C. PERFORMANCE RESULTS

The basic AGS modes that were simulated included aborts from powered descent, aborts from the lunar surface and aborts from primary ascent. In each case the nominal characteristics of the abort trajectory, the variations produced by off-nominal conditions at abort time, and the variations produced by the AGS sensor and thrust errors were determined. The trajectory parameters of interest include pericynthion altitude, total  $\Delta V$  and midcourse  $\Delta V$ . Pericynthion altitude and total  $\Delta V$  are measures of safety and mission success, while midcourse  $\Delta V$  is a measure of the guidance law accuracy.

Abort From Descent (No Beacon)

Tables IV-1 and IV-2 present some typical performance results for aborts from powered descent when using Delta and Thrust Velocity guidance, respectively. The aborts were performed from several points along a nominal descent trajectory at times between 100 and 564 seconds. The nominal abort trajectory characteristics were determined for each case. The early aborts (before 350 seconds) resulted in direct intercept orbits, while the later aborts (350 to 564 seconds) resulted in parking orbits. Injection into an intercept orbit from a parking orbit was initiated 20 minutes after burnout. Tables IV-1 and IV-2 show that the abort pericynthion altitude was well above the required 30,000 feet for both Delta and Thrust Velocity guidance. Also, the total  $\Delta V$  was less than the budget for both guidance techniques. For the direct intercept orbits, the delta guidance technique required considerably smaller midcourse corrections than the thrust velocity technique. This smaller midcourse correction is indicative of the greater guidance law accuracy inherent in the delta guidance technique due to its closed loop character.

The R.S.S. trajectory variations resulting from the ACS sensor errors and thrust magnitude variations were also determined and are shown on the right hand side of Tables IV-1 and IV-2. In all cases, the three-sigma variations of pericynthion altitude and total  $\Delta V$  are sufficiently small so that their addition to the nominal values does not cause a violation of the pericynthion altitude and total  $\Delta V$  constraints.

Tables IV-3 and IV-4 show the percentage contribution of the major ACS errors to the change in pericynthion altitude and total  $\Delta V$  for delta guidance and thrust velocity guidance, respectively. The major contributors to change in pericynthion altitude are:

1.  $\Delta\theta_A$  = pitch misalignment (rotation about Y-body axis)
2.  $\Delta\dot{\theta}_A$  = pitch gyro drift rate and
3.  $\mathcal{K}_D$  = Thrust error (ascent engine).

The major contributors to change in total  $\Delta V$  are:

1.  $\Delta\theta_A$  = pitch misalignment (rotation about Y-body axis)
2.  $\Delta\gamma_A$  = roll misalignment (rotation about x-body axis)
3.  $\Delta\dot{\theta}_A$  = pitch gyro drift rate
4.  $\Delta\dot{\phi}_A$  = yaw gyro drift rate
5.  $\mathcal{K}_D$  = Thrust error (ascent engine)

The effects of off-nominal descents on the abort trajectories were determined by aborting from descents produced by abnormally large PGNS errors. The PGNS errors considered were 80% of the error that would result in the LEM violating the dead man's curve (boundary of altitude versus altitude rate which will result in the LEM hitting the lunar surface even if maximum vertical thrust is applied). The abort trajectory characteristics for three possible PGNS errors and abort times are shown at the bottom of Tables IV-1 and IV-2. These results are representative of a large number of aborts that were performed for various PGNS errors and abort times. A summary of all of the aborts performed is contained in Appendices A and B. In all cases the pericynthion altitude and total  $\Delta V$  constraints were satisfied.

Abort From Descent With Ascent Engine Only (No Beacon)

Tables IV-5 and IV-6 present the performance results of aborts from powered descent performed with the ascent engine only. All of the abort trajectories maintained pericynthion altitudes well above the 30,000 ft. minimum, and completed rendezvous with the CSM within the LEM  $\Delta V$  budget.

The effect of AGS errors on these abort trajectories is the same as the effect on aborts using the descent/ascent engine combination previously discussed. The AGS error contributions are contained in Tables IV-1 through IV-4.

The effects of off-nominal descents on the abort trajectories were determined by aborting from descents produced by large PGNCS errors. For this study, only the trajectory times (i.e. 399,464, and 565 seconds) that used large amounts of  $\Delta V$  were considered. The PGNCS errors that contributed the most significant errors in total  $\Delta V$ , midcourse  $\Delta V$  and pericyynthion altitude were:

1.  $\Delta\theta_p$  = pitch misalignment and
2.  $\epsilon Z_p$  = Z - accelerometer bias.

A summary of results is presented in the right-hand columns of Tables IV-5 and IV-6. All of the results from the study are given in Appendicies A and B. The results show that even with these errors the abort trajectory remains within the  $\Delta V$  budget and well above the 30,000 feet minimum pericynthion altitude.

Aborts From Descent (Beacon-Aided , Descent/Ascent Engines).

Tables IV-7 and IV 8 present the performance results of aborts from beacon-aided powered descent for delta and thrust-velocity guidance, respectively. The trajectory used for a beacon-aided descent is slightly different from that used for a nominal powered descent without a beacon. The major difference between the two trajectories is that the visibility phase (Phase 2) of the beacon-aided trajectory starts at an altitude of 36,000 feet above the lunar surface and at a range of 20 n. mi. prior to the hover point, while Phase 2, for the nominal powered descent, starts at an altitude of 10,600 feet and a range of 7 n. mi. from the hover point. In addition, the beacon-aided trajectory uses 200 fps more  $\Delta V$  to reach the hover point than is used for the nominal powered descent.

The results contained in Table IV-7 show that delta guidance is not affected by the use of the beacon-aided descent, that the trajectories still maintain clear pericynthion altitudes, and that rendezvous with the CSM is attained within the LEM  $\Delta V$  budget. Thrust-velocity guidance, however, is affected by the change in descent trajectory. The results contained in Table IV-8 show that the late aborts (i.e. 399,464, and 565 seconds) would need delta functions differing from those used in order to maintain a clear pericynthion altitude.

The effects of AGS errors on these abort trajectories is about the same as the effects of AGS errors on the nominal powered descent. These results are summarized in Tables IV-1 to IV-4.

The errors due to off-nominal position and velocity at the start of powered descent coupled with an off-nominal beacon position were evaluated. In addition, these errors were then coupled with an off-nominal descent trajectory and the total effect investigated. The results of this study indicated that the largest trajectory errors are due to off-nominal beacon position, and off-nominal beacon position coupled with a PENEIS pitch-axis misalignment. These errors are indicated on the right-hand side of Tables IV-7 and IV-8. The results indicate that despite these errors the clear pericyynthion altitude is still maintained, and rendezvous is achieved within the  $\Delta V$  budget for both Delta and Thrust Velocity guidance (except for those cases of Thrust-velocity where delta functions differing from those used would be required).

Ascent From The Lunar Surface

Ascents from the lunar surface were simulated for various lift-off times, and for in-plane and 0.5 degree out-of-plane launch sites. A summary of the simulation results for the Delta and Thrust Velocity guidance techniques is presented in Tables IV-9 and IV-10, respectively. The results show that both guidance laws give satisfactory performance, since the pericynthion altitude and  $\Delta V$  constraints are satisfied in all cases when the 3 sigma deviations due to AGS errors are added to the nominal values. Ascents to a direct intercept were performed over a 300 second range of lift-off times, with the earliest lift-off occurring when the CSM radius vector is 20° before the landing site vertical. The early ascents result in a larger total  $\Delta V$  than the later direct intercept ascents, but are still within the  $\Delta V$  budget. This  $\Delta V$  increase is due to an excessive difference in phasing between the LEM and the CSM that requires a LEM  $\Delta V$  and large maneuvers in order to rendezvous with the CSM. A late ascent was also performed, where the phasing was such that a direct intercept was no longer possible. In this case, the LEM was inserted into a parking orbit for 20 minutes. Upon expiration of the 20 minutes, a transfer to an intercept orbit was initiated. The out-of-plane launches resulted in trajectory characteristics very similar to those for the in-plane launches. The principal differences were a small increase in  $\Delta V$  (7 fps) and a small decrease in pericynthion altitude (200 feet for delta guidance and 1000 feet for Thrust-velocity guidance).

Aborts From Ascent

Aborts were performed from early launch primary ascents resulting in direct intercept trajectories, and from late launch ascents resulting parking orbits. Abort times of 100, 200 and 300 seconds after lift-off were considered. A summary of the significant trajectory parameters is shown in Tables IV-11 and IV-12. Here, again, the nominal trajectory parameters, plus the 3 sigma deviations due to AGS errors, satisfy the pericynthion altitude and  $\Delta V$  constraints. It can be seen that pericynthion altitude varies considerably, depending on the time of abort, for both guidance techniques. This is due to the fact that the open-loop steering profile used for initiation of

these aborts was the same as that used for an abort from the lunar surface, and no attempt was made to optimize the profile for aborts from ascent.

The results of all of the abort cases studied, as well as the effects of all of the error sources considered are contained in Appendices A and B of this report.

Table IV - 1

Delta Guidance Performance

Abort From Descent

Abort Time	Type Of Orbit	Pericyynthion Altitude (ft)	Total $\Delta V$ (fps)	Midcourse Or Transfer $\Delta V$ (fps)	Central Angle (deg)	See Note #4		
						$3G$ hp1 (ft)	$3\sigma$ $\Delta V_T$ ft	$3\sigma$ $\Delta V_{MC}$ fps
100	D.I.	72,426	2204	3.65	268.64	57	1.62	4.89
310	D.I.	154,662	5523	2.90	249.65	251.2	12.92	14.74
349	D.I.	159,394	5972	2.81	229.11	2881	19.68	20.61
350	P.O.	158,094	6052	96.23	228.77	2944	26.39	26.56
399	P.O.	144,777	6145	90.96	202.07	2758	38.45	43.78
464	P.O.	69,107	6167	139.25	140.94	6239	50.02	52.10
564	P.O.	56,267	6131	92.75	160.50	9157	21.61	76.55
310	D.I.	179,156	5477	4.39	254.37	3112	10.71	14.88
Note #1 349	D.I.	169,764	5885	.84	233.49	3341	22.29	20.77
Note #2 464	P.O.	63,665	6179	143.09	140.96	7331	49.20	51.38

- Note (1) 1.12° PGNS Pitch Misalignment (240)
- Note (2) 0.265 fps<sup>2</sup> x Accel. Bias (400)
- Note (3) 0.265 fps<sup>2</sup> x Accel. Bias (400)
- Note (4) 3 Variations due to AGS sensor errors (including 6% thrust variations)

D. I. - Direct intercept with midcourse correction at burnout  
 P.O. - Parking orbit with transfer at 20 minutes



Table IV - 2

Thrust Velocity Guidance  
Abort From Descent

Abort Time Sec	Type of Orbit	Pericyathion Altitude (ft)	Total $\Delta V$ fps	Midcourse or Transfer $\Delta V$ fps	Central Angle deg	See Note #4		
						$ \delta \text{hp} $ ft.	$ \delta \Delta V_T $ fps	$ \delta \Delta V_{MC} $ fps
100	D.I.	72,336	2177	24.51	259.73	45	1.67	3.59
310	D.I.	158,465	5486	10.23	235.81	3392	8.57	14.36
349	D.I.	158,848	5917	32.12	156.39	4237	13.65	14.96
399	P.O.	62,163	6106	168.25	204.64	11596	10.92	32.04
464	P.O.	66,804	6122	102.11	151.74	5339	21.96	33.15
564	P.O.	58,243	6156	108.86	210.21	11157	9.18	44.12
310 Note #1	D.I.	181,024	5441	13.75	225.86	5420	12.35	17.37
349 Note #2	D.I.	153,460	5797	11.35	146.20	6264	7.02	15.67
464 Note #3	P.O.	65,106	6148	115.53	151.62	4655	27.38	34.60

Note (1) 1.12° PGNS Pitch Misalignment (245)  
 Note (2) 0.265 fps<sup>2</sup> x Accel. Bias (405)  
 Note (3) 0.265 fps<sup>2</sup> x Accel. Bias (405)  
 Note (4) 3σ Variations Due to AGS Sensor Errors (Including 6% Thrust Variations)

D.I. - Direct Intercept with Midcourse Correction at Burnout  
 P.O. - Parking Orbit with Transfer at 20 Minutes

Table IV - 3  
Percent Contribution of AGS Errors To  
 Change In Pericynthion Altitude And Total  $\Delta V$

Delta Guidance

Abort Time	Type Of Orbit	Percent Contribution To $\delta h_p$		Percent Contribution To $\delta \Delta V_m$				$R_T$	
		$\Delta \theta_A$	$\Delta \theta_A$	$\Delta \theta_A$	$\Delta \psi_A$	$\Delta \phi_A$	$\Delta \phi_A$		
100	D.I.	4.04	78.49	Note (1)	neg.	11.32	2.95	8.04	Note (1)
310	D.I.	3.99	22.84	73.14	43.08	6.48	27.11	5.02	17.33
349	D.I.	11.99	37.91	50.08	17.03	8.99	28.21	7.45	37.09
350	P.O.	3.10	44.08	52.8	85.61	neg.	.12	neg.	14.08
399	P.O.	.49	99.49	neg.	85.01	.77	.13	1.02	12.91
464	P.O.	7.06	21.33	71.50	99.09	.18	.13	0.14	.21
564	P.O.	29.66	9.75	60.59	34.64	18.59	1.75	36.70	7.47

Neg. = Negligible

Note (1) = Ascent Engine Not Used

Table IV -4

Percent Contribution of AGS Errors to

Change in Pericynthion Altitude and Total  $\Delta V$

Thrust-Velocity Guidance

Abort Time	Type of Orbit	Percent Contribution To $\Delta V$			Percent Contribution To $\Delta V_T$			$R_T$	
		$\Delta \theta_A$	$\Delta \theta$	$R_T$	$\Delta \theta_A$	$\Delta \psi_A$	$\Delta \theta_A$		
100	D.I.	13.0	72.0	Note (1)	84.0	0.1	13.9	0.2	Note (1)
310	D.I.	9.7	1.7	88.4	66.4	3.0	24.7	2.3	3.2
349	D.I.	23.5	0.9	74.6	2.3	0.1	55.6	0.1	40.8
399	P.O.	3.6	95.0	0.9	37.1	19.5	0.4	22.0	17.7
464	P.O.	19.3	67.9	8.4	59.3	1.2	1.8	1.7	35.8
564	P.O.	1.3	33.3	65.3	24.8	15.1	20.0	37.3	0.6

Neg. = Negligible

Note (1) = Ascent Engine Not Used

Table IV - 5

Delta Guidance Performance  
Abort From Powered Descent With Ascent Engine Only

Abort Time	Type of Orbit	Pericyynthion Altitude (ft)	Total $\Delta V$ (fps)	Midcourse or Transfer $\Delta V$ (fps)	$\delta$ hp/ (ft)		$\delta \Delta V_T$ (fps)		$\delta \Delta V_{MC}$ (fps)	
					* $\Delta \theta_p$	* $\epsilon Z_p$	* $\Delta \theta_p$	* $\epsilon Z_p$	* $\Delta \theta_p$	* $\epsilon Z_p$
100	D.I.	71,598	2,204	3.56	-	-	-	-	-	-
300	D.I.	113,424	5,525	7.27	-	-	-	-	-	-
349	D.I.	107,017	5,995	7.67	-	-	-	-	-	-
350	F.O.	105,480	6,095	112.53	-	-	-	-	-	-
399	F.O.	95,163	6,190	107.94	1,498	412	11.5	3.4	1.9	0.5
464	F.O.	38,359	6,212	157.95	104	443	0.5	2.8	.4	1.3
564	F.O.	37,840	6,130	91.12	243	435	7.9	0.5	4.2	.3

\*  $\Delta \theta_p = 0.82$  mr.       $\epsilon Z_p = .00656 \text{ fps}^2$

Table IV - 6

Thrust Velocity Guidance Performance

Abort From Powered Descent With Ascent Engine Only

Abort Time	Type of Orbit	Pericyynthion Altitude (ft)	Total $\Delta V$ (fps)	Midcourse or Transfer $\Delta V$ (fps)	$\delta$ hp/ (ft)		$\delta/\Delta V_T$ (fps)		$\delta \Delta V_{Md}$ (fps)	
					* $\Delta \theta_p$	* $\epsilon Z_p$	* $\Delta \theta_p$	* $\epsilon Z_p$	* $\Delta \theta_p$	* $\epsilon Z_p$
100	D.I.	71,239	2176	22.85	-	-	-	-	-	-
310	D.I.	111,895	5475	27.73	-	-	-	-	-	-
349	D.I.	108,403	5967	37.78	-	-	-	-	-	-
399	P.O.	58,922	6042	72.78	7332	3514	16.0	2.0	2.7	2.2
464	P.O.	32,123	6236	119.22	1058	1948	2.4	.5	.5	2.4
564	P.O.	25,508	6136	89.78	1701	1617	1.1	1.73	2.5	2.5

\*  $\Delta \theta_p = 0.82$  ,  $\epsilon Z_p = .00656 \text{ fps}^2$

Table IV - 7

Delta Guidance Performance  
Abort From Beacon - Aided Descent  
(Descent/Ascent Engine Combination)

Abort Time	Type of Orbit	Periapsis Altitude (ft)	Total $\Delta V$ (fps)	Midcourse or Transfer $\Delta V$ (fps)	Central Angle (deg)	$ \delta $ hp / (ft)		$\delta / \Delta V_{ij}$ (fps)		$ \delta \Delta V_{MC} $ (fps)	
						Off-Nom Beacon	$\Delta \theta_p$	Off-Nom Beacon	$\Delta \theta_p$	Off-Nom Beacon	$\Delta \theta_p$
100	D.I.	95,064	2216	2.00	269.09	4,685	3,084	5.62	6.48	1.61	1.82
310	D.I.	146,246	5518	5.54	245.33	8,294	7,646	14.82	1.22	.92	2.32
349	D.I.	142,365	5720	4.17	233.15	9,946	5,490	42.43	26.50	.64	.65
350	P.O.	141,513	5799	108.41	232.64	10,028	5,355	48.12	26.65	5.04	.85
399	P.O.	127,766	5902	100.39	220.29	12,837	12,662	97.79	88.17	3.12	3.81
464	P.O.	54,497	5910	123.18	202.73	6,412	28,759	99.47	133.61	3.59	15.25
564	P.O.	58,714	6125	92.53	160.49	5,990	5,018	2.99	5.72	2.21	2.23

Table IV - 8  
Thrust Velocity Guidance Performance  
Abort From Beacon-Aided Descent  
(Descent/Ascent Engine Combination)

Abort Time	Type of Orbit	Pericynthion Altitude (ft)	Total $\Delta V$ (fps)	Midcourse or Transfer $\Delta V$ (fps)	Central Angle (deg)	$ \delta_{hp} $ (ft)		$ \delta \Delta V_M $ (fps)		$ \delta \Delta V_{MC} $ (fps)	
						Off-Nom Beacon	$\Delta \theta_p$	Off-Nom Beacon	$\Delta \theta_p$	Off-Nom Beacon	$\Delta \theta_p$
100	D.I.	95,009	2200	9.45	265.07	4,646	3,034	2.03	4.47	5.10	4.43
310	D.I.	150,401	5482	11.84	236.37	8,161	7,701	1.62	1.22	9.04	4.60
349	D.I.	80,976	5618	32.09	131.19	2,187	17,187	6.78	26.21	27.78	6.62
399	P.O.	*-117,664	5832	238.17	268.65	39,459	32,709	89.17	83.31	1.13	.58
464	P.O.	*-157,036	5805	168.56	206.22	61,148	16,405	89.71	75.59	32.90	48.27
564	P.O.	32,512	6172	154.01	210.94	14,527	10,418	12.72	14.79	19.05	15.04

\*Indicates non-clear pericynthion altitude due to the need for a new set of delta functions for beacon-aided landing.

TABLE IV-9  
DELTA GUIDANCE  
ASCENT FROM THE LUNAR SURFACE

LIFT OFF TIME sec.	TYPE OF ORBIT	PERICYN-THION ALT. ft.	TOTAL $\Delta V$ fps	MIDCOURSE OR TRANSFER $\Delta V$ fps	CENTRAL ANGLE deg.	$3\sigma^*$ $\frac{hp}{ft}$	$3\sigma^*$ $\frac{\delta AV_T}{fps}$	$3\sigma^*$ $\frac{\delta AV_{MC}}{fps}$
0	D.I.	48319	6557	4.42	268.46	14275	18.87	31.95
100	D.I.	48444	6493	14.77	258.73	14193	17.83	31.61
200	D.I.	48567	6408	9.51	248.99	14157	15.74	31.85
300	D.I.	48688	6308	5.72	234.38	14098	21.83	32.27
600	P.O.	49131	6210	147.60	212.78	13981	11.41	39.36
0	D.I.	48127	6563	4.60	268.46	14285	18.32	32.76
100	D.I.	48252	6500	14.79	255.73	14200	17.61	32.52
200	D.I.	48375	6414	9.63	248.99	14167	15.37	31.79
300	D.I.	48496	6315	5.65	234.38	14064	21.99	33.98
600	P.O.	48939	6217	147.69	212.78	13997	11.22	39.57

t = 0 occurs when the CSM is 20° before the landing site vertical  
 D.I. - direct intercept with midcourse correction at burnout  
 P.O. - parking orbit with transfer at 20 minutes  
 \* - 3 $\sigma$  variations due to ACS sensor errors (Including 6% thrust variation)



TABLE IV-10

THRUST VELOCITY GUIDANCE

ASCENT FROM THE LUNAR SURFACE

LIFT OFF TIME SEC.	TYPE OF ORBIT	PERICYNTHION ALT. FT.	TOTAL $\Delta V$ fps	MIDCOURSE OR TRANSFER $\Delta V$ fps	CENTRAL ANGLE DEG.	$3\sigma^*$ $ \delta hp $ FT.	$3\sigma^*$ $\delta / \Delta V \uparrow$ fps	$3\sigma^*$ $ \delta \Delta V_{rel} $ fps
0	D.I.	50,170	6549	5.39	269.35	15,391	22.13	30.66
100	D.I.	50,279	6475	7.87	259.57	15,383	15.41	31.77
200	D.I.	50,389	6387	1.81	249.79	15,325	26.17	32.40
300	D.I.	50,498	6288	6.23	230.23	15,487	20.00	34.67
600	P.O.	50,597	6449	308.60	228.08	15,436	22.11	32.63
0	D.I.	49,207	6553	4.09	269.34	15,401	21.64	31.47
100	D.I.	49,318	6482	9.55	259.57	15,373	15.23	32.68
200	D.I.	49,427	6395	3.84	249.79	15,340	25.82	32.63
300	D.I.	49,535	6296	8.30	230.23	15,502	20.18	36.71
600	P.O.	49,629	6451	305.16	223.14	15,448	21.92	32.86

A

B

t = 0 occurs when the CSM is 20° before the landing site vertical  
 D.I. - Direct Intercept with midcourse correction at burnout  
 P.O. - Parking Orbit with transfer at 20 minutes  
 \*  $3\sigma$  variations due to ACS sensor errors (including 6% thrust variation)

A = In Plane Launches  
 B = 0.5° Out of Plane Launches

TABLE IV-11  
DELTA GUIDANCE  
ABORT FROM ASCENT

ABORT TIME	TYPE OF ORBIT	PERICYNTHION ALT (ft)	TOTAL ΔV (fps)	MIDCOURSE/ or TRANSFER ΔV (fps)	CENTRAL ANGLE (DEG)	3σ Variations Due to 3σ AGS Sensor Errors		
						$\frac{3\sigma}{ \delta \text{ hp} }$	$\frac{3\sigma}{ \delta \Delta V_1 }$	$\frac{3\sigma}{ \delta \Delta V_{MC} }$
Early Launch (Direct Intercept) } CSM Phasing 3.85° Before I.S. Vert	D.I.	52,360	6283	12.28	221.30	1626	15.35	12.55
	D.I.	37,471	6259	7.01	226.05	3474	17.19	31.38
	D.I.	44,153	6262	6.85	226.07	4113	17.32	30.39
Late Launch (Parking) } Orbit CSM .27° Ahead of I.S. Vertical	P.O.	59,077	6267	147.27	145.47	1466	25.19	30.16
	P.O.	44,309	6264	113.06	203.62	2837	18.73	53.57
	P.O.	46,354	6259	157.23	154.68	3331	25.20	35.33

D.I. - Direct intercept with midcourse correction at burnout

P.O. - Parking orbit with transfer at 20 minutes

TABLE IV-12

THRUST VELOCITY GUIDANCE

ABORT FROM ASCENT

ABORT TIME sec.	TYPE OF ORBIT	PERICYN- THION ALT. ft.	TOTAL $\Delta V$ fps	MIDCOURSE/ or TRANSFER $\Delta V$ fps	CENTRAL ANGLE deg.	$3\sigma$ $ \Delta V_T $ fps	$3\sigma$ $ \Delta V_{MC} $ fps
100	D.I.	53650	6272	10.15	222.03	16.13	34.78
200	D.I.	39489	6230	7.27	221.87	17.71	36.42
300	D.I.	45665	6237	4.70	221.90	19.72	35.62
100	P.O.	59667	6264	93.77	135.98	12.70	26.12
200	P.O.	45699	6188	57.47	125.95	14.93	25.62
300	P.O.	47369	6191	60.69	125.97	12.66	25.14

\* CSM Phasing 3.85° before landing site vertical

\*\* CSM Phasing 0.27° after landing site vertical

#  $3\sigma$  Variations due to AGS Sensor errors

D.I. - Direct Intercept with midcourse correction at burnout

P.O. - Parking orbit with transfer at 20 minutes

V. CONCLUSIONS

Based upon the results of the studies discussed in this report, several conclusions can be reached regarding the ability of Delta Guidance and Thrust Velocity guidance to fulfill the primary and secondary guidance law requirements that are outlined in Section II. The discussion will be divided into two categories, namely primary and secondary requirements, and will follow the order of the requirements as listed in Section II.

PRIMARY REQUIREMENTS

1. An examination of Tables IV-1, 2, 7, 8, 9, 10, 11 and 12 indicates that both Delta and Thrust Velocity Guidance are able to perform aborts from non-beacon-aided powered descent, from the lunar surface and from powered ascent while maintaining a clear 30,000 ft. pericyynthion altitude and intercepting the CSM within the  $\Delta V$  budget. In addition, an examination of Tables IV-7 and 8 reveals that Delta Guidance is able to perform an abort from a beacon-aided descent utilizing the same constants as used for the non-beacon-aided descent. Thrust Velocity Guidance, however, would need a different set of delta-functions than those used in this study to perform this type of abort. The reason for this is that the delta guidance loop is closed through a navigation system, while the thrust velocity guidance technique depends only upon the measurement of thrust velocity.

The performance of the Delta and Thrust Velocity guidance techniques is degraded somewhat when used to perform aborts from powered ascent. For aborts from powered descent and from the lunar surface, both guidance laws are able to attain pericynthion altitudes no lower than 50,000 ft. However, for aborts from powered ascent, the pericynthion altitudes are as low as 37,000 ft. The reason for this is that the guidance laws and open-loop steering profile, as formulated for this study, were optimized for aborts from powered descent. Both guidance laws could be made to yield improved performance in this abort situation by the addition of another set of constants and a change in the open-loop portion of the abort trajectory.

2. Both Delta and Thrust Velocity guidance provide the capability of choosing either a direct intercept trajectory or a parking orbit burnout conditions. It should be noted, however, that due to the horizontal burnout constraint used for these studies it is not possible to attain a direct intercept trajectory for the later (350 seconds and after) aborts from powered descent.

3. Both Delta and Thrust Velocity Guidance are capable of performing aborts with the descent engine, descent/ascent engine combination and ascent engine only. However, an examination of Table IV-6 shows that Thrust Velocity guidance does not maintain a clear pericynthion parking orbit when using the ascent engine only for aborts from powered descent. Thrust Velocity guidance could be made to yield satisfactory performance in this abort situation by the addition of another set of constants.

4. Except for the specific cases previously mentioned, all of the Delta and Thrust Velocity Guidance abort trajectories maintained a clear 30,000 ft. pericyynthion altitude.

5. The latest  $\Delta V$  Budget (Reference V-1) allows a total of 6664 fps for the LEM ascent stage. All of the abort trajectories studied using both Delta and Thrust Velocity Guidance utilized an average of about 6200 fps of  $\Delta V$  to rendezvous with the CSM. This is well within 98% of the total ascent stage  $\Delta V$  budget when the vehicle is subjected to 36 AGS errors.

SECONDARY REQUIREMENTS

1. Neither Delta Guidance nor Thrust Velocity Guidance, as formulated, can perform aborts from coasting descent. It would be necessary to add additional logic and equations to fulfill this requirement.

2. As presently formulated, neither Delta Guidance nor Thrust Velocity Guidance have the capability of performing a self-contained midcourse correction. However, due to the navigation capability possessed by Delta Guidance a self-contained midcourse correction scheme can be added.

3. Neither of the guidance laws studied has the capability of determining the time and thrust vectoring requirements for injecting from a phasing orbit into an ascent transfer orbit that intercepts the CSM at a point selected by the astronaut. However, due to its navigation loop, Delta Guidance can be more readily adapted to performing such a maneuver than can Thrust Velocity Guidance.

In summary, it can be concluded that Delta Guidance provides greater flexibility and greater accuracy for the AGS than does Thrust Velocity Guidance for fulfilling the primary guidance requirements. In addition, due to its navigation capability, Delta Guidance is more adaptable to additions that would be needed in order to fulfill the secondary guidance requirements. Also, a navigation capability would be necessary in order to perform abort monitoring.

VI - REFERENCES

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- IV-2 LED-500-1, "Trajectory Characteristics During the LEM Mission (U)," by A. Nathan, V. Asbedian, H. Sperling, T. Hamilton, dated 11 August 1964 (Confidential).
- V-1 LMC-500-37, Revision F, "LEM  $\Delta V$  Budget," by A. Nathan, dated 9 January 1965 (Confidential).

~~CONFIDENTIAL~~APPENDIX A - DELTA GUIDANCE RESULTS

The tables contained in this appendix summarize the results of all of the Delta Guidance error analyses conducted as part of the AGS redefinition. Included are the numerical values of the PGNCs and AGS errors used in the study as well as the burnout conditions of the nominal abort trajectories.

Table A-1 lists the nominal trajectory characteristics. Tables A-2 and A-3 list the numerical values of the errors used in the analysis for both Delta Guidance and Thrust Velocity Guidance. Tables A-4 to A-17 list the errors occurring during aborts from powered descent using the combination of the descent and ascent engines. Tables A-18 to A-21 deal with aborts from powered descent using the ascent engine only. Tables A-22 and A-23 are concerned with In-Plane Lunar launches, while Tables A-24 and A-25 list the results of analyses of 0.5 degrees Out-of-Plane lunar launches. Tables A-26 and A-27 present data on aborts from powered ascent. Tables A-28 to A-31 list the results of error analyses of aborts from beacon-aided powered descents.

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TABLE A-1  
CHARACTERISTICS OF NOMINAL TRAJECTORIES - NO AGS OR IMU ERRORS

TD Nominal	DIRECT ASCENT				PARKING ORBIT			
	100 SEC.	310 SEC.	349 SEC.	350 SEC.	399 SEC.	464,276 SEC.	564,701 SEC.	
$H_p$ (ft)	72426	154,662	159,394	158,094	144,777	69107	56267	
$\Delta V_T$ (fps)	2204.04	5523.69	5972.07	6052.25	6145.83	6167.60	6131.75	
$\Delta V_{MC}$ (fps)	3.65	2.90	2.81	96.23	90.96	139.25	92.75	
$\delta I$ (deg.)	268.64	249.65	229.11	228.77	202.07	140.94	160.50	

DELTA GUIDANCE

REPORT  
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LED-500-4  
31 March 1965

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TABLE A-2  
MAXIMUM PFCNS ERRORS - USE IN BOTH DELTA & T-V GUIDANCE

IMJ Error About Time	1 $\Delta\theta_p$	2 $\Delta\psi_p$	3 $\Delta\phi_p$	4 $\Delta\dot{\theta}_p$	5 $\Delta\dot{\psi}_p$	6 $\Delta\dot{\phi}_p$	7 $\dot{\epsilon}_{xp}$	8 $\dot{\epsilon}_{yp}$	9 $\dot{\epsilon}_{zp}$	10 $k_{xp}$	11 $k_{yp}$	12 $k_{zp}$	I.C. $\frac{\dot{\epsilon}_V(0)}{\dot{\epsilon}_P(0)}$
100	400	600	600	300	600	600	600	600	600	500	600	600	36
310	240	400	400	280	400	400	400	400	400	1000	1000	400	36
340	240	240	400	280	240	400	400	400	400	1000	1000	400	36
350	240	240	400	280	240	400	400	400	400	1000	1000	400	36
399	240	140	400	250	140	400	400	400	400	1000	1000	400	36
464, 276	240	140	400	280	140	400	400	400	400	1000	1000	400	36
564, 701	240	140	400	280	140	400	400	400	400	1000	1000	400	36

16 PFCNS ERRORS \*

$\Delta\theta_p = .82$  mr.  
 $\Delta\psi_p = .82$  mr.  
 $\Delta\phi_p = .82$  mr.

$\Delta\dot{\theta}_p = .15^\circ$ /hr.  
 $\Delta\dot{\psi}_p = .15^\circ$ /hr.  
 $\Delta\dot{\phi}_p = .15^\circ$ /hr.

$\dot{\epsilon}_{xp} = .00656$  fps<sup>2</sup>  
 $\dot{\epsilon}_{yp} = .00656$  fps<sup>2</sup>  
 $\dot{\epsilon}_{zp} = .00656$  fps<sup>2</sup>

$k_{xp} = 100$  ppm  
 $k_{yp} = 100$  ppm  
 $k_{zp} = 100$  ppm

\* See Reference T7-1

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TABLE A-3

3 GPGMS INITIAL CONDITION ERRORS \*

$\delta X_p = -2090 \text{ ft.}$   
 $\delta Y_p = -1877 \text{ ft.}$   
 $\delta Z_p = 9780 \text{ ft.}$   
 $\delta \dot{X}_p = -9.30 \text{ fps.}$   
 $\delta \dot{Y}_p = -1.83 \text{ fps.}$   
 $\delta \dot{Z}_p = 2.76 \text{ fps.}$

3 G AGS ERRORS

1 → $\Delta\theta_A = 3.5 \text{ mr}$	4 → $\Delta\dot{\theta}_A = 1^\circ/\text{hr.}$	7 → $\epsilon_{X_A} = .0016 \text{ fps.}$
2 → $\Delta\psi_A = 3.5 \text{ mr}$	5 → $\Delta\dot{\psi}_A = 1^\circ/\text{hr.}$	8 → $\epsilon_{Y_A} = .0016 \text{ fps.}$
3 → $\Delta\phi_A = 3.5 \text{ mr}$	6 → $\Delta\dot{\phi}_A = 1^\circ/\text{hr.}$	9 → $\epsilon_{Z_A} = .0016 \text{ fps.}$
10 → $K_a = 200 \text{ ppm}$		
	11 → $K_T = 6\%$	

\* See Reference IV-1

TABLE A-4  
Δhp DUE TO OFF-NOMINAL DESCENTS - NO AGS ERRORS  
LOG PGNC S ERRORS

IMU Error Abort Time	1 Δθp	2 Δψp	3 Δφp	4 Δθ̇p	5 Δψ̇p	6 Δφ̇p	7 εxp	8 εyp	9 εzp	10 kxp	11 kyp	12 kzp	(36) I.C.
100	-1571	1	-1	-65	0	0	-51	-12	42	16	0	-22	4622
310	10230	-20	6	126	-1	0	513	-3	-1083	177	0	237	-12871
349	-6485	-5	6	171	-1	-1	352	-5	-1395	-101	0	289	-29754
350	-11122	-4	6	-495	0	-2	-971	-5	-1396	-102	0	279	-27813
399	114	9	-46	180	1	1	-27	-16	-589	41	0	112	1901
464.276	-1433	-10	-51	-148	-3	-4	-456	-22	-631	-11	0	116	-2121
564.701	-74	3	-61	915	3	-3	371	-22	-640	-4	0	126	-2878

DELTA GUIDANCE

TABLE A-5

$\delta h$  DUE TO OFF-NOMINAL DESCENTS - NO ACS ERRORS

MAX.  $\sigma$  FCNCS ERRORS

IMU Error Abort Time	1	2	3	4	5	6	7	8	9	10	11	12	I.C. (36)
	$\Delta\phi$	$\Delta\psi$	$\Delta\phi$	$\Delta\theta$	$\Delta\psi$	$\Delta\phi$	Exp	Exp	Exp	Exp	Exp	Exp	
100	-56,269	3,651	-1,036	-3,181	-9	-15	-29,393	59	2,609	955	0	-579	4,622
310	24,494	-191	234	541	-4	-8	14,956	2	-3,747	-1647	0	655	-12,871
349	1,912	-3,959	90	-984	-93	4	10,370	-86	-5,682	-1032	0	1147	-29,754
350	-15,756	-3,887	113	-1,796	-128	3	-7,074	-88	-5,643	-1015	0	1132	-27,813
399	-2,654	1,759	-747	427	165	-22	-381	-254	-2,507	395	0	451	1,901
464.276	-4,823	-1,734	-730	-524	-196	-22	-5,442	-314	-2,659	-658	0	470	-2,121
564.701	-5,775	7,276	-556	3,105	625	-26	-715	-353	-2,704	267	0	501	-2,878

DELTA GUIDANCE

TABLE A-6  
 $\delta \Delta V_T$  DUE TO OFF-NOMINAL DESCENTS - NO AGS ERRORS  
 LOG PCNCS ERRORS

IMU Errors Abort Time	1	2	3	4	5	6	7	8	9	10	11	12	(30) I.C.
	$\Delta \theta p$	$\Delta \psi p$	$\Delta \phi p$	$\Delta \theta p$	$\Delta \psi p$	$\Delta \phi p$	$\epsilon X p$	$\epsilon Y p$	$\epsilon Z p$	$R X p$	$R Y p$	$R Z p$	
100	-1.48	.41	.15	-.33	.37	.45	-.26	-.39	2.40	-.06	0	-1.38	-8.50
310	-4.54	.23	.95	.56	.32	.45	-1.38	1.11	18.22	.01	0	-3.44	.43
349	16.34	.76	.65	2.52	.95	1.07	8.62	.97	13.65	.20	0	-2.97	-16.58
350	23.90	.04	.43	3.06	.03	.04	7.18	.16	15.54	.32	0	-3.17	-9.33
399	1.22	.35	.66	.18	.38	.09	2.49	.41	-2.78	-.05	0	.67	-2.76
464.276	3.48	.46	.58	1.11	.47	.42	.73	.95	-1.57	.46	0	.47	-3.58
564.701	-12.52	-.21	0	-10.24	-.34	-.33	-9.60	.06	-.68	-.29	0	-.22	-1.14

DELTA GUIDANCE

TABLE A-7

$\Delta V_T$  DUE TO OFF-NOMINAL DESCENTS - NO A/GS ERRORS

MAX. G PGNC'S ERRORS

IMU Error Abort Time	1 $\Delta \theta$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\Delta \dot{\theta}$	5 $\Delta \dot{\psi}$	6 $\Delta \dot{\phi}$	7 $\epsilon_X$	8 $\epsilon_Y$	9 $\epsilon_Z$	10 $K_X$	11 $K_Y$	12 $K_Z$	I.C. $\dot{E}_V(0)$ $\dot{E}_P(0)$
100	-41.24	0.10	-68.08	-1.77	-0.77	-0.34	5.89	4.04	19.52	-0.77	0	-0.33	-8.50
310	-46.46	0.96	2.17	1.80	0.37	0.09	-49.10	2.79	77.42	0.46	0	-14.22	0.43
349	-53.98	2.43	3.77	6.12	1.38	0.68	-87.90	2.67	58.16	0.65	0	-11.57	-16.58
350	-31.02	3.32	2.53	7.01	0.39	0.03	-64.58	2.04	52.56	1.08	0	-13.12	-9.33
399	78.54	-1.78	4.77	1.00	-0.19	0.45	86.33	1.47	-12.63	-0.41	0	2.75	-2.76
464.276	11.97	3.90	2.53	1.74	1.09	0.40	11.79	1.96	-6.63	0.32	0	1.75	-3.58
564.701	9.74	-15.51	-5.30	-26.01	-6.37	0	-27.56	0.40	-1.84	-3.70	0	0.28	-1.14

DELTA GUIDANCE

TABLE A-8  
 $\delta \Delta V_{MC}$  DUE TO OFF-NOMINAL DESCENTS - NO AGS ERRORS

106 PGNC S ERRORS

IMU Error Abort Time	1 $\Delta \phi$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\Delta \psi$	5 $\Delta \phi$	6 $\Delta \psi$	7 $\Delta \phi$	8 $\Delta \psi$	9 $\Delta \phi$	10 $\Delta \psi$	11 $\Delta \phi$	12 $\Delta \psi$	(36) I.C.
100	-0.28	.40	.47	-0.02	.37	.45	-0.18	.19	-0.21	-0.05	0	-2.23	-0.72
310	1.77	.21	.63	-0.03	.32	.46	.82	.73	1.32	-0.08	0	.40	-1.80
349	-0.68	.75	.52	-0.19	.95	1.09	-0.68	.85	-1.93	.13	0	.41	2.08
350	5.14	.03	.35	.04	.03	.03	.56	.03	-0.10	.36	0	.16	12.46
399	-1.10	.45	.48	.20	.47	.09	-0.17	.45	.49	-0.03	0	.03	-3.47
464,276	1.49	.53	.54	1.10	.54	.50	.56	1.02	-0.16	.52	0	.16	-1.07
564,701	-6.72	-0.05	.02	-4.91	-0.17	-0.17	-3.95	.01	.28	-0.13	0	-0.21	0.66

DELTA GUIDANCE

TABLE A-9  
 $\Sigma \Delta V_{MC}$  DUE TO OFF-NOMINAL DESCENTS - NO A/GS ERRORS  
 MAX.  $\sigma$  PGNCS ERRORS

IMU Error Abort Time	1	2	3	4	5	6	7	8	9	10	11	12	I.C. $\Sigma \bar{V}$ (0) $\Sigma \bar{P}$ (0)
	$\Delta \theta P$	$\Delta \psi P$	$\Delta \phi P$	$\Delta \theta P$	$\Delta \psi P$	$\Delta \phi P$	$\Sigma X P$	$\Sigma Y P$	$\Sigma Z P$	$R X P$	$R Y P$	$R Z P$	
100	-0.72	0.66	2.72	-0.35	-0.18	+0.33	-1.28	+0.33	-0.36	-0.10	0	+0.48	-0.72
310	+1.49	+0.63	+0.59	-0.05	+0.38	+0.11	+5.27	+0.51	5.77	-0.28	0	1.38	-1.80
349	-0.46	+0.78	1.52	-0.51	+1.07	+0.70	-1.97	+0.75	+0.26	.09	0	1.70	2.08
350	+7.93	+2.29	+0.12	+0.51	+0.06	+0.04	+4.67	+0.10	+1.19	.81	0	-0.02	12.46
399	-3.65	-0.90	+0.50	-0.22	-0.11	+0.41	-5.75	+0.84	-0.31	-0.30	0	.18	-3.47
464.276	+3.32	+2.55	+0.87	+0.79	+1.29	+0.51	+3.84	+1.05	-1.16	.60	0	.54	-1.07
564.701	-0.30	+5.86	-0.38	-10.72	-2.63	-0.06	-8.45	-0.06	+1.79	-1.58	0	-0.35	+0.66

DELTA GUIDANCE



TABLE A-10  
 $\Sigma$  h<sub>p</sub> DUE TO AGS ERRORS (3 $\sigma$  VALUES)

10 $\sigma$  PGNCs ERRORS

IMU Error / Abort Time	0 Nominal Descent	1 $\Delta\theta_p$	2 $\Delta\psi_p$	3 $\Delta\phi_p$	4 $\Delta\dot{\theta}_p$	5 $\Delta\dot{\psi}_p$	6 $\Delta\dot{\phi}_p$	7 $\Sigma X_p$	8 $\Sigma Y_p$	9 $\Sigma Z_p$	10 $KX_p$	11 $KY_p$	12 $KZ_p$
100	57	61	56	60	60	57	57	61	54	62	54	57	57
310	2512	2510	2511	2509	2522	2512	2512	2642	2509	2486	2508	2511	2533
349	2881	2711	2882	2883	2873	2881	2882	2865	2883	2795	2880	2882	2895
350	2944	2640	2945	2946	2925	2944	2944	2897	2945	2864	2941	2944	2962
399	2758	2751	2759	2758	2760	2759	2758	2754	2759	2763	2760	2758	2759
464.276	6239	6520	6241	6253	6253	6240	6240	6325	6245	6295	6240	6239	6227
564.701	9157	9120	9159	9173	8905	9159	9159	9050	9162	9222	9159	9157	9147

DELTA GUIDANCE

TABLE A-11

$\delta h_p$  DUE TO AGS ERRORS (36 VALUES)

MAX  $\sigma$  PENCILS ERRORS

IMU Error Abort Time	0 Nominal Descent	1 $\Delta\theta_p$	2 $\Delta\psi_p$	3 $\Delta\phi_p$	4 $\Delta\dot{\theta}_p$	5 $\Delta\dot{\psi}_p$	6 $\Delta\dot{\phi}_p$	7 $\Sigma X_p$	8 $\Sigma Y_p$	9 $\Sigma Z_p$	10 $KX_p$	11 $KY_p$	12 $KZ_p$
100	57	70	57	81	66	54	65	85	55	53	63	57	58
310	2512	3112	2505	2544	2534	2512	2511	2971	2520	2465	2486	2512	2525
349	2881	3051	2796	2906	2859	2881	2882	3341	2885	2566	2862	2882	2963
350	2944	3659	2861	2969	2888	2941	2944	2915	2944	2636	2919	2944	3012
399	2758	2958	2763	2745	2760	2758	2759	2974	2757	2769	2761	2758	2758
464.276	6239	7267	6350	6405	6293	6251	6245	7331	6304	6489	6246	6239	6209
564.701	9157	10501	7245	9342	8339	9019	9164	9223	9236	9452	9080	9157	9108

DELTA GUIDANCE

TABLE A-12  
 $\Delta V_T$  DUE TO AGS ERRORS (3 $\sigma$  VALUES)  
 LOG PGNC S ERRORS

IMU Error / Abort Time	0 Nominal Descent	1 $\Delta \phi$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\Delta \theta$	5 $\Delta \psi$	6 $\Delta \phi$	7 $\Delta X$	8 $\Delta Y$	9 $\Delta Z$	10 $R_X$	11 $R_Y$	12 $R_Z$
100	1.62	2.10	1.52	1.18	1.71	1.14	1.35	1.44	2.27	2.22	1.40	1.46	2.22
310	12.92	12.46	12.46	11.64	13.22	12.89	11.97	13.08	11.00	13.50	13.08	12.92	12.40
349	19.68	19.89	18.64	18.92	20.09	17.91	17.32	20.27	18.59	21.20	19.56	19.71	19.76
350	26.39	26.01	26.12	25.84	26.02	26.00	26.05	25.65	26.12	26.06	25.82	26.39	26.18
399	38.45	37.89	37.97	37.58	37.63	37.67	38.06	37.70	37.89	37.16	38.40	38.45	38.08
464, 276	50.02	49.08	49.47	49.47	49.06	48.99	49.47	49.54	48.99	48.99	49.47	50.02	49.55
564, 701	21.61	17.26	21.50	21.06	17.63	21.61	21.69	18.20	21.87	21.79	21.80	21.60	21.57

DELTA GUIDANCE

TABLE A-13

$\delta \Delta V_T$  DUE TO AGS ERRORS (3 $\sigma$  VALUES)

MAX.  $\sigma$  PGMS ERRORS

IMU Error / Abort Time	0 Nominal Descent	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta \theta_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \theta_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \theta_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \psi_p$	$\Delta \phi_p$
100	1.62	1.74	1.43	1.21	1.56	3.24	1.57	2.77	1.28	1.42	1.63	1.46	1.29
310	12.92	10.71	11.36	12.11	12.77	12.64	13.19	12.16	12.42	11.43	13.19	13.09	12.41
349	19.68	18.09	18.67	17.19	20.22	17.51	18.52	22.29	19.38	19.95	18.76	19.71	19.11
350	26.39	59.89	25.71	26.71	26.60	26.48	26.05	24.98	26.98	26.88	25.81	26.39	26.63
399	38.45	36.84	38.03	37.85	37.72	38.49	37.72	36.21	37.27	37.23	38.49	38.45	38.10
464, 276	50.02	49.16	49.24	49.56	49.56	49.06	49.49	49.20	49.12	48.54	49.50	50.02	49.15
564, 701	21.61	20.08	42.79	19.68	23.92	18.84	21.62	31.81	22.34	23.13	20.22	21.61	21.38

DELTA GUIDANCE

TABLE A-14  
 $\delta \Delta V_{MC}$  DUE TO AGS ERRORS (36 VALUES)

105 PGCS ERRORS

IMU Error / Abort Time	0 Nominal Descent	1 $\Delta \theta$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\Delta \theta$	5 $\Delta \psi$	6 $\Delta \phi$	7 $\epsilon \chi$	8 $\epsilon \psi$	9 $\epsilon \zeta$	10 $\chi \psi$	11 $\chi \zeta$	12 $\chi \zeta$
100	4.89	4.00	5.04	6.16	3.49	5.77	6.91	4.73	5.04	4.55	4.33	4.63	4.14
310	14.74	14.65	14.66	17.17	14.73	14.48	16.92	14.81	13.91	14.67	14.82	14.73	14.71
349	20.61	20.44	19.61	21.88	20.39	19.59	19.80	20.51	19.98	20.56	20.63	20.50	20.47
350	26.56	26.55	26.18	25.74	26.25	26.21	26.26	25.86	27.32	26.55	25.80	26.56	26.07
399	43.78	43.54	42.61	47.70	43.39	42.29	43.00	43.15	46.92	42.96	43.90	43.78	43.55
464.276	52.10	51.28	51.66	51.46	51.23	51.98	51.63	51.70	51.68	51.17	51.60	52.10	51.73
564.701	76.55	73.46	80.24	80.10	74.13	76.61	76.37	74.73	74.57	76.45	76.18	76.54	75.60

DELTA GUIDANCE

TABLE A-15

$\Delta V_{MC}$  DUE TO ACS ERRORS (3 $\sigma$  VALUES)

MAX. G PGMCS ERRORS

IMU Error Abort Time	Nominal Descent	1	2	3	4	5	6	7	8	9	10	11	12
		$\Delta \theta_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \dot{\theta}_p$	$\Delta \dot{\psi}_p$	$\Delta \dot{\phi}_p$	$\epsilon X_p$	$\epsilon Y_p$	$\epsilon Z_p$	$R X_p$	$R Y_p$	$R Z_p$
100	4.89	4.44	1.70	9.56	4.08	5.61	5.79	4.72	3.91	3.78	3.70	4.63	2.13
310	14.74	14.88	14.33	16.18	15.00	14.25	15.24	14.88	14.67	15.36	14.96	15.00	14.81
349	20.61	20.05	21.60	21.77	20.49	23.23	22.54	20.77	20.18	21.49	20.39	20.50	20.40
350	26.56	30.43	25.56	26.45	26.98	26.91	26.31	25.63	26.48	27.65	25.73	26.56	26.39
399	43.78	43.54	43.83	47.00	43.27	44.69	42.71	43.54	42.35	45.23	45.26	43.79	45.46
464, 276	52.10	51.38	51.18	52.02	51.59	51.35	51.70	51.38	51.23	51.41	51.63	52.10	51.14
564, 701	76.55	76.54	57.80	77.50	69.50	79.42	79.10	67.05	74.05	76.90	75.48	76.55	75.88

DELTA GUIDANCE

TABLE A-16  
 $\delta$  hp PERCENT CONTRIBUTION FOR AGS ERRORS (36)

USING NOMINAL DESCENT

AGS Errors Abort Time	1 $\Delta\theta$	2 $\Delta\psi$	3 $\Delta\phi$	4 $\Delta\theta$	5 $\Delta\psi$	6 $\Delta\phi$	7 $\epsilon_X$	8 $\epsilon_Y$	9 $\epsilon_Z$	10 $K_X$	11 $K_T$
100	4.04	neg.	4.66	78.49	neg.	neg.	neg.	neg.	8.37	4.43	*
310	3.99	neg.	neg.	22.84	neg.	neg.	neg.	neg.	neg.	neg.	73.14
349	11.99	neg.	neg.	37.91	neg.	neg.	neg.	neg.	neg.	neg.	50.08
350	3.10	neg.	neg.	44.08	neg.	neg.	neg.	neg.	neg.	neg.	5.28
399	.49	neg.	neg.	99.49	neg.	neg.	neg.	neg.	neg.	neg.	neg.
464.276	7.06	neg.	neg.	21.33	neg.	neg.	neg.	neg.	neg.	neg.	71.50
564.701	29.66	neg.	neg.	9.75	neg.	neg.	neg.	neg.	neg.	neg.	60.59

DELTA GUIDANCE

\* Ascent Engine not used

TABLE A-17

$\delta \Delta V_T$  PERCENT CONTRIBUTION FOR AGS ERRORS 36

(USING NOMINAL DESCENT)

AGS Errors Abort Time	1 $\Delta \theta A$	2 $\Delta \psi A$	3 $\Delta \phi A$	4 $\Delta \theta A$	5 $\Delta \dot{\psi} A$	6 $\Delta \dot{\phi} A$	7 $\epsilon X A$	8 $\epsilon Y A$	9 $\epsilon Z A$	10 $R X A$	11 $R T$
100	neg.	11.32	3.24	2.95	5.23	8.04	.13	6.52	31.98	30.56	*
310	43.08	6.48	.39	27.11	.12	5.02	neg.	.35	neg.	neg.	17.33
349	17.03	8.99	.46	28.21	.42	7.45	neg.	.31	neg.	neg.	37.09
350	85.61	neg.	neg.	.12	neg.	neg.	neg.	neg.	neg.	neg.	14.08
399	85.01	.77	neg.	.13	neg.	1.02	neg.	neg.	.11	neg.	12.91
464.276	99.09	.18	neg.	0.13	neg.	0.14	neg.	neg.	.14	neg.	.21
564.701	34.64	18.59	neg.	1.75	neg.	36.70	neg.	neg.	neg.	neg.	7.47

DELTA GUIDANCE

\*Ascent Engine Not Used.



TABLE A-18  
NOMINAL ABORT FROM POWERED DESCENT  
ASCENT ENGINE ONLY

Time of Abort Variable	100	310	349	350	399	464.276	564.701
$h_p$	71,598	113,424	107,017	105,480	95,163	38,359	37,840
$\Delta V_T$	2,204.55	5,525.25	5,995.36	6,094.75	6,190.03	6,212.08	6130.22
$\Delta V_{MC}$	3.56	7.27	7.67	112.53	107.94	157.95	91.12

DELTA GUIDANCE

TABLE A-19  
 $\delta \Delta V_T$  DUE TO OFF-NOMINAL DESCENTS - NO AGS ERRORS  
 ASCENT ENGINE ONLY - 10G PGNC'S ERRORS

IMU Error Abort Time	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta \theta_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \dot{\theta}_p$	$\Delta \dot{\psi}_p$	$\Delta \dot{\phi}_p$	$\epsilon X_p$	$\epsilon Y_p$	$\epsilon Z_p$	$K X_p$	$K Y_p$	$K Z_p$
399	11.49	-0.22	+0.34	-.11	+0.10	-.23	+2.26	-.07	-3.38	-.05	0	+0.70
464.276	0.50	+0.02	+0.13	-.31	0	-.01	-.53	+0.05	-2.76	-0.01	0	+0.46
564.701	-7.86	+0.14	+0.22	-6.87	+0.06	+0.11	-6.97	+0.06	-.50	+0.02	0	+0.13

DELTA GUIDANCE

TABLE A-20

$\sum \Delta V_{mc}$  DUE TO OFF - NOMINAL DESCENTS - NO AGS ERRORS  
- ASCENT ENGINE ONLY - 10G PCNCS ERRORS

IMU Error Abort Time	1 $\Delta \theta_p$	2 $\Delta \psi_p$	3 $\Delta \phi_p$	4 $\Delta \dot{\theta}_p$	5 $\Delta \dot{\psi}_p$	6 $\Delta \dot{\phi}_p$	7 $\Sigma X_p$	8 $\Sigma Y_p$	9 $\Sigma Z_p$	10 $KX_p$	11 $KY_p$	12 $KZ_p$
399	-1.89	-0.28	+0.08	-0.16	+0.11	-0.30	-0.42	-0.18	-0.45	-0.03	0	+0.09
464.276	-0.40	+0.02	+0.05	+0.09	0	-0.01	+0.07	0	-1.33	-0.03	0	+0.13
564.701	-4.22	+0.12	+0.07	-3.26	+0.06	+0.11	-2.67	+0.01	+0.30	+0.01	0	-0.06

DELTA GUIDANCE

TABLE A-21

$\delta h_p$  DUE TO OFF - NOMINAL DESCENTS - NO AGS ERRORS

- ASCENT ENGINE ONLY - 10G PGNCs ERRORS

IMU Abort Error Time	1 $\Delta \theta$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\dot{\Delta \theta}$	5 $\dot{\Delta \psi}$	6 $\dot{\Delta \phi}$	7 $\Sigma X$	8 $\Sigma Y$	9 $\Sigma Z$	10 $KXP$	11 $KYP$	12 $KZP$
399	1,498	9	-11	219	0	0	374	-3	-412	42	0	80
464.276	-104	-9	2	-37	0	0	12	-3	-443	-7	0	87
564.701	-243	8	5	-136	4	3	-21	1	-435	2	0	86

DELTA GUIDANCE

TABLE A-22

ABORT FROM THE LUNAR SURFACE

NOMINAL IN-PLANE

Para- meter	Lift-Off Time	0	100	200	300	Parking Orbit 600
$h_p$		48,319	48,444	48,567	48,688	49,131
$\Delta V_t$		6,557.33	6,493.55	6,408.12	6,308.95	6,210.74
$\Delta V_{mc}$		4.42	14.77	9.51	5.72	147.60
$\sigma_I$		268.46	258.73	248.99	234.38	212.78

DELTA GUIDANCE

TABLE A-23  
ABORT FROM THE LUNAR SURFACE - IN PLANE  
- EFFECTS OF 3G AGS ERRORS

Lift-off Time meter	0	100	200	300	Parking Orbit 600
$\delta_{h_p}$	14,275	14,193	14,157	14,098	13,981
$\delta \Delta v_t$	18.87	17.83	15.74	21.83	11.41
$\delta \Delta v_{mc}$	31.95	31.61	31.82	32.27	39.36

DELTA GUIDANCE

TABLE A-24

ABORT FROM THE LUNAR SURFACE

- NOMINAL 0.5° OUT - OF - PLANE

Lift-Off Para- meter	0	100	200	300	Parking Orbit 600
$h_p$	48,127	48,252	48,375	48,496	48,939
$\Delta V_t$	6563.87	6500.16	6414.90	6315.09	6217.53
$\sigma_1$	268.46	258.73	248.99	234.38	212.78
$\Delta V_{MC}$	4.60	14.79	9.63	5.65	147.69

DELTA GUIDANCE

TABLE A-25

ABORT FROM THE LUNAR SURFACE - 0.5° OUT-OF-PLANE

-EFFECTS OF 3σ ACS ERRORS

Lift-Off Para- meter	0	100	200	300	Parking Orbit 600
$\delta h_p$	14,285	14,200	14,167	14,064	13,997
$\delta \Delta v_t$	18.32	17.61	15.37	21.99	11.22
$\delta \Delta v_{mc}$	32.76	32.52	31.79	33.98	39.57

DELTA GUIDANCE



TABLE A-26

ABORT FROM POWERED ASCENT

- NOMINAL

Para-meter	EARLY LAUNCH (DIRECT INTERCEPT)			LATE LAUNCH (PARKING ORBIT)		
	100	200	300	100	200	300
Abort Time	52,360	37,471	44,153	59,077	44,309	46,354
$h_p$	6283.12	6259.19	6262.38	6267.54	6264.62	6259.80
$\Delta V_t^*$	12.28	7.01	6.85	147.27	113.06	157.23
$\Delta V_{mc}$	221.30	226.05	226.07	145.47	203.62	154.88

\* Includes Primary Ascent

DELTA GUIDANCE

TABLE A-27

ABORT FROM POWERED ASCENT

-EFFECTS OF 3G AGS ERRORS

Abort Time Para- meter	EARLY LAUNCH (DIRECT INTERCEPT)			LATE LAUNCH (PARKING ORBIT)		
	100	200	300	100	200	300
$\delta h_p$	1,626	3,479	4,113	1,466	2,837	3,331
$\delta \Delta v_t$	15.85	17.19	17.32	25.19	18.78	25.20
$\delta \Delta v_{mc}$	32.55	31.38	30.39	30.16	53.57	38.33

DELTA GUIDANCE

TABLE A-28

ABORTS FROM BEACON-AIDED DESCENT

-NOMINAL TRAJECTORY CHARACTERISTICS

Parameter	Td	100	310	349	350	399	464.276	564.701
$h_p$		95,064	146,246	142,365	141,513	127,766	54,497	58,714
$\Delta VT$		2,216.35	5,518.07	5,719.83	5,799.29	5,901.73	5,909.63	6,125.27
$\Delta V_{mc}$		2.00	5.54	4.17	108.41	100.39	123.18	92.53
GI		269.09	245.33	233.15	232.64	220.29	202.73	160.49

DELTA GUIDANCE

TABLE A-29

$\delta_{h_p}$  DUE TO OFF-NOMINAL BEACON-INITIAL CONDITION ERRORS  
AND LOS PGM'S ERRORS - ABORT FROM BEACON AIDED DESCENT

Abort Time	1 $\Delta\theta_p$	2 $\Delta\psi_p$	3 $\Delta\phi_p$	4 $\dot{\Delta\theta}_p$	5 $\dot{\Delta\psi}_p$	6 $\dot{\Delta\phi}_p$	7 $\epsilon_{xp}$	8 $\epsilon_{yp}$	9 $\epsilon_{zp}$	10 $R_{xp}$	11 $R_{yp}$	12 $R_{zp}$	Initial Condition Errors
100	3,084	4,686	4,696	4,630	4,685	4,686	4,136	4,685	4,746	4,691	4,685	4,670	4,685
310	-7,646	8,290	8,315	6,249	8,294	8,295	-1,840	8,297	7,640	8,247	8,294	8,453	8,294
349	-5,490	9,926	9,962	7,674	9,941	9,947	1,181	9,941	9,034	9,880	9,946	10,126	9,946
350	-5,355	10,009	10,042	7,750	10,027	10,034	12,837	10,025	9,127	9,962	10,028	10,214	10,028
399	12,662	12,779	12,817	11,881	12,818	12,839	11,778	12,809	12,635	12,691	12,837	12,872	12,837
464.276	28,759	6,466	6,304	9,594	6,428	6,411	20,585	6,357	8,865	6,533	6,412	5,925	6,412
564.701	5,018	5,994	5,789	5,727	5,998	5,996	5,623	5,820	5,664	5,990	5,991	6,045	5,990

DELTA GUIDANCE

TABLE A-30

$\Sigma \Delta V_t$  DUE TO OFF-NOMINAL BEACON - INITIAL CONDITION ERRORS

AND  $10\sigma$  FGCS ERRORS - ABORT FROM BEACON AIDED DESCENT

Abort Time	IMEJ 1 Err. $\Delta \theta p$	2 $\Delta \psi p$	3 $\Delta \phi p$	4 $\Delta \theta p$	5 $\Delta \psi p$	6 $\Delta \phi p$	7 $\Delta x p$	8 $\Delta y p$	9 $\Delta z p$	10 $\Delta x p$	11 $\Delta y p$	12 $\Delta z p$	Initial Condition Errors
100	-6.48	-5.60	-5.85	-6.06	-5.56	-5.70	-5.85	-5.71	-2.33	-5.58	-5.62	-6.22	-5.62
310	-1.22	-14.58	-14.25	-13.00	-14.42	-14.42	-6.33	-14.79	2.60	-14.07	-14.82	-17.58	-14.82
349	-26.50	-42.11	-41.56	-40.16	-42.58	-42.22	-34.14	-42.62	-35.75	-42.54	-42.57	-44.32	-42.43
350	-26.65	-48.11	-47.43	-45.01	-48.35	-48.33	-36.98	-47.92	-39.62	-48.08	-48.12	-49.86	-48.12
399	-88.17	-97.94	-97.69	-95.60	-97.97	-97.73	-93.14	-98.11	-107.43	-97.90	-97.75	-96.24	-97.79
464.276	-133.61	-99.54	-99.18	-105.36	-99.53	-99.46	-119.91	-98.98	-145.50	-99.32	-99.51	-89.86	-99.47
564.701	5.72	2.68	2.39	3.86	3.01	2.89	3.14	2.98	2.36	2.91	2.62	2.72	2.99

DELTA GUIDANCE

TABLE A-31

$\delta \Delta V_{mc}$  DUE TO OFF - NOMINAL BEACON - INITIAL CONDITION ERRORS  
AND 10G PCNS ERRORS - ABORT FROM BEACON AIDED DESCENT

IMU Err. Abort Time	1 $\Delta \phi$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\Delta \dot{\phi}$	5 $\Delta \dot{\psi}$	6 $\Delta \phi$	7 $\Sigma X$	8 $\Sigma Y$	9 $\Sigma Z$	10 $RXP$	11 $RYP$	12 $RZP$	Initial Condition Errors
100	1.82	1.63	1.69	1.47	1.66	1.53	1.76	1.52	1.62	1.65	1.61	1.61	1.61
310	-2.32	-0.91	-0.86	-1.10	-0.53	-0.54	-1.10	-0.89	-2.06	-0.19	-0.92	0	-0.92
349	.65	.71	.87	.27	.24	.61	.88	.22	-1.26	.27	.50	.67	.64
350	.85	-5.06	-4.71	-4.01	-5.37	-5.36	-5.57	-4.74	-5.02	-5.04	-5.05	-4.93	-5.04
399	-3.81	-3.43	-3.82	-2.71	-3.44	-3.06	-3.38	-3.50	-3.56	-3.39	-3.08	-3.87	-3.12
464.276	-15.23	-3.61	-3.63	-5.70	-3.63	-3.60	-9.92	-3.24	-3.11	-3.29	-3.62	-3.08	-3.59
564.701	2.23	2.08	2.10	2.00	2.22	2.11	2.04	2.13	2.08	2.12	2.03	2.06	2.21

DELTA GUIDANCE

APPENDIX B - THRUST VELOCITY GUIDANCE RESULTS

The tables contained in this appendix summarize the results of all of the thrust velocity guidance error analyses conducted as part of the AGS redefinition. Included are the characteristics of the nominal abort trajectories. The numerical values of the PGNC and AGS errors used in the study are listed in Tables A-2 and A-3 of Appendix A.

Table B-1 lists the nominal trajectory characteristics. Tables B-2 to B-15 list the errors occurring during aborts from powered descent using the combination of the descent and ascent engines. Tables B-16 to B-19 deal with aborts from powered descent using the ascent engine only. Tables B-20 to B-23 are concerned with both in-plane and 0.5 deg. out-of-plane lunar launches. Tables B-24 and B-25 present data on aborts from powered ascent. Tables B-26 to B-29 list the results of error analyses of aborts from beacon-aided powered descents.

TABLE B-1

CHARACTERISTICS OF NOMINAL TRAJECTORIES

NO AGS OR IMU ERRORS

	Direct Intercept			Parking Orbit	
	ID	310	349	399	564.701
Non	100				
Hp (ft)	72,336	158,465	158,848	62,163	58,243
$\Delta V_T$ (fps)	2177.90	5486.78	5917.05	6106.01	6156.13
$\Delta V_{MC}$ (fps)	24.51	10.23	32.12	168.25	108.86
$\zeta_I$ (deg)	259.73	235.81	156.39	204.64	210.21

Thrust Velocity Guidance



TABLE B-2

$\delta \dot{\theta}_p$  DUE TO OFF NOMINAL DESCHEW

NO ACS ERRORS

LOG FONCS ERRORS

LMU Error Id	1 $\Delta \theta_p$	2 $\Delta \psi_p$	3 $\Delta \phi_p$	4 $\Delta \dot{\theta}_p$	5 $\Delta \dot{\psi}_p$	6 $\Delta \dot{\phi}_p$	7 $\epsilon_{xp}$	8 $\epsilon_{yp}$	9 $\epsilon_{zp}$	10 $\kappa_{xp}$	11 $\kappa_{yp}$	12 $\kappa_{zp}$
100	-1,336	-141	-192	-62	-238	-237	-495	-403	89	16	0	-15
310	10,234	-158	-1271	147	-1681	-119	5157	-1976	-842	-177	0	70
349	-5395	-6	595	105	29	-67	1257	-453	532	-105	0	-218
399	8415	16	-506	620	141	4	2158	-471	4303	59	0	-863
464,276	-27	-597	-58	-28	3	-276	15	-6	1543	-8	0	-355
564,701	-349	3	-729	1046	-332	-2	424	-21	-1236	-4	0	211

Thrust Velocity Guidance

TABLE B-3

SAV<sub>MC</sub> DUE TO OFF-NOMINAL DESCENTIS

NO AGS ERRORS

10.6 FCNCS ERRORS

IMU Error Td	1 $\Delta\theta$	2 $\Delta\psi$	3 $\Delta\phi$	4 $\dot{\Delta\theta}$	5 $\Delta\dot{\psi}$	6 $\Delta\dot{\phi}$	7 $\Sigma XP$	8 $\Sigma YP$	9 $\Sigma ZP$	10 $RXP$	11 $RYP$	12 $RZP$
100	.85	.14	.18	.02	.31	.26	.51	.52	-2.96	-.02	0	-.05
310	-6.54	.54	1.57	.10	2.00	1.45	-3.49	2.75	-1.20	.13	0	-.97
349	8.65	.55	14.31	1.00	.31	1.55	2.83	8.80	8.42	.06	0	-1.72
399	-4.14	.02	-.54	.10	-.01	.04	-1.09	-.62	-.17	.05	0	.04
464.276	3.31	1.37	.23	.28	.003	.61	1.01	.07	-1.75	.03	0	.55
564.701	-17.65	.08	-8.66	-13.04	-.15	.03	-12.35	.13	-9.50	-.007	0	.09

Thrust Velocity Guidance

TABLE B-4

$\delta \Delta V_T$  DUE TO OFF-NOMINAL DESCENTS

NO AGS ERRORS

106 FCMS ERRORS

IMU Error Td	1 $\Delta \theta_P$	2 $\Delta \psi_P$	3 $\Delta \phi_P$	4 $\Delta \theta_P$	5 $\Delta \psi_P$	6 $\Delta \phi_P$	7 $\epsilon X_P$	8 $\epsilon Y_P$	9 $\epsilon Z_P$	10 $K X_P$	11 $K Y_P$	12 $K Z_P$
100	-1.02	3.03	1.76	-.04	3.02	3.31	.14	3.51	3.65	-.004	0	-.65
310	-5.50	5.18	-7.29	.91	9.60	7.20	-1.78	10.15	26.15	.06	0	5.77
349	21.21	.41	26.05	4.06	2.02	5.55	14.28	12.57	28.04	.01	0	-5.83
399	15.33	.02	1.72	.50	1.85	.05	3.12	1.48	-.17	.05	0	.10
464,276	6.93	3.78	.21	.53	.002	2.95	1.67	.10	-.04	.03	0	.08
564,701	-15.67	.10	1.78	-9.19	2.33	.03	-9.02	2.33	-.31	.009	0	-.23

Thrust Velocity Guidance

TABLE B-5

$\delta H_P$  DUE TO OFF-NOMINAL DESCENT

NO AGS ERRORS

MAX.  $\sigma$  PGNC'S ERRORS

IMU Error Td	1	2	3	4	5	6	7	8	9	10	11	12	(36)
	$\Delta\theta_P$	$\Delta\psi_P$	$\Delta\phi_P$	$\Delta\dot{\theta}_P$	$\Delta\dot{\psi}_P$	$\Delta\dot{\phi}_P$	$\dot{E}X_P$	$\dot{E}Y_P$	$\dot{E}Z_P$	$RXP$	$RYP$	$RZP$	IC
100	-55,927	3617	-1988	-3109	-371	-142	-28,750	13	2779	948	0	-980	4550
310	22,559	-2403	-1004	583	-267	-153	12,644	-1118	-6582	-1674	0	37	-13,089
349	-8061	-4249	121	-346	-316	-666	-5388	94	-2796	-1057	0	-82	-35,058
399	35,758	2453	-643	2164	225	23	42,654	-397	16,280	514	0	-348	6319
464.276	-1093	-1736	-1122	-22	-172	-545	-1698	-1179	1936	-152	0	-130	-2327
564.701	-10,692	5899	-303	3435	760	-340	-955	-685	-6172	346	0	88	-2977

THRUST VELOCITY GUIDANCE

TABLE B-6

$\delta \Delta V_{MC}$  DUE TO OFF-NOMINAL DESCENDENTS

NO AGS ERRORS

MAX. 6 FGNCs ERRORS

IMU Error Td	1 $\Delta \theta p$	2 $\Delta \psi p$	3 $\Delta \phi p$	4 $\Delta \theta p$	5 $\Delta \psi p$	6 $\Delta \phi p$	7 $\Delta \theta p$	8 $\Delta \psi p$	9 $\Delta \phi p$	10 $\Delta \theta p$	11 $\Delta \psi p$	12 $\Delta \phi p$	(3G) IC
100	40.91	-5.35	-4.02	1.82	.37	.15	20.36	.05	-6.12	-.61	0	-2.36	-3.98
310	3.52	2.56	8.27	.13	.65	.73	-6.54	7.75	-2.37	1.25	0	-.44	7.40
349	-21.70	24.37	43.03	2.84	9.64	9.44	-19.77	29.84	-28.17	.62	0	-.69	10.55
399	-35.82	2.47	1.19	-.06	.28	.04	-34.65	.29	-.80	.52	0	.02	9.57
464.276	12.58	3.70	3.89	1.03	.48	1.19	13.42	3.52	-6.64	.07	0	.13	-5.74
564.701	-19.50	-18.38	-6.64	-21.23	-8.44	-.07	-22.67	-8.55	-13.77	-9.34	0	.04	3.85

Thrust Velocity Guidance

TABLE B-7

$\Sigma \Delta V_T$  DUE TO OFF NOMINAL DESCENT

NO AGS ERRORS

MAX G PGNC'S ERRORS

IMC Error Std	1 $\Delta \theta$	2 $\Delta \psi$	3 $\Delta \phi$	4 $\Delta \theta$	5 $\Delta \psi$	6 $\Delta \phi$	7 $\Sigma \theta$	8 $\Sigma \psi$	9 $\Sigma \phi$	10 $\Sigma \theta$	11 $\Sigma \psi$	12 $\Sigma \phi$	(36) ID
100	-39.10	1.55	-21.37	-1.21	3.58	1.78	7.21	14.70	20.13	-0.25	0	-37.95	-8.02
310	-45.41	11.66	23.57	2.53	4.07	2.47	-61.64	20.70	103.3	.64	0	-2.37	.50
349	-91.69	39.71	96.37	9.82	14.35	15.16	-120.60	57.63	100.95	.10	0	-2.34	-39.72
399	77.78	2.26	6.35	2.51	.30	.18	94.71	2.67	-.28	.58	0	.04	16.59
461.276	26.59	4.59	7.61	2.72	2.24	3.45	26.61	8.82	.36	-.25	0	.02	-5.93
561.701	-5.73	-45.05	-3.15	-28.99	-2.68	2.45	-38.25	2.77	-3.58	-2.48	0	-.08	5.65

Thrust Velocity Guidance

TABLE B-8

$\Sigma$  H PERCENT CONTRIBUTION FOR ACS ERRORS (3G)

USING NOMINAL DESCENT

ACS Error Id	1 $\Delta\theta A$	2 $\Delta\psi A$	3 $\Delta\phi A$	4 $\Delta\theta A$	5 $\Delta\psi A$	6 $\Delta\phi A$	7 $\epsilon X A$	8 $\epsilon Y A$	9 $\epsilon Z A$	10 $R X A$	11 $R T$
100	13.0	Neg	Neg	72.0	Neg	Neg	0.7	Neg	0.6	13.7	0.*
310	9.7	Neg	Neg	1.7	Neg	Neg	Neg	Neg	Neg	0.2	88.4
349	23.5	Neg	Neg	0.9	Neg	Neg	0.2	Neg	Neg	0.8	74.6
399	3.6	Neg	0.1	95.0	Neg	Neg	0.1	Neg	Neg	0.3	0.9
464.276	19.3	Neg	Neg	67.9	Neg	Neg	1.8	Neg	Neg	2.6	8.4
564.701	1.3	Neg	Neg	33.3	Neg	Neg	Neg	Neg	Neg	0.1	65.3

\* Ascent Engine Not Used

Thrust Velocity Guidance

TABLE B-9

$\delta \Delta V_T$  PERCENT CONTRIBUTION FOR AGS ERRORS (36)

AGS Error Td	USING NOMINAL DESCENT										
	<sup>1</sup> $\Delta \theta_A$	<sup>2</sup> $\Delta \psi_A$	<sup>3</sup> $\Delta \phi_A$	<sup>4</sup> $\Delta \theta_A$	<sup>5</sup> $\Delta \psi_A$	<sup>6</sup> $\Delta \phi_A$	<sup>7</sup> $\epsilon \chi_A$	<sup>8</sup> $\epsilon \psi_A$	<sup>9</sup> $\epsilon \theta_A$	<sup>10</sup> $\epsilon \chi_A$	<sup>11</sup> $\epsilon \theta_A$
100	84.0	0.1	0.1	13.9	Neg	0.2	Neg	0.1	Neg	1.6	0.*
310	66.4	3.0	Neg	24.7	Neg	2.3	0.1	Neg	Neg	0.5	3.2
349	2.3	0.1	0.3	55.6	Neg	0.1	0.2	Neg	Neg	0.6	40.8
399	37.1	19.5	2.1	0.4	Neg	22.0	0.9	Neg	0.2	0.1	17.7
464.276	59.3	1.2	Neg	1.8	Neg	1.7	Neg	Neg	0.1	0.1	35.8
564.701	24.8	15.1	Neg	20.0	Neg	37.3	0.8	Neg	0.4	1.0	0.6

\* Ascent Engine Not Used

Thrust Velocity Guidance



TABLE B-10

$\delta H_F$  TUE PAGE ERRORS (16)

LOGPANS ERRORS

EMF Error	0	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\theta$	$\Delta\psi$	$\Delta\phi$	$\Delta\psi$	$\Delta\phi$	$\Delta\theta$	$\Delta\psi$	$\Delta\phi$	$E\psi$	$E\psi$	$E\psi$	$R\psi$	$R\psi$	$R\psi$
100	45	44	343	66	42	389	678	40	1,043	44	42	42	42
310	3,392	3,659	4,044	4,614	3,404	5,479	4,760	3,486	6,152	2,769	3,375	3,388	3,548
349	4,237	3,777	4,168	5,644	4,160	3,988	5,092	4,035	4,828	3,700	4,210	4,214	4,324
399	11,596	11,081	11,577	12,137	11,613	11,593	11,347	11,476	12,170	11,243	11,167	11,596	11,678
464.276	5,339	4,607	5,452	5,733	5,243	5,148	5,170	5,066	7,417	4,136	5,344	5,339	5,605
564.701	11,157	25,179	11,198	11,568	20,214	11,331	11,325	15,594	11,035	12,681	11,158	11,157	10,744

Thrust Velocity Guidance

TABLE B-11

$\delta \Delta V_{MC}$  DUE TO AGS ERRORS (36)

LOG PCNCS ERRORS

IMU Error	0	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta \theta$	$\Delta \psi$	$\Delta \phi$	$\Delta \theta$	$\Delta \dot{\theta}$	$\Delta \dot{\psi}$	$\Delta \dot{\phi}$	$\dot{E}XP$	$\dot{E}XP$	$\dot{E}XP$	$\dot{E}XP$	$\dot{E}XP$	$\dot{E}XP$
100	3.59	2.94	5.56	4.59	3.46	9.54	4.62	3.46	4.82	3.92	3.46	4.03	3.91
310	14.36	16.89	16.50	14.48	14.80	18.02	14.71	14.89	15.63	14.70	14.70	14.82	14.67
349	14.96	15.56	17.59	13.44	15.58	19.82	12.13	16.54	11.62	16.15	15.02	15.28	15.48
399	32.04	31.53	33.41	32.55	32.15	36.65	35.70	31.86	29.52	31.59	32.03	32.04	31.73
464.276	33.15	33.45	33.12	32.75	33.09	31.98	33.25	33.00	34.08	33.22	33.17	33.15	33.29
564.701	44.12	43.49	47.71	56.48	43.56	46.30	45.83	43.61	42.52	57.36	44.02	44.12	43.96

Thrust Velocity Guidance

TABLE B-12

$\delta \Delta V$  DUE TO ACS ERRORS (°G)

LOG RANGE ERRORS

IMU Error $\Gamma_d$	0	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta \theta$	$\Delta \theta$	$\Delta \psi$	$\Delta \phi$	$\Delta \theta$	$\Delta \psi$	$\Delta \phi$	EXP	EXP	EXP	KXP	KXP	REP
100	1.67	1.65	8.85	4.50	1.67	7.41	8.58	1.65	8.86	1.67	1.65	1.66	1.67
310	8.57	16.53	20.10	44.06	8.64	23.25	17.21	9.57	23.56	8.98	8.62	8.65	8.85
349	13.65	13.53	20.72	15.03	13.57	14.62	14.33	13.56	11.66	13.35	13.57	13.60	13.60
399	10.92	10.79	12.36	10.47	10.75	9.02	10.96	10.74	9.75	10.84	10.87	10.92	10.77
464.276	21.96	23.49	23.23	21.95	22.12	19.68	24.82	22.46	28.15	22.30	21.97	21.96	21.94
564.701	9.18	11.64	8.78	23.99	11.04	9.71	8.15	10.31	10.87	25.24	9.18	9.18	9.08

Thrust Velocity Guidance

TABLE B-13

$\Sigma H_P$  DUE TO AGS ERRORS (30)

MAX  $G$  FGNS ERRORS

IMU Error Td	0	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta\theta_P$	$\Delta\psi_P$	$\Delta\phi_P$	$\Delta\theta_P$	$\Delta\psi_P$	$\Delta\phi_P$	$\Delta\theta_P$	$\Delta\psi_P$	$\Delta\phi_P$	$\Sigma Y_P$	$\Sigma Z_P$	$RXP$	$RYP$
100	45	67	158	683	45	1101	479	34	708	37	45	42	57
310	5392	5420	7047	4420	3362	5527	4057	5067	4941	1957	5068	5185	3909
349	4237	5624	4479	4089	4076	4347	5296	6264	4248	2773	4212	4214	4655
399	11,596	8804	11,419	11,768	11,496	11,575	11,873	5263	11,842	10,010	11,601	11,596	11,951
464.276	5359	4635	6422	4869	3051	3145	3283	4635	4794	5637	5431	5459	6734
564.701	11,457	19,445	30,522	9909	50,706	9852	11,036	31,415	11,751	15,581	7386	11,157	9586

THRUST VELOCITY GUIDANCE

TABLE B-14

$\Sigma \Delta V_{MC}$  DUE TO ACS ERRORS (36)

MAX.  $\sigma$  PGNC'S ERRORS

IMU Error Td	0	1 $\Delta \psi$	2 $\Delta \psi$	3 $\Delta \psi$	4 $\Delta \psi$	5 $\Delta \psi$	6 $\Delta \psi$	7 EXP	8 EXP	9 EXP	10 EXP	11 EXP	12 EXP
100	3.60	3.75	4.00	1.35	3.46	5.10	5.40	3.03	1.48	3.47	3.46	4.03	3.72
310	14.36	17.37	15.56	14.23	14.78	16.01	14.11	14.85	13.89	14.96	14.75	14.82	14.73
349	14.96	15.72	13.18	14.54	15.27	13.13	12.15	15.67	15.00	16.30	15.99	15.28	15.16
399	32.04	27.72	35.55	30.04	31.65	34.43	32.54	27.82	29.89	32.03	32.12	32.04	31.73
464.276	33.15	34.57	32.64	33.08	33.17	33.19	31.56	34.60	34.72	33.14	33.08	33.15	32.87
564.701	44.12	58.23	19.28	56.35	36.18	43.94	45.15	32.52	58.79	57.32	43.83	44.12	43.99

Thrust Velocity Guidance

TABLE B-15

SAV<sub>T</sub> DUE TO AGS ERRORS (3G)

MAX. G PGNC'S ERRORS

IMU Error Td	0	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta\theta$	$\Delta\psi$	$\Delta\phi$	$\Delta\dot{\theta}$	$\Delta\dot{\psi}$	$\Delta\dot{\phi}$	$\dot{\Delta\phi}$	$\dot{\Delta\psi}$	$\dot{\Delta\theta}$	$\dot{\Delta\psi}$	$\dot{\Delta\theta}$	$\dot{\Delta\psi}$	$\dot{\Delta\theta}$
100	1.67	1.67	2.72	2.51	1.66	9.61	4.37	1.61	4.34	1.65	1.66	1.66	1.66
310	8.57	12.35	38.14	12.85	8.64	24.47	18.26	10.65	25.93	9.52	8.40	8.65	8.81
349	13.65	14.59	11.26	16.06	13.53	13.29	17.39	7.02	14.53	12.63	13.61	13.60	13.72
399	10.92	14.70	12.28	11.12	10.85	12.12	11.28	15.05	13.73	10.87	10.84	10.92	10.74
464.276	21.96	27.15	22.24	25.91	22.40	21.40	20.43	27.35	28.30	23.35	21.99	21.96	21.76
564.701	9.18	22.00	13.23	23.94	15.70	9.47	7.56	15.43	25.73	26.56	9.60	9.18	8.93

Thrust Velocity Guidance

TABLE B-16  
CHARACTERISTICS OF TRAJECTORIES USING ASCENT ENGINE ONLY  
NO AGS OR PGNC'S ERRORS

Parameter	100	310	349	399	464.276	564.701
$H_p$ (ft)	71,239	111,895	108,403	58,922	32,123	25,508
$\Delta V_T$ (fps)	2176.14	5474.93	5966.68	6042.42	6236.15	6136.39
$\Delta V_{MC}$ (fps)	22.85	27.73	37.78	72.78	119.22	89.78
$\sigma_I$ (deg)	259.76	222.23	206.14	135.23	204.96	160.25

Thrust Velocity Guidance

TABLE B-17

$\delta H_P$  DUE TO OFF-NOMINAL DESCENTS USING ASCENT ENGINE ONLY

NO AGS ERRORS

LOG PCNCS ERRORS

IMU Error Td	$\Delta \theta_p$	$\Delta \psi_p$	$\Delta \phi_p$	$\Delta \dot{\theta}_p$	$\Delta \dot{\psi}_p$	$\Delta \dot{\phi}_p$	$\epsilon X_p$	$\epsilon Y_p$	$\epsilon Z_p$	$R X_p$	$R Y_p$	$R Z_p$
	1	2	3	4	5	6	7	8	9	10	11	12
399	7332	6	76	548	1	-6	1878	-350	3514	36	0	-720
464.276	-1058	-7	-35	-28	.43	1	-163	-877	-1948	-10	0	368
564.701	-1701	-934	23	-397	-101	-102	-118	-702	-1617	-7	0	308

Thrust Velocity Guidance



TABLE B-18

$\delta \Delta V_{MC}$  DUE TO OFF-NOMINAL DESCENTS USING ASCENT ENGINE ONLY

NO ACS ERRORS

LOG PCNCS ERRORS

IMU Error	$\Delta \theta$	$\Delta \psi$	$\Delta \phi$	$\Delta \dot{\theta}$	$\Delta \dot{\psi}$	$\Delta \dot{\phi}$	$\Delta \ddot{\theta}$	$\Delta \ddot{\psi}$	$\Delta \ddot{\phi}$	$\epsilon \chi$	$\epsilon \gamma$	$\epsilon Z$	$R \chi$	$R \gamma$	$R Z$
Td	1	2	3	4	5	6	7	8	9	10	11	12			
399	-2.68	.0002	.29	-.25	.02	.04	-.69	.33	-2.17	-.01	0	.43			
464.276	.47	.08	.43	.008	.005	.03	.06	1.21	-2.35	.02	0	.47			
564.701	2.47	.46	.11	1.13	.02	-.06	.75	.45	-2.50	.007	0	.50			

Thrust Velocity Guidance

TABLE B-19

$\Delta V_T$  DUE TO OFF-NOMINAL DESCENTS USING ASCENT ENGINE ONLY

NO AGS ERRORS

10  $\sigma$  PGCS ERRORS

IMU Error Td	$\Delta \theta$ 1	$\Delta \psi$ 2	$\Delta \phi$ 3	$\Delta \dot{\theta}$ 4	$\Delta \dot{\psi}$ 5	$\Delta \dot{\phi}$ 6	$\epsilon X \rho$ 7	$\epsilon Y \rho$ 8	$\epsilon Z \rho$ 9	$R X \rho$ 10	$R Y \rho$ 11	$R Z \rho$ 12
399	15.96	-.007	2.78	.11	.02	.03	3.28	2.89	-2.00	-.02	0	.44
464.276	2.39	.09	2.42	-.37	.009	.03	-.30	7.14	-.5	.02	0	.15
564.701	1.13	2.52	.22	-.97	2.06	1.98	-2.40	2.66	1.73	.003	0	.35

Thrust Velocity Guidance

TABLE B-20

CHARACTERISTICS OF NOMINAL ABORTS FROM LUNAR SURFACE

Par.	In Plane						1/2° Out of Plane				
	0	100	200	300	600		0	100	200	300	600
$H_T$ (ft)	50,170	50,279	50,389	50,498	50,597		49,207	49,318	49,427	49,535	49,629
$\Delta V_T$ (fps)	6349.75	6475.77	6387.62	6288.60	6449.50		6553.17	6483.02	6394.69	6296.14	6451.92
$\Delta V_{MC}$ (fps)	5.39	7.87	1.81	6.23	308.60		3.46	9.73	3.45	8.27	305.17
$\delta_I$ (deg)	269.35	259.57	249.79	230.23	228.08		269.34	259.57	249.79	230.23	223.14

Thrust Velocity Guidance

TABLE B-21  
EFFECT OF AGS ERRORS (3σ) ON ABORT FROM THE LUNAR SURFACE

$T_L$ Par.	0	100	200	300	600
$\delta H_P$	15,391	15,383	15,325	15,487	15,436
$\delta \Delta V_T$	22.13	15.41	26.17	20.00	22.11
$\delta \Delta V_{MC}$	30.66	31.77	32.40	34.67	32.63
$\delta H_P$	15,700	15,645	15,589	15,725	15,676
$\delta \Delta V_T$	23.43	15.17	22.38	17.26	26.26
$\delta \Delta V_{MC}$	30.84	33.15	32.72	36.09	39.55

0.5°  
Out  
of  
Plane

Thrust Velocity Guidance

TABLE B-22

PERCENT CONTRIBUTION OF AGS ERRORS TO  $\delta H_p$

IN-PLANE ABOUT FROM THE LUNAR SURFACE

AGS Err. $T_L$	$\Delta\theta_A$	$\Delta\psi_A$	$\Delta\phi_A$	$\Delta\omega_A$	$\Delta\dot{\psi}_A$	$\Delta\dot{\phi}_A$	$\epsilon_X A$	$\epsilon_Y A$	$\epsilon_Z A$	$R_X A$	$R_T$
0	1	2	3	4	5	6	7	8	9	10	11
0	3.7	Neg	Neg	.4	0	Neg	Neg	Neg	Neg	Neg	95.9
100	3.7	Neg	Neg	.3	Neg	Neg	Neg	Neg	Neg	Neg	96.0
200	3.6	Neg	Neg	.3	Neg	Neg	Neg	Neg	Neg	Neg	96.1
300	3.4	Neg	Neg	.4	Neg	Neg	Neg	Neg	Neg	Neg	96.2
600	3.2	Neg	Neg	.4	Neg	Neg	Neg	Neg	Neg	Neg	96.4

Thrust Velocity Guidance

TABLE B-23

PERCENT CONTRIBUTION OF AGS ERRORS TO  $\delta AV_T$

IN-PLANE ABOUT FROM THE LUNAR SURFACE

AGS Err. / $T_L$	$\Delta\theta_A$	$\Delta\gamma_A$	$\Delta\phi_A$	$\Delta\dot{\theta}_A$	$\Delta\dot{\gamma}_A$	$\Delta\dot{\phi}_A$	$\epsilon X_A$	$\epsilon Y_A$	$\epsilon Z_A$	$R X_A$	$R T$
0	1	2	3	4	5	6	7	8	9	10	11
0	38.1	.5	46.1	Neg	1.7	Neg	.2	Neg	Neg	1.0	12.4
100	Neg	.4	78.2	18.5	1.9	Neg	.2	Neg	.3	.5	Neg
200	21.5	1.8	52.1	7.0	3.4	.2	Neg	Neg	.1	.1	13.8
300	3.8	1.3	70.0	10.8	2.0	Neg	Neg	Neg	.1	.3	11.7
600	1.9	Neg	3.3	1.0	Neg	Neg	.8	Neg	Neg	2.5	90.5

Thrust Velocity Guidance

TABLE B-24

CHARACTERISTICS OF NOMINAL TRAJECTORIES

ABORT FROM POWERED ASCENT

$T_{ab}$ Par.	Early Launch (Direct)			Late Launch (Park)		
	100	200	300	100	200	300
$H_P$	53,650	39,489	45,665	59,667	45,699	47,369
$\Delta V_{MC}$	10.15	7.27	4.70	93.77	57.47	60.69
$\Delta V_T^*$	6272.96	6230.90	6237.20	6264.61	6188.40	6191.51
$\sigma_I$	222.03	221.87	221.90	135.98	125.95	125.97

\*Including Primary Ascent

Thrust Velocity Guidance

TABLE B-25  
ABORTS FROM POWERED ASCENT  
EFFECTS OF AGS ERRORS (36)

Par.	Early Launch			Late Launch		
	With Thrust Error	Without Thrust Error	Thrust Error	With Thrust Error	Without Thrust Error	Thrust Error
$T_{ab}$	100	200	300	100	200	300
$\Sigma \Delta V_P$	16,645	22,886	28,855	5434	3925	5009
$\Sigma \Delta V_{MC}$	35.18	36.66	38.60	34.78	36.42	35.62
$\Sigma \Delta V_T$	63.56	148.49	249.58	16.13	17.71	19.72
				17,180	23,263	29,193
				48.31	66.41	80.83
				33.25	90.47	186.57
				100	200	300
				100	200	300
				1984	4654	5195
				26.12	25.62	25.14
				12.70	14.93	12.66

Thrust Velocity Guidance



TABLE B-26  
ABORTS FROM BEACON-AIDED DESCENT  
NOMINAL TRAJECTORY CHARACTERISTICS

$T_d$ Nom.	100	310	349	399	464.276	564.701
$H_P$ (ft)	95,009	150,401	80,967	-117,664	-157,036	32,512
$\Delta V_T$ (fps)	2200.47	5482.26	5617.58	5831.71	5804.95	6172.38
$\Delta V_{MC}$ (fps)	9.45	11.84	32.09	238.17	168.56	154.01
$\dot{\phi}_I$ (deg)	265.07	236.37	131.19	268.65	206.22	210.94

Thrust Velocity Guidance

TABLE E-27

$\Sigma \mu_p$  DUE TO OFF-NOMINAL BEACON INITIAL CONDITION ERRORS AND

10G PCNCS ERRORS - ABERT FROM PEACON-AIDED DESCENT

IMU Err	O.N. Beac. + I.C.	1 $\Delta\theta_p$	2 $\Delta\psi_p$	3 $\Delta\phi_p$	4 $\Delta\dot{\theta}_p$	5 $\Delta\dot{\psi}_p$	6 $\Delta\dot{\phi}_p$	7 $\epsilon X_p$	8 $\epsilon Y_p$	9 $\epsilon Z_p$	10 $KX_p$	11 $KY_p$	12 $KZ_p$
100	4646	3034	4706	4371	4580	4726	4573	4089	4551	4763	4651	4646	4625
310	8161	-7701	6739	7247	6131	7063	7544	-1975	6444	7836	8116	8161	8128
349	-2187	-17,187	-2552	-1828	-4716	-2154	-1768	-1136	-1565	3209	-1669	-2566	-3655
399	-39,459	-32,709	-39,552	-39,683	-40,109	-39,434	-39,871	-38,563	-39,605	-37,781	-40,102	-39,460	-40,159
464.276	-61,148	-16,405	-61,569	-60,995	-55,210	-61,128	-61,139	-32,962	-61,067	-76,637	-60,922	-61,148	-58,236
564.701	-14,527	-10,418	-14,043	-14,619	-13,768	-14,513	-14,525	-12,205	-14,500	-14,453	-14,786	-14,527	-14,652

Thrust Velocity Guidance

TABLE B-28

$\sigma_{\Delta V}_{MC}$  DUE TO OFF-NOMINAL BEACON, INITIAL CONDITION ERRORS AND

$1\sigma$  PGNCS ERRORS

ABORT FROM BEACON-AIDED DESCENT

IMU Err. Td	O.N. Beac. + I.C.	1	2	3	4	5	6	7	8	9	10	11	12
	$\Delta\theta_p$	$\Delta\psi_p$	$\Delta\phi_p$	$\Delta\dot{\theta}_p$	$\Delta\dot{\psi}_p$	$\Delta\dot{\phi}_p$	$\epsilon_X p$	$\epsilon_Y p$	$\epsilon_Z p$	$K_X p$	$K_Y p$	$K_Z p$	
100	5.10	4.43	5.04	5.06	5.08	5.08	4.92	5.19	5.57	5.02	5.10	4.98	
310	9.04	4.60	8.49	8.10	8.68	8.96	3.05	8.34	8.56	9.07	9.04	8.36	
349	27.78	6.62	27.36	24.30	27.83	28.26	15.64	28.36	24.54	28.23	27.30	28.48	
399	-1.13	-0.58	-1.06	-0.75	-1.09	-1.09	-0.55	-1.15	-0.20	-1.06	-1.15	-1.25	
464.276	32.90	48.27	32.74	35.33	32.90	32.86	42.08	33.01	43.89	32.98	32.90	30.74	
564.701	19.05	15.04	18.91	18.32	19.08	19.08	17.46	18.79	19.33	18.83	19.07	18.89	

Thrust Velocity Guidance

TABLE B-29

$\Sigma \Delta V$  DUE TO OFF-NOMINAL BEACON, INITIALS CONDITION ERRORS AND

LOG RANGE ERRORS

ABORT FROM BEACON-ALIGNED OBSERVANT

IMV Err. Beac. + R.C.	1 $\Delta \theta p$	2 $\Delta \psi p$	3 $\Delta \phi p$	4 $\Delta \dot{\theta} p$	5 $\Delta \dot{\psi} p$	6 $\Delta \dot{\phi} p$	7 $\Sigma X p$	8 $\Sigma Y p$	9 $\Sigma Z p$	10 $\Sigma X$	11 $\Sigma Y$	12 $\Sigma Z p$
100	-2.03	-4.47	-1.19	-2.14	-1.17	-2.23	-2.72	1.02	2.05	-2.11	-2.03	-2.81
310	-1.62	1.22	4.42	-2.10	2.28	.10	-2.61	4.97	23.95	-1.60	-1.62	-6.90
349	-6.78	-26.21	-5.37	-8.14	-6.69	-4.40	-17.49	-6.44	4.07	-6.47	-5.54	-6.92
399	-89.17	-83.31	-88.92	-88.17	-87.53	-87.85	-88.91	-87.00	-96.37	-88.11	-89.20	-86.25
464.276	-89.71	-75.59	-88.03	-89.02	-89.75	-89.92	-79.32	-86.52	-128.15	-89.54	-89.70	-81.87
564.701	12.72	14.79	17.27	13.41	12.76	12.75	12.09	12.57	15.42	15.20	12.74	12.33

Thrust Velocity Guidance