CR 151009

MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-4-14

RETURN-TO-LAUNCH-SITE TRAJECTORY SHAPING

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

---

17 OCTOBER 1975

This Design Note is Submitted to NASA Under Task Order No. D0303, Task Assignment 1.4-4-D in Fulfillment of Contract NAS 9-13970.

PREPARED BY: R. L. Bown
Senior Engineer
488-5660, Ext. 243

APPROVED BY: L. C. Winans
Task Manager
488-5660, Ext. 243

APPROVED BY: W. W. Hinton, Jr.
FPB Work Package Manager
488-5660, Ext. 240

APPROVED BY: W. E. Hayes
Project Manager
Mission Planning, Mission Analysis and Software Formulation
488-5660, Ext. 266

1.0 SUMMARY

This document presents the results of a study to show the effect on flyback trajectories of constant inertial attitude during the fuel dissipation phase of a Return-to-Launch-Site (RTLS) abort. Results are presented which show that the value of the constant inertial attitude can be chosen to shape the flyback trajectory.

2.0 INTRODUCTION

Preliminary RTLS guidance and targeting software for the Space Shuttle is documented in Reference (A). This note documents another in a series of performance verification studies planned to verify the adequacy of that software.

After a space shuttle main engine (SSME) shutdown and crew selection of the RTLS mode, a fuel dissipation phase will be required. The use of a constant inertial attitude during this phase to shape the trajectory was proposed in Reference (B). This study, was conducted to determine the feasibility of shaping all RTLS trajectories neighboring to that of a mode boundary abort.

3.0 DISCUSSION

The abort conditions or times used in this study were liftoff, Solid Rocket Booster (SRB) separation, 140, 180, and 220 seconds from liftoff. The trajectories were shaped in the inertial velocity - altitude plane to obtain a maximum altitude of approximately 385,000 feet similar to that of the mode boundary abort.

The constant inertial attitude (zero body rates) was maintained by holding a constant inertial thrust direction. For the three degree of freedom simulation used in this study the thrust axis was alined with the X-body axis. The inertial thrust angle is measured from the launch site local horizontal plane which was fixed in Earth Centered Inertial coordinates at time of launch. The thrust angle is measured positive upward in the nominal down-range flight configuration shown in Figure 1.

The excess Orbit Maneuvering System (OMS) and Reaction Control System (RCS) fuel was dissipated by igniting the two OMS and the four aft axial RCS engines. Subsequently a preselected quantity of OMS fuel was burned by the same RCS engines to insure complete consumption of the OMS fuel before main engine cutoff (MECO). The guidance software computed the time for turnaround. The RTLS abort procedures are assumed to commence at time of engine shutdown except for shutdowns prior to staging when the procedures commence at staging.

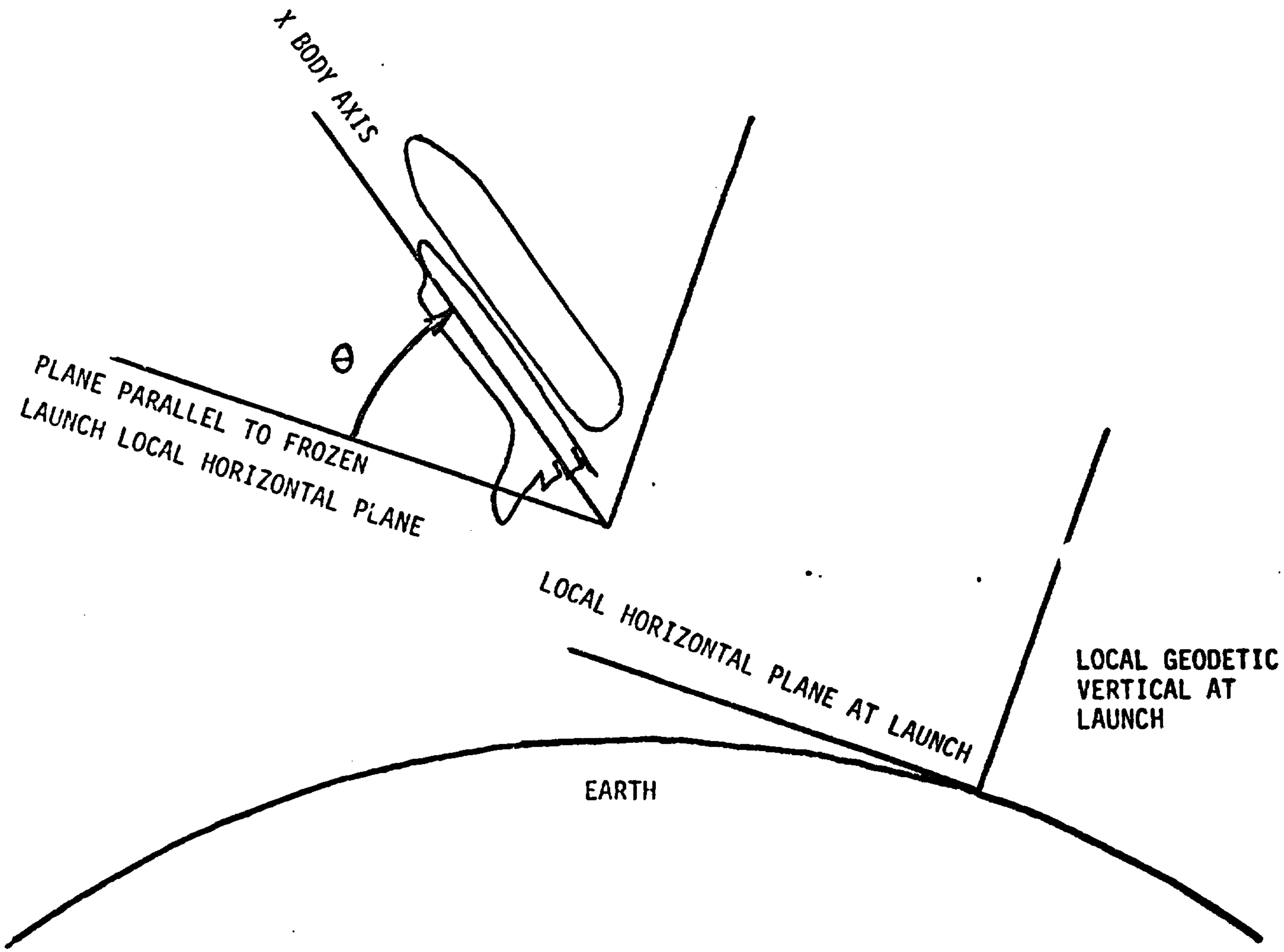

Figure 1 - Definition of Inertial Attitude Angle

This study used a three degree of freedom simulation contained on a modified Space Vehicle Dynamic Simulation (SVDS) 2.3.11 milestone file (Reference (C)) for a mission 3A RTLS abort launched from the Western Test Range. The modifications to SVDS were:

a) Addition of the turnaround time prediction logic (Reference (D)).

b) Addition of the thrust termination logic (Reference (D)).

The targets input to the Powered Explicit Guidance (PEG) module were biased to the Main Engine Cutoff minus ten seconds (MECO-10) conditions of 310,000 pounds of total weight, 230,000 feet altitude, and a four degree relative flight path angle. The biased desired flight path angle at the MECO-10 R-V target line results in an angle near zero at external tank separation. The Rockwell International (RI) R-V target line for MECO-10 was used.

$R = .069V_E - 110.1$

For thrust termination the target was the RI MECO R-V line:

$R = .068V_E - 171.5$

All ranges are from the landing site at the Western Test Range in nautical miles and the relative velocity (V_E) is in feet per second.

The inertial attitude required to shape an unperturbed RTLS trajectory to that of the mode boundary is computed as a function of the inertial velocity at the time of abort. For aborts occurring prior to staging the velocity at abort is defined as the inertial velocity at staging. The algorithm includes partial terms to modify the inertial attitude for off nominal SRB staging conditions.

$$\Theta = 90.0 - \left[\Theta_{NOM} + \Sigma\Delta h \Big/ (\Delta h_{MAX}/\Delta\Theta_{NOM})\right] \tag{3-1}$$

where

Θ_{NOM} = nominal inertial attitude

$\Sigma\Delta h$ = summation of quadratic terms and numerical partial derivatives to account for off-nominal SRB staging conditions. In particular,

$$\Sigma\Delta h = \left[\left(\frac{\Delta h_{MAX}}{\Delta V_{I_s}}\right) \Delta V_{I_s} + \left(\frac{\Delta h_{MAX}}{\Delta h_s}\right) \Delta h_s + \left(\frac{\Delta h_{MAX}}{\Delta \gamma_{I,s}}\right) \Delta \gamma_{I,s}\right]$$

$\Delta h_{MAX}/\Delta\Theta_{NOM}$ - change in maximum altitude with respect to a change in attitude.

s - denotes evaluation at SRB staging.

h - altitude

γ - inertial flight path angle

$\Delta V_{I,s}$, Δh, $\Delta \gamma_s$ - actual minus nominal conditions at SRB staging.

4.0 RESULTS

The interim analysis leading to a selection of the algorithm started by obtaining the maximum altitudes for unperturbed RTLS trajectories at three attitudes as shown in Figure 2. The maximum altitude for the mode boundary abort was used as the parameter to choose the required attitude for the five study cases. These angles are shown in Figure 3 plotted versus the inertial velocity at abort. The data points were curve fit as a quadratic function of inertial velocity at abort. The shaped trajectories for the unperturbed cases are shown in Figure 4.

The nominal SRB staging conditions were perturbed in velocity, flight path angle, altitude, and range. The perturbed trajectories were generated at the nominal attitude to determine the change in maximum altitude with respect to the perturbed condition at SRB staging. The numerical partial derivatives are shown in Figure 5 as a function of the inertial velocity at time of abort. The maximum altitude is insensitive to a change in range at SRB staging since the result is that the trajectory is translated in range only.

The partial derivatives were curve fitted with quadratic functions of inertial velocity. The change in altitude caused by each off nominal SRB staging condition is obtained by multiplying each partial derivative by the associated difference between actual and nominal SRB staging condition. The result is a cummulative

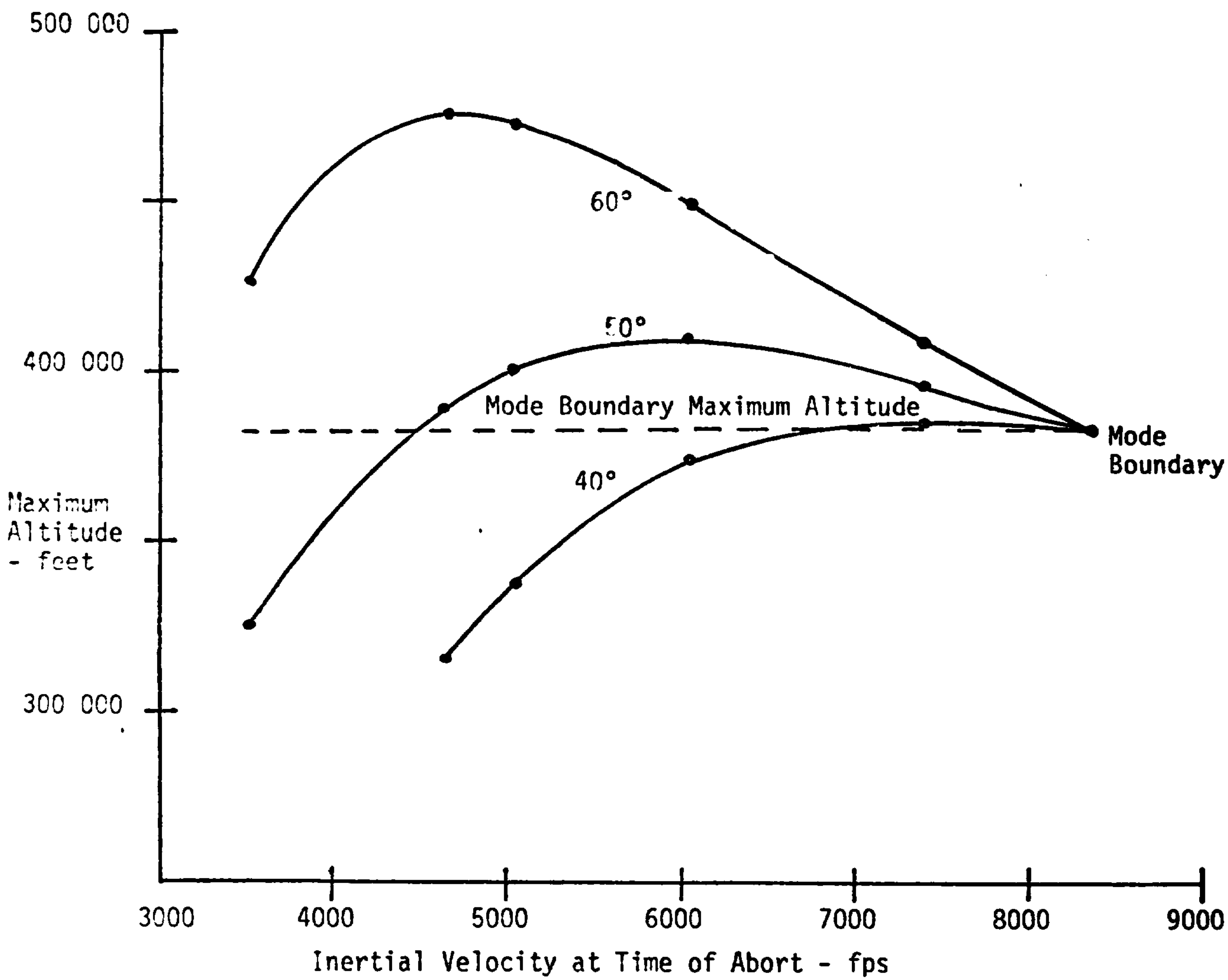

Figure 2 - Downrange Inertial Attitude Effect on RTLS Maximum Altitude vs Abort Inertial Velocity

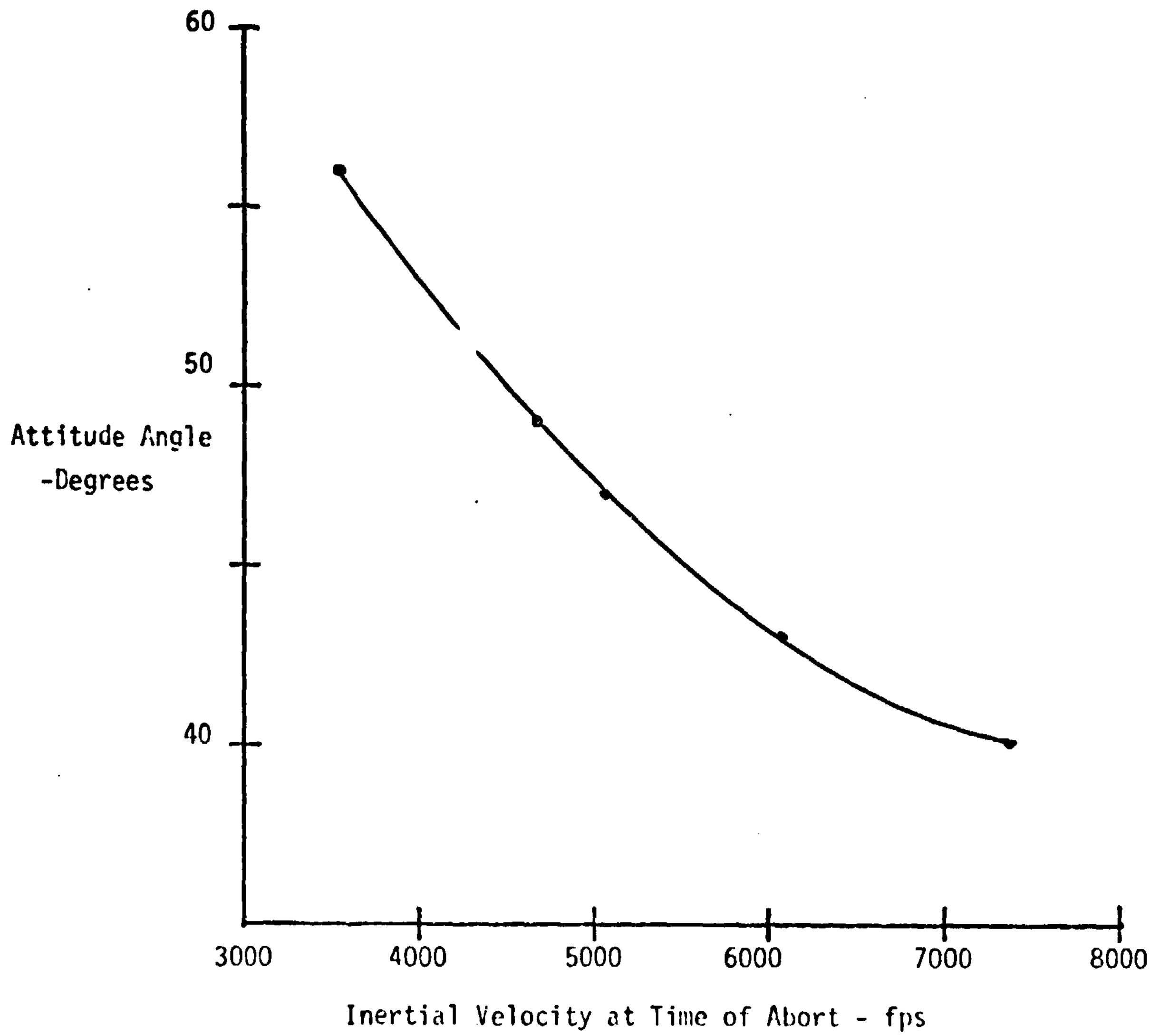

Figure 3 - Attitude Angle Required to Match Mode Boundary Trajectory vs Inertial Velocity at Time of Abort - Unperturbed Trajectory

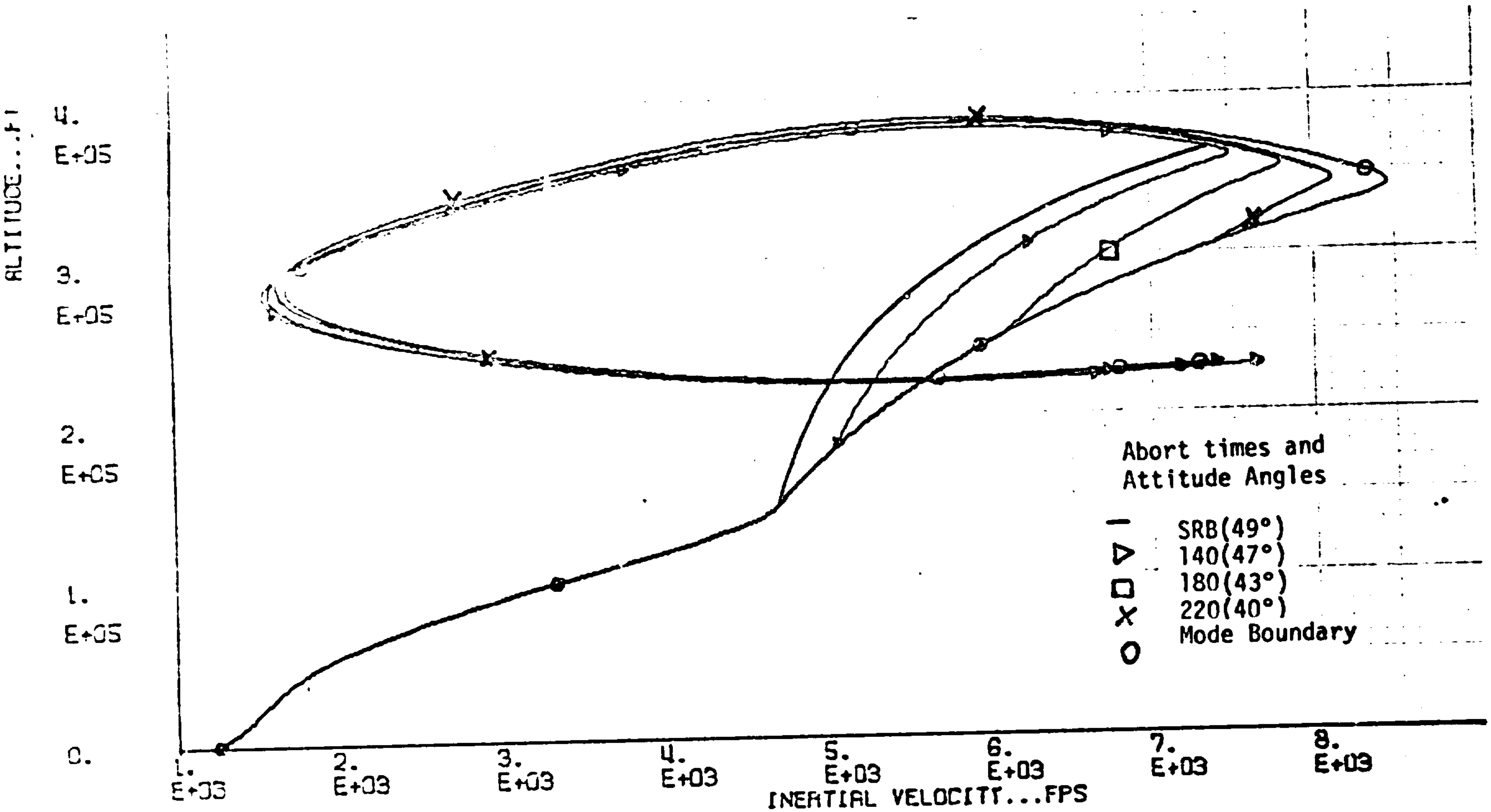

Figure 4 - Trajectory Shaping Altitude vs Inertial Velocity for Varying Attitude Angles and Abort Time

Nominal Trajectories

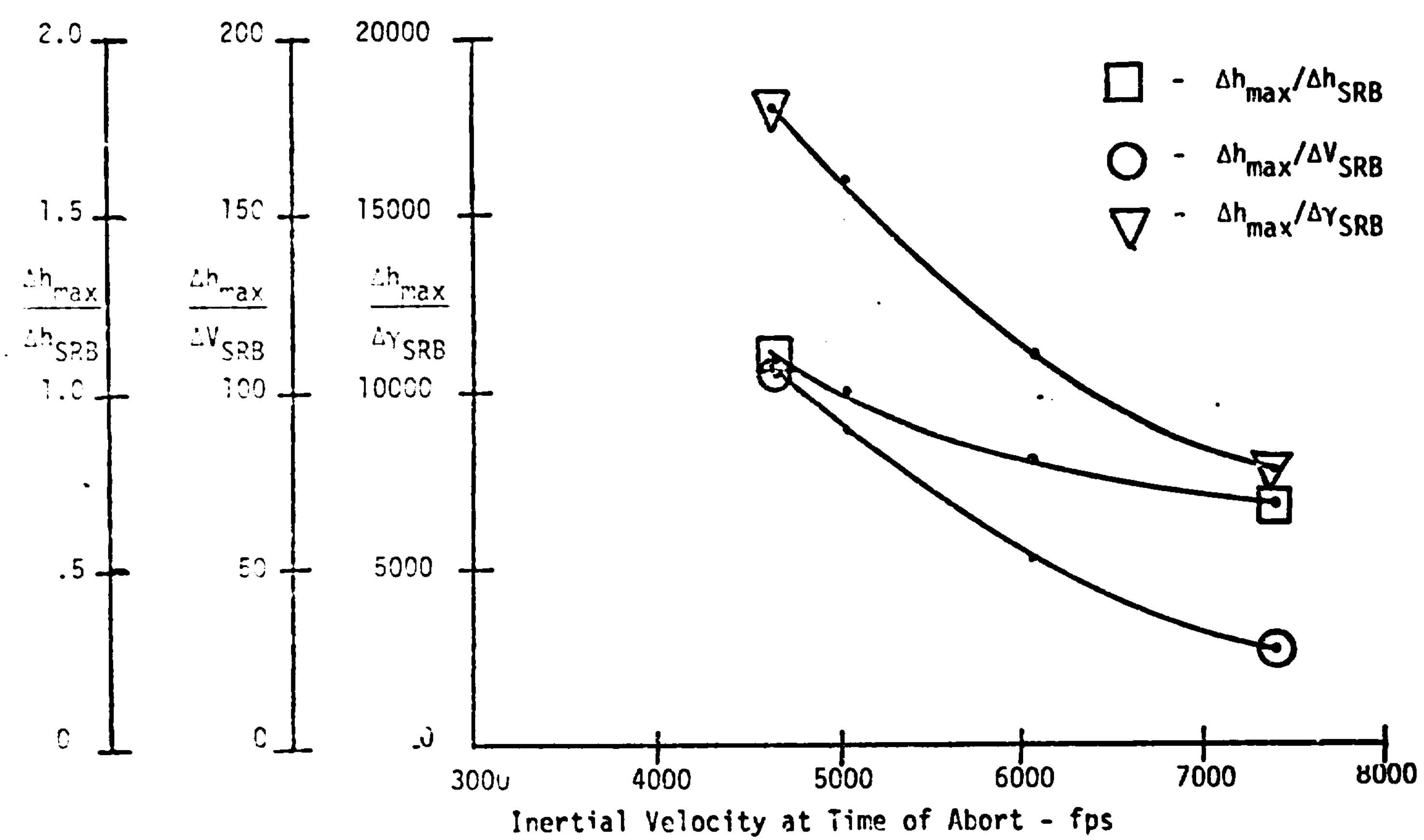

Figure 5 - Change in Maximum Altitude with Respect to Perturbations at SRB Separation

change in maximum altitude ($\Sigma\Delta h$) caused by off nominal SRB staging conditions. The nominal attitude must be modified to account for this $\Sigma\Delta h$. The change in maximum altitude with respect to a change in the nominal attitude ($\Delta h_{max}/\Delta\Theta_{nom}$) was obtained from Figure 2 and is shown in Figure 6 as a function of inertial velocity at abort. The required change to the nominal attitude is obtained by dividing $\Sigma\Delta h$ by ($\Delta h_{max}/\Delta\Theta_{nom}$).

The resulting algorithm is

$$\Theta = 90.0 - \left[\Theta_{NOM} + \left\{\left(\frac{\Delta h_{MAX}}{\Delta V_{I,s}}\right)\Delta V_{I,s} + \left(\frac{\Delta h_{MAX}}{\Delta h_s}\right)\Delta h_s + \left(\frac{\Delta h_{MAX}}{\Delta \gamma_{I,s}}\right)\Delta\gamma_{I,s}\right\} \Big/ \left(\frac{\Delta h_{MAX}}{\Delta\Theta_{NOM}}\right)\right] \qquad (4\text{-}1)$$

The terms Θ_{NOM}, $\left(\frac{\Delta h_{MAX}}{\Delta V_{I,s}}\right)$, $\left(\frac{\Delta h_{MAX}}{\Delta h_s}\right)$, $\left(\frac{\Delta h_{MAX}}{\Delta h_{\gamma_{I,s}}}\right)$ and $\left(\frac{\Delta h_{MAX}}{\Delta\Theta_{NOM}}\right)$ were fitted by quadratics and the coefficients (for the Mission 3A simulation used in the study) are shown in Table I.

For example:

$$\Theta_{NOM} = .474 + .0121 V_{I,AB} - 7.31 \times 10^{-7} V_{I,AB}^2$$

where

$V_{I,AB}$ - inertial velocity at time of abort

The conditions at abort attitude, and P-V line arrival points are shown in Table II for the nominal study cases. The algorithm was tested for perturbed SRB staging conditions of ± 200 feet per second

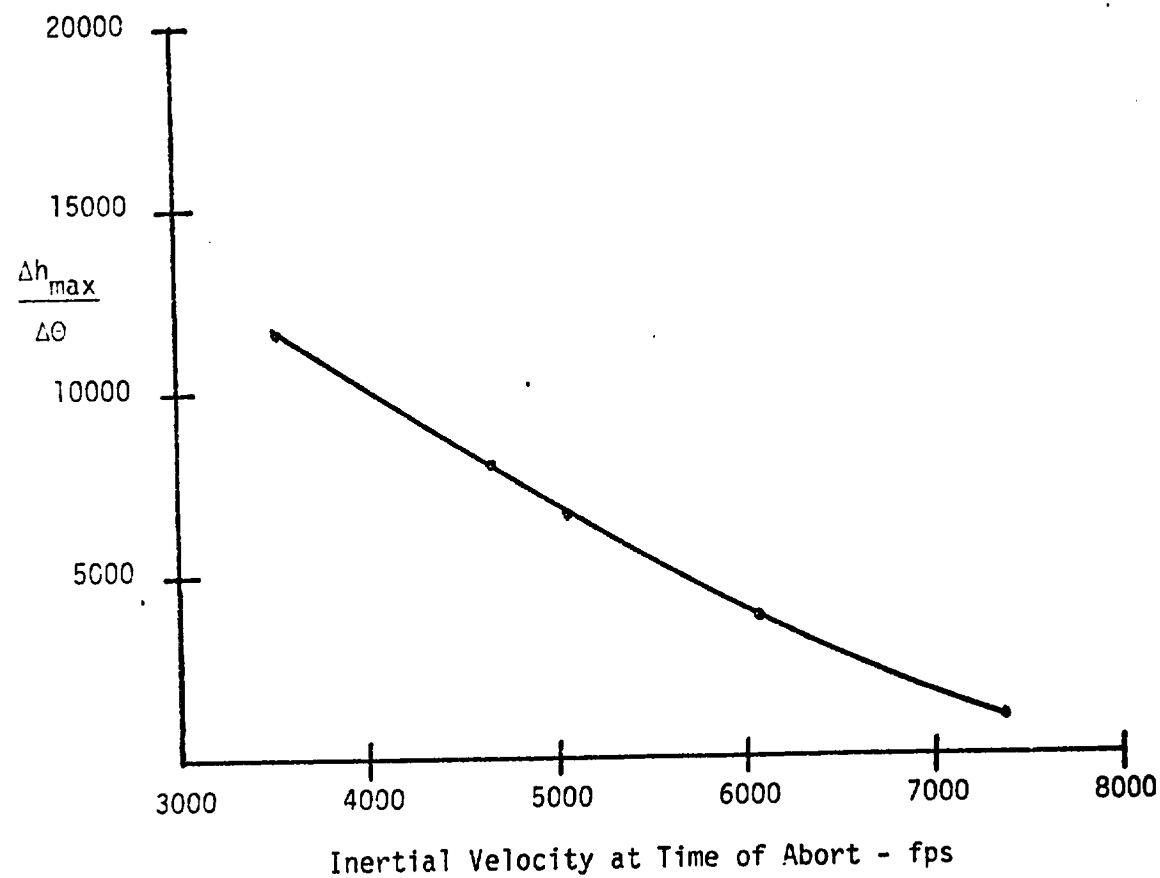

Figure 6 - Change in Maximum Altitude with Respect to Change in Attitude Angle

TABLE I

QUADRATIC COEFFICIENTS - Mission 3A RTLS Trajectory Shaping

Term	Quadratic Coefficients		
	a	b	c
Θ_{NOM}	.474	.0121	-7.31×10^{-7}
$\Delta h_{MAX}/\Delta V_{I,s}$	450.	.01023	6.12×10^{-6}
$\Delta h_{MAX}/\Delta h_s$	3.31	-6.75×10^{-4}	4.36×10^{-8}
$\Delta h_{MAX}/\Delta \gamma_{I,s}$	67600	-14.91	9.22×10^{-4}
$\Delta h_{MAX}/\Delta \Theta_{NOM}$	26809	-5.05	2.12×10^{-4}

TABLE II

MATCHING TRAJECTORIES - Nominal Conditions

Abort Time	Conditions at Abort VI FPS	γ_I DEG	Alt. FT	Range N.M.	ATTITUDES Θ DEG	MECO R N.M.	V_E FPS
LIFTOFF*	3517	38.78	134840	27.40	56	303.6	6985
SRB Sep.	4673	27.21	143358	35.61	49	311.7	7103
140 Sec.	5045	22.42	180420	49.63	47	311.6	7103
180 Sec.	6078	14.80	249118	85.71	43	305.2	7009
220 Sec.	7396	9.78	304273	130.4	40	296.4	6864
245 Sec.	8361	7.67	333298	163.4	Immediate Turn-around	289.5	6763

* Conditions at SRB separation

of velocity, ± 1.5 degrees of flight path angle, and ± 15,000 feet of altitude. Single perturbations resulted in $\Delta\Theta$ values from 2.0 to 4.1 degrees for aborts occurring at 180 seconds and earlier. Perturbations of the late 220 second trajectory yielded significantly larger corrections to Θ: 5.1 to 10.6 degrees. The corrections are larger at the late abort due to the limited time available to affect the trajectory.

For a late abort if the perturbations result in below nominal performance the $\Delta\Theta$ will be a correction to loft the trajectory. This is acceptable since the rotation is in the direction of the subsequent turnaround maneuver. If the performance is significantly better than nominal the $\Delta\Theta$ will command a rotation toward the earth to decrease the rate of change of altitude. The rotation is opposite to that of the turnaround maneuver. To prevent undesirable reverse pitch maneuvers the algorithm requires a limit on the computed attitude for late aborts. If the computed attitude is lower on the horizion than the actual angle at abort, the current actual angle becomes the commanded angle. The higher altitude that will occur during flyback must be accepted as a characteristic of late aborts.

The conditions for selected perturbed cases are shown in Table III. The shaped perturbed trajectories shown in Figure 7 were generated using the algorithm. The MECO-RV arrival points varied from 6812 to 7188 feet per second relative velocity and 291.9 to 318.6

TABLE III

MATCHING TRAJECTORIES - Perturbed Conditions

Abort Time	Conditions at Abort VI FPS	γ_I DEG	Alt. FT	Range N.M.	Θ DEG	MECO R N.M.	MECO V_E FPS
SRB Sep.	487. (1)	28.7 (1)	143358	35.6	42.7	318.6	7188
SRB Sep.	4476 (2)	25.6 (2)	143358	35.6	54.3	306.8	7032
140 Sec.	4852 (2)	21.1 (2)	176871	49.2	52.2	306.6	7030
180 Sec.	5877 (2)	14.0 (2)	239431	84.3	49.0	301.1	6949
220 Sec.	7608 (1)	10.0 (1)	318150	133.0	30.0	296.4	6879
220 Sec.	7173 (2)	9.5 (2)	290674	127.7	56.6	291.9	6812

(1) - Positive dispersion at SRB separation

(2) - Negative dispersion at SRB separation

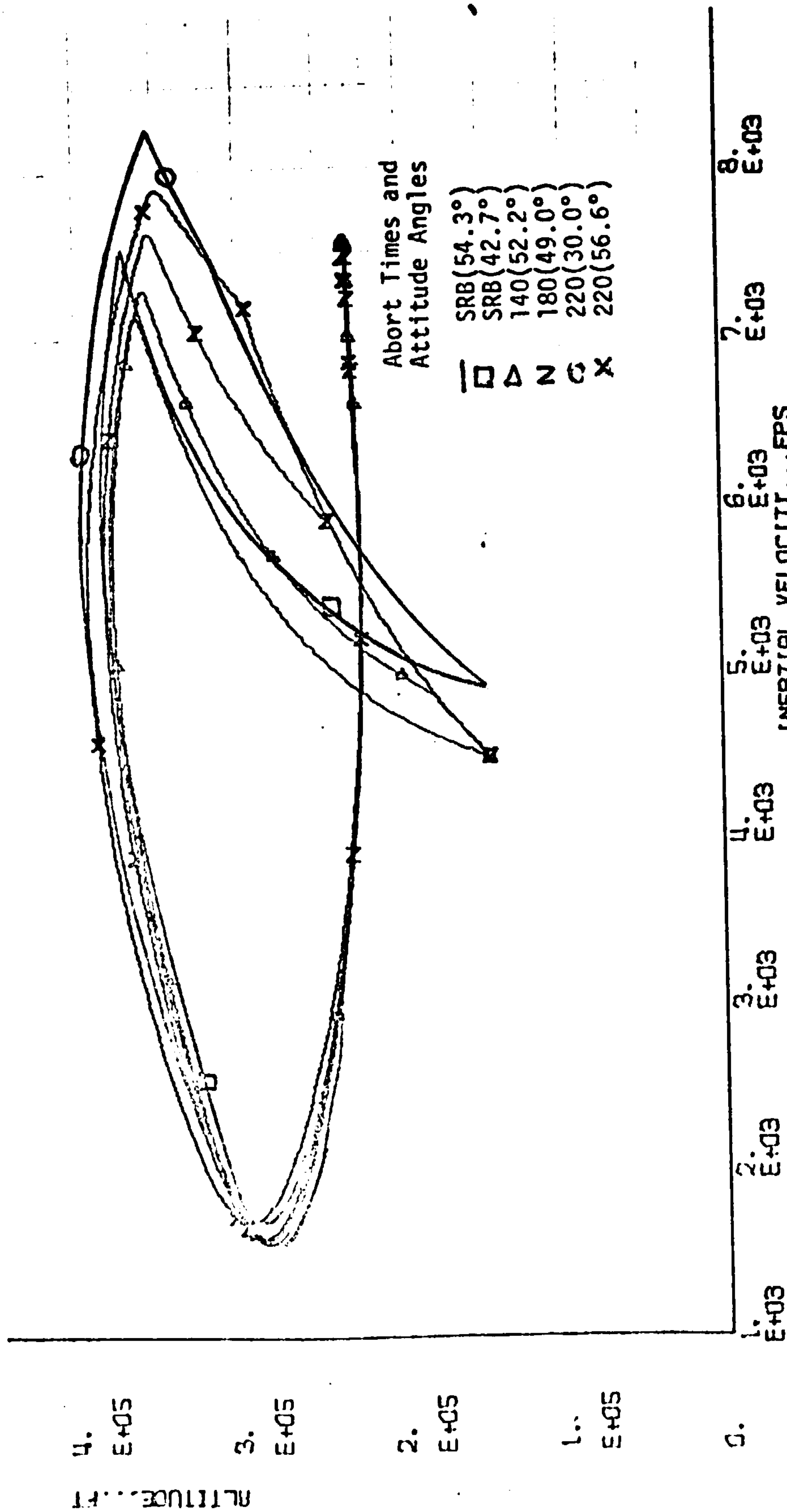

Figure 7 - Trajectory Shaping Altitude vs Inertial Velocity for Varying Attitudes and Abort Time

Perturbed Trajectories

nautical miles. The results are from additive dispersions, that is a higher velocity was combined with a higher flight path angle. The algorithm provided a good result for the double dispersed cases which are considered less likely to occur. The algorithm requires storage of 18 prelaunch computed coefficients and nominal SRB staging conditions, the measurement of three trajectory states at SRB separation, and the use of the actual inertial velocity. The computation of the commanded attitude requires the evaluation of a combination of quadratic terms and limit logic.

5.0 CONCLUSIONS

The following conclusions can be made concerning shaped RTLS trajectories:

1. It is possible to shape the RTLS trajectories within a few thousand feet altitude band of the mode boundary abort trajectory maximum altitude.
2. The shaped trajectories arrive within a 425 feet per second band on the MECO-RV line.
3. The algorithm is simple incurring minimal requirements for the onboard software and accounts for perturbations from nominal SRB staging conditions.
4. Near the mode boundary a limiter needs to be introduced to avoid pitch reversals.

6.0 REFERENCES

(A) FM41 (75-32), Return-to-Launch-Site (RTLS) Preliminary Combined Guidance and Targeting Formulation Presented to the Powered Flight Working Group (April 2-3, 1975), April 28, 1975.

(B) MDTSCO Design Note No. 1.4-4-7 "Return-to-Launch-Site Three Degree of Freedom Analysis, Constant Inertial Attitude During the Fuel Dissipation Phase", October 17, 1975.

(C) User's Guide for the Space Vehicle Dynamics Simulation (SVDS) Program Revision 2, JSC Internal Note No. 73-FM-67 November 14, 1974.

(D) "Powered Flight Guidance Ascent Supervisor", John P. Higgins, December 18, 1974.