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MARS SAMPLE RETURN ASCENT VEHICLE CONCEPTUAL GUIDANCE ALGORITHM

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Abstract

A conceptual guidance algorithm has been developed for the boost phase of the MARS Ascent Vehicle (MAV) based on numeric prediction/correction techniques. A numeric algorithm was chosen for its ability to model external forces such as aerodynamic drag. This algorithm has been tested under dispersed conditions and has been found fast enough and accurate enough to satisfy the projected MARS sample return ascent requirements.

Introduction

This document summarizes the ascent guidance analysis performed to support the Jet Propulsion Laboratory (JPL) and Johnson Space Center (JSC) joint conceptual design of a MARS Sample Return Mission MARS ascent vehicle. This analysis was primarily in the areas of optimal ascent trajectory determination, ascent guidance system algorithm definition and ascent dispersion analysis.

The current mission baseline includes an automatic MARS orbit rendezvous with the MARS ascent vehicle (MAV) transferring a sample canister to the MARS orbiter vehicle (MOV). The MOV contains the Earth Return Vehicle (ERV) for eventual transfer of the sample canister back to Earth.

The MARS rendezvous scenario consists of the MAV being placed in a parking orbit ahead and above of the MOV. This allows the MOV, which will perform the active rendezvous maneuvers, to view the MAV with its optical sensors against a dark star background rather than the MARS surface.

The primary objective for the MAV guidance system will be to place the MAV as close as possible to a pre-flight planned orbital position, relative to the MOV, under any and all environmental and system dispersed conditions. Minimization of MAV position dispersions reduces the MOV optical search cone and enhances the likelihood of successful automatic rendezvous.

Trajectory optimality studies and ascent dispersion analysis were performed in the definition of a conceptual ascent guidance algorithm.

Vehicle Configuration

During the course of 1985, JPL's conceptual MAV configuration evolved from a three-stage, all-solid propellant vehicle to a two-stage, solid boost stage/liquid upper stage configuration. The solid/liquid two-stage configuration offers advantages in physical size (smaller overall length

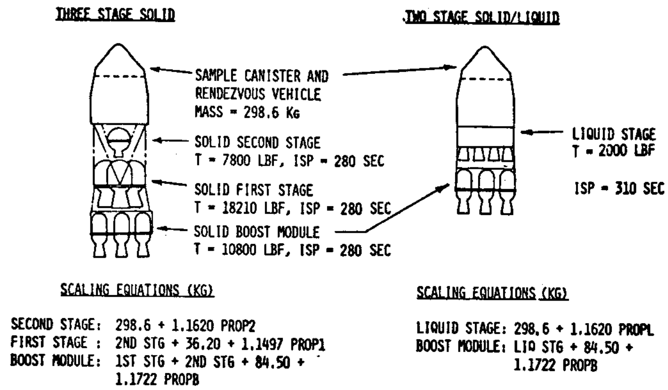


FIG. 1 CONFIGURATION DESCRIPTION

would allow entire vehicle including Centaur G to fit within the Space Shuttle cargo bay) making it a more attractive option than the three-stage, all solid configuration. Figure 1 illustrates the two configurations considered by JPL including the JPL defined thrust, specific impulse (ISP), payload mass and vehicle scaling equations. The two stage solid/liquid configuration utilizing a 2000 lbf thrust liquid engine was selected for guidance algorithm design. This specific configuration and thrust level was selected as representative of an actual vehicle which would approach the physical constraints of minimal overall vehicle length and minimal total vehicle mass at MARS liftoff.

Optimal Trajectory

The initial requirement in the design of this guidance algorithm is the determination of the optimal flight path to achieve the desired target conditions. With the decision to utilize an automatic MARS rendezvous and sample transfer between an ascent vehicle and an orbiting earth return vehicle, the primary targeting requirement for the ascent guidance system becomes orbital insertion of the MAV such that the likelyhood of a successful automatic rendezvous is maximized. The MOV would perform all active rendezvous maneuvers and would utilize optical sensors to track the passive MAV. This system definition results in the requirement for the MAV to be placed in an orbital position above and ahead of the MOV, enabling the MOV optical sensors to view the MAV acquisiton strobe lights against a dark star background rather than the bright MARS surface.

The MAV's contribution to maximum likelyhood of successful rendezvous is to be at the correct orbital position at a specified time. This requirement defines the primary targeting constraint for the ascent guidance system. A preliminary analysis was performed to determine

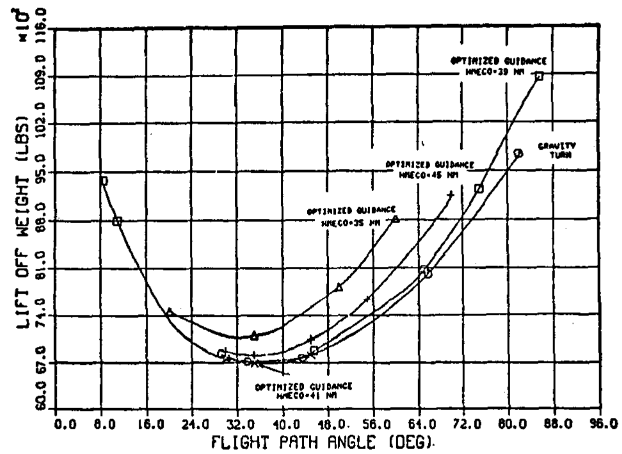


FIG. 2 MARS ASCENT INSERTION PERFORMANCE

the trajectory control strategy which when coupled with the JPL defined scaling laws results in a minimum total vehicle liftoff weight. A parametric analysis of boost cutoff conditions was performed with the Program to Optimize Simulated Trajectories (POST) to locate the minimum liftoff weight trajectory which passed through the desired orbit position. The results of this study indicated that a gravity turn trajectory utilizing an initial optimal pitch and yaw attitude is very near minimum for this problem (see Figure 2). This result enabled the definition of the total ascent control strategy. Illustrated in Figure 3 the ascent trajectory would be broken into five phases consisting of a short vertical rise to clear the launch platform, a short open loop fixed attitude phase to setup the proper launch altitude and azimuth profiles, a relatively long closed loop gravity turn phase to compensate for inflight dispersions, a long coast phase after liquid engine boost cutoff to reach the desired orbit and finally a circularization burn to raise the perigee above the MARS surface. Utilizing this control strategy and the groundrules and assumptions defined in Table 1, a nominal trajectory was designed for the solid/liquid two stage vehicle configuration described in Figure 1. A summary of key aspects of this trajectory is included in Table 2.

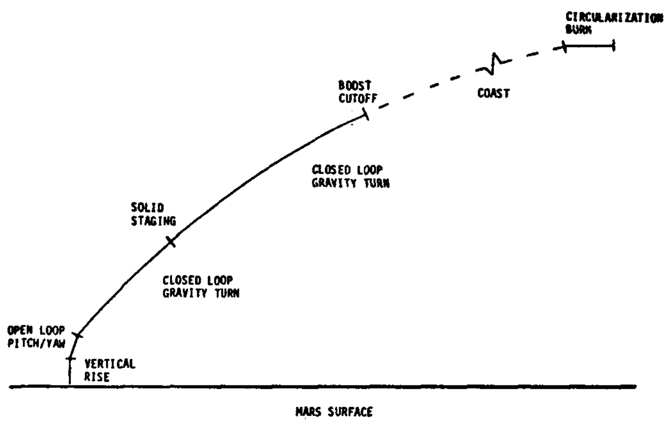


FIG. 3 BOOST TRAJECTORY PHASES

Table 1 Trajectory Groundrules and Constraints

* Launch Site Latitude : 23 deg North
* Launch Site Longitude : 312 deg
* Nominal Mars Atmosphere
* Fixed Payload of 298.6 kg
* Series Burn Launch Configuration
* No Maximum Load Factor Constraint
* Posigrade Launch (Easterly)
* Orbit Inclination : 30 deg
* Aerodynamics : CL = 0.0
  CD = 0.7
  Base Pressure = 0.0
* No Maximum Dynamic Pressure Constraint

Ascent Guidance Conceptual Algorithm

A close loop guidance algorithm is necessary to compensate for any environmental or system dispersions effects that may occur by utilizing the available vehicle controls to alter the trajectory to achieve the position/time target.

The controls available during the closed loop near-gravity turn phase to attain the position/time target after coast are angle of attack, sideslip, and cutoff time. During the circularization burn at the targeted position, the controls are inertial pitch, yaw, and cutoff time.

A numeric prediction/correction algorithm was selected as the MAV boost phase guidance baseline. Although slower in execution time than an analytic prediction algorithm such as the Space Shuttle Powered Explicit Guidance (PEG), a numeric prediction algorithm has the advantage of being able to accurately model many external forces simultaneously which cannot be easily represented analytically. The modeling of these significant external forces eliminates the requirement for trajectory dependent target biasing while resulting in an extremely accurate trajectory prediction. MAV aerodynamic drag utilizing an exponential MARS atmosphere model and MARS oblate gravitational perturbations were included in the baseline numeric predictor in addition to the primary forces of MAV thrust and the MARS gravity field.

Table 2 Trajectory Summary

* Injection Orbit Apogee x Perigee, km	581 x -2830
* Target Apogee, km	582
* Injection Burnout Time, sec	171.4
* Staging Time, sec	48.0
* Injection Altitude, km	155.8
* Injection Relative Flight Path Angle, deg	40.5
* Injection Inclination, deg	30.0
* Injection Gravity Losses, m/sec	449.6
* Max Acceleration, Earth G's	3.6
* Circularization Impulsive Delta V, m/sec	1651.0
* Boost Module Mass, kg	1066.2
* Second Stage Mass, kg	756.7
* Payload Mass, kg	298.6
* Total Liftoff Mass, kg	2121.5

The assumed guidance, navigation, and control (GN&C) real time structure includes execution of these functions cyclicly through the boost phase of the MAV trajectory (see Figure 4). Cyclic guidance execution during the trajectory allows the guidance close loop system to respond to time dependent dispersions which may occur during flight. The selected guidance execution frequency of 0.2 Hz was found to be high enough to provide accurate target acquisition under dispersed conditions while remaining practical for whatever on-board computer is eventually chosen.

Figure 5 provides an overview of the baseline guidance algorithm and Figure 6 gives a more detailed description of the various guidance modules.

Although projected late 1990's computer execution rates will be much improved over current hardware, minimization of guidance execution time requirements is still considered advantageous. Steps were taken in two areas to lower the MAV guidance execution requirements; reducing the number of required trajectory propagations per cycle to two and reducing the number of propagation steps per cycle to two during the thrust phase and two during the coast phase. Selection of the number of propagation steps was accomplished by parametricly evaluating final coast position accuracy versus number of steps. These results are presented in Table 3.

Reducing the number of trajectory propagations to two (nominal and perturbation) was accomplished by transforming the inertial target position errors into a coordinate system defined by the boost cutoff position and velocity vector. Because of a small coast (8.2 deg), this problem can be

FIGURE 4 GUIDANCE, NAVIGATION AND CONTROL SEQUENCING

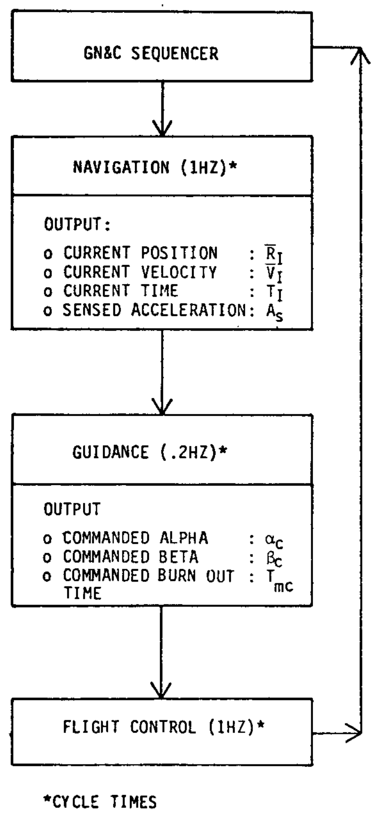
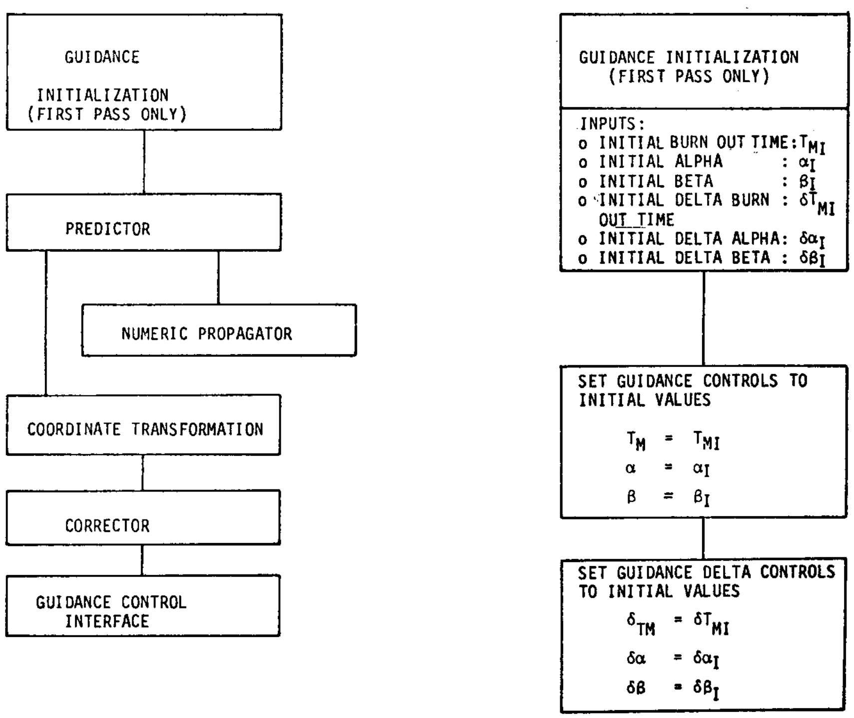


FIGURE 5 GUIDANCE OVERVIEW AND INITIALIZATION



PREDICTOR

INPUTS:
- o CURRENT POSITION VECTOR: $\bar{R}_I$
- o CURRENT VELOCITY VECTOR: $\bar{V}_I$
- o CURRENT TIME VECTOR : T_I
- o SENSED ACCELERATION : A_s
- o GUIDANCE ALPHA : α
- o GUIDANCE BETA : β
- o GUIDANCE BURN OUT TIME : T_m
- o GUIDANCE DELTA ALPHA : $\delta\alpha$
- o GUIDANCE DELTA BETA : $\delta\beta$
- o GUIDANCE DELTA BURN OUT TIME: δT_m

SET PREDICTOR CONTROLS TO THE GUIDANCE CONTROLS

$$\alpha_p = \alpha$$
$$\beta p = \beta$$
$$T_{mp} = T_m$$

PROPAGATE NOMINAL TRAJECTORY TO TARGET TIME

OUTPUT:
- o POSITION VECTOR AT TARGET TIME : $\bar{R}_N$
- o ANGLE BETWEEN INITIAL RELATIVE VELOCITY VECTOR AND RELATIVE VELOCITY VECTOR AT BURN OUT TIME : θ_R

SET PREDICTOR CONTROLS TO THE GUIDANCE CONTROLS PLUS THE GUIDANCE DELTA CONTROLS

$$\alpha p = \alpha + \delta\alpha$$
$$\beta p = \beta + \delta\beta$$
$$T_{mp} = T_m + \delta T_m$$

PROPAGATE DISPERSED TRAJECTORY TO TARGET TIME

OUTPUT:
- o POSITION VECTOR AT TARGET TIME : $\bar{R}_d$

NUMERIC PROPAGATOR

INPUTS:
- o INITIAL POSITION VECTOR: $\bar{R}_I$
- o INITIAL VELOCITY VECTOR: $\bar{V}_I$
- o INITIAL TIME : T_I
- o 1st STAGE THRUST : TH_1
- o 1st STAGE EXHAUST VELOCITY : V_{ex1}
- o 1st STAGE MASS : M_1
- o STAGING TIME : T_s
- o 2nd STAGE THRUST : TH_2
- o 2nd STAGE EXHAUST VELOCITY : V_{ex2}
- o 2nd STAGE MASS : M_2
- o PREDICTOR BURN OUT TIME: T_{mp}
- o PREDICTOR ALPHA : αp
- o PREDICTOR BETA : βp
- o TARGET TIME : T_t

IF THE CURRENT TIME IS LESS THAN STAGING TIME PROPAGATE TO STAGING TIME

OUTPUT:
- o POSITION VECTOR: $\bar{R}_S$
- o VELOCITY VECTOR: $\bar{V}_S$

PROPAGATE TO PREDICTOR BURN OUT TIME

OUTPUT:
- o POSITION VECTOR : $\bar{R}_m$
- o VELOCITY VECTOR : $\bar{V}_m$
- o RELATIVE VELOCITY VECTOR : $\bar{V}_{RM}$

COMPUTE THE ANGLE BETWEEN THE RELATIVE VELOCITY VECTOR AT THE INITIAL TIME AND RELATIVE VELOCITY VECTOR AT BURNOUT TIME

$$\theta_R = \cos^{-1}(\bar{V}_{RI} \cdot \bar{V}_{RM})$$

PROPAGATE TO TARGET TIME

OUTPUT:
- o POSITION VECTOR : $\bar{R}$

COORDINATE TRANSFORMATION

INPUTS:
- o CURRENT POSITION VECTOR: $\bar{R}_I$
- o CURRENT VELOCITY VECTOR: $\bar{V}_I$
- o ANGLE BETWEEN RELATIVE VELOCITY VECTORS : θ_R

COMPUTE TRANSFORMATION MATRIX (RELATIVE COORD. TO INERTIAL COORD): $T_{I\leftarrow R}$

$$\bar{V}_{RI} = \bar{V}_I - \bar{W}_m \times \bar{R}_I$$
$$\hat{i}_x = \frac{\bar{V}_R}{|\bar{V}_R|}$$
$$\hat{i}_y = \frac{\bar{R}_I \times \bar{V}_I}{|\bar{R}_I \times \bar{V}_I|}$$
$$\hat{i}_z = \hat{i}_x \times \hat{i}_y$$
$$T_{I\leftarrow R} = (\hat{i}_x : \hat{i}_y : \hat{i}_z)$$

ROTATE THE TRANSFORMATION MATRIX ABOUT THE $\hat{i}_y$ AXIS AN ANGLE OF $-\theta_R$

$$T_\theta = \begin{bmatrix} \cos\text{-}\theta_R & 0 & -\sin\text{-}\theta_R \\ 0 & 1 & 0 \\ \sin\text{-}\theta_R & & \cos\text{-}\theta_R \end{bmatrix}$$

$$T_{I\leftarrow R} = T_{I\leftarrow R}{}^* \, T_\theta$$

CORRECTOR

INPUTS:
- o TRANSFORMATION MATRIX : $T_{I\leftarrow R}$
- o NOMINAL POSITION VECTOR : $\bar{R}_N$
- o DISPERSED POSITION VECTOR: $\bar{R}_D$
- o CHANGE IN CONTROLS : $\delta\alpha$, $\delta\beta$, δT
- o DESIRED TARGET VECTOR : $\bar{R}_T$

COMPUTE CHANGE IN POSITION VECTOR DUE TO CHANGE IN CONTROLS IN RELATIVE COORDINATE SYSTEM: $\delta\bar{R}_R$

$$\delta\bar{R}_R = T^*_{I\leftarrow R}(\bar{R}_D - \bar{R}_N)$$

COMPUTE PARTIAL DERIVATIVES OF THE CHANGE IN POSITION VECTOR WRT THE CHANGE IN CONTROLS

$$\frac{\partial x}{\partial T} = \frac{\delta\bar{R}_R(1)}{\delta T_m}$$
$$\frac{\partial y}{\partial \beta} = \frac{\delta\bar{R}_R(2)}{\delta\beta}$$
$$\frac{\partial z}{\partial \alpha} = \frac{\delta\bar{R}_R(3)}{\delta\alpha}$$

COMPUTE DIFFERENCE IN THE TARGET POSITION VECTOR AND THE NOMINAL POSITION VECTOR IN RELATIVE COORDINATE SYSTEM: $\Delta\bar{R}_M$

$$\Delta\bar{R}_M = T^*_{I\leftarrow R}(\bar{R}_T - \bar{R}_N)$$

COMPUTE THE CHANGE IN CONTROLS NEEDED TO CORRECT THE TARGET MISS VECTOR ($\Delta\bar{R}_M$)

$$\Delta T_M = \frac{\Delta\bar{R}_M(1)}{\frac{\partial x}{\partial T}}$$
$$\Delta\beta = \frac{\Delta\bar{R}_M(2)}{\frac{\partial y}{\partial \beta}}$$
$$\Delta\alpha = \frac{\Delta\bar{R}_M(3)}{\frac{\partial z}{\partial \alpha}}$$

GUIDANCE CONTROL INTERFACE

INPUTS:
- o GUIDANCE ALPHA : α
- o GUIDANCE BETA : β
- o GUIDANCE BURN OUT TIME: T_M
- o CHANGE IN CONTROLS : $\Delta\alpha$, $\Delta\beta$, ΔT_M
- o CONVERGENCE TOLERANCE : Tol

ADD THE CHANGE IN CONTROLS TO THE GUIDANCE CONTROLS

$$\alpha = \alpha + \Delta\alpha$$
$$\beta = \beta + \Delta\beta$$
$$T_m = T_m + \Delta T$$

TEST FOR CONVERGENCE

IF (T_m < Tol • T_m)

THEN: SET COMMANDED CONTROLS EQUAL TO THE GUIDANCE CONTROLS

$$\alpha_C = \alpha$$
$$\beta_C = \beta$$
$$T_{mc} = T_m$$

FIGURE 6 GUIDANCE MODULES DESCRIPTIONS

Table 3 Guidance Propagation Trade Results

		Number of Steps During Burn		
		2	4	20
	1	38/414	65/411	275/410
Number	2	48/99	75/98	286/98
of	3	58/60	85/59	295/59
Steps	4	68/44	95/43	305/43
During	5	78/35	105/35	315/35
Coast	6	88/30	----	325/30
	7	98/28	----	335/27
	8	108/26	----	345/26

Execution Time,milsec/Target Position error,ft

represented by a flat earth gravity field approximation. This allows the closed loop controls (angle of attack, sideslip and cutoff time) to have approximate independent effect on the target position constraints when they are transformed into a boost cutoff coordinate system. This near independence allows introduction of deltas to each contol in the same trajectory propagation instead of independent trajectory propagations for each control. In this case the net result was to reduce from three propagations (one for each control) to one combined control propagation. This effort has resulted in a final algorithm that is accurate within 100 meters of the target position while requiring 50 milliseconds of Univac 1184 mainframe execution time per guidance cycle. To provide perspective to this timing number, a similar analysis was made with the Space Shuttle's PEG analytic algorithm resulting in a PEG requirement of 10 milliseconds Univac per guidance cycle. Although slower than PEG by five times, the MAV numeric algorithm offers significant advantages over analytic solutions in terms of accuracy without requiring extensive flight planning activities. It should also be considered that advances in computer execution rate capabilities during the next decade could make this issue insignificant.

The conceptual algorithm was specifically designed to solve the MAV boost phase guidance problem. However with modifications to the constraints and controls, a similar algorithm could be developed for the MAV circularization burns. Whether the assumptions utilized in the development of the ascent algorithm would be valid for the circularization burn requires further analysis.

Environmental Dispersion Analysis

In order to stress test the conceptual guidance algorithm, a dispersion analysis was performed which compared performance results between the conceptual algorithm and a numerically derived optimal solution. The representative dispersions selected included first and second stage specific impulse (Isp), first stage solid motor burn rate, vehicle aerodynamic drag, and dispersed Martian atmosphere.

The analysis was performed by applying each individual dispersion to a trajectory simulation utilizing the conceptual guidance algorithm and the POST optimization program set up with the same controls and constraints.

Table 4 presents a summary of the results from this analysis, and the dispersion induced performance differential is expressed as liquid stage delta velocity.

In summary, the conceptual algorithm performed at nearly the same level as the optimal solution for each dispersion with a maximum differential of 0.6 m/s for the dispersed high Martian atmosphere. These results demonstrate that the linear correction technique utilized in the numeric algorithm does not induce excessive performance penalties while still attaining the position at time target. It should be noted that the nominal conceptual algorithm trajectory results in a 100 meter position error due to the numeric streamlining steps, but the maximum dispersion induced position error from the nominal was only 34 meters.

Table 4 Guidance Algorithm Environmental Dispersion Results

Dispersion	Time of Boost Cutoff, sec	Liquid Stage Delta Velocity, m/sec	Position Error at Target Time, M
Nominal	118.76	0.0/0.0	100.3
High Solid Isp (1.3%)	116.88	-17.6/-17.5	106.1
Low Solid Isp (1.3%)	120.64	+17.6/+17.6	86.0
High Liquid Isp (1.3%)	117.81	-0.2/-0.3	105.5
Low Liquid Isp (1.3%)	119.75	+0.2/+0.2	96.3
High Solid Burn Rate (10.4%)	113.42	-1.6/-1.1	116.4
Low Solid Burn Rate (10.4%)	124.23	+1.9/+2.1	86.0
High Aerodynamic Drag (9%)	119.73	+9.2/+9.3	94.8
Low Aerodynamic Drag (9%)	117.79	-9.2/-9.4	105.8
High Martian Atmosphere	121.57	+26.9/+27.5	66.5
Low Martian Atmosphere	117.71	-10.3/-10.4	115.2

* Liquid Stage Delta Velocity Includes Total for Boost and Circularization Burns, Numeric Optimal/Algorithm

Conclusions

A conceptual guidance algorithm has been developed for the boost phase of the MARS Ascent Vehicle (MAV) based on numeric prediction/correction techniques. A numeric algorithm was chosen for its ability to model external forces such as aerodynamic drag. This algorithm has been tested under dispersed conditions and has been found fast enough and accurate enough to satisfy the projected MARS sample return ascent requirements.

The algorithm development approach utilized for this specific vehicle is generic in nature and could be used to define numeric prediction/correction algorithms for other vehicle configurations.

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