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The Controllability of the Aeroassist Flight Experiment Atmospheric Skip Trajectory

by
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The Aeroassist Flight Experiment (AFE) will be the first vehicle to simulate a return from geosynchronous orbit, deplete energy during an aerobraking maneuver, and navigate back out of the atmosphere to a low earth orbit. It will gather scientific data necessary for future Aeroassisted Orbital Transfer Vehicles (AOTV's). Critical to mission success is the ability of the atmospheric guidance to accurately attain a targeted post-aeropass orbital apogee while nulling inclination errors and compensating for dispersions in state, aerodynamic, and atmospheric parameters. In trying to satisfy mission constraints, atmospheric entry-interface (EI) conditions, guidance gains, and Earth-atmosphere modeling were investigated for effects on the trajectory. This paper presents the results of the investigation; emphasizing the adverse effects of dispersed atmospheres on trajectory controllability.

THE CONTROLLABILITY OF THE AEROASSIST FLIGHT EXPERIMENT ATMOSPHERIC SKIP TRAJECTORY

1.0 OBJECTIVES

The Aeroassist Flight Experiment (AFE) will be the first vehicle to simulate a return from geosynchronous orbit (GEO), deplete energy during an aerobraking maneuver, and navigate back out of the atmosphere to a low earth orbit (LEO). The objective of this study was to evaluate the controllability of the atmospheric skip trajectory and investigate the relative contributions of the factors detrimental to that control.

2.0 BACKGROUND

2.1 Mission Purpose & Definition

The AFE is to serve as the precursor for future missions involving Aeroassisted Orbital Transfer Vehicles (AOTV's). AOTV's will someday be the combination wrecker/taxi that will transport people and machines back and forth between LEO and higher orbits, and will eventually be used for lunar and mars journeys. Aerobraking is advantageous when decellerationg from a high energy state (such as a geosynchronous or lunar-to-earth transfer orbit) to a low energy state (such as a LEO). The decelleration can be performed in either of two ways. The first way is to fire engines, but large amounts of fuel are needed for this type of maneuver. The other way to decellerate is to plunge through a planetary atmosphere and let the aerodynamic drag do the work. This technique is to be used with the AFE.

The AFE mission will consist of many phases (Ref. 1). First, the vehicle will be transported to LEO by the Space Shuttle in the mid 1990's. Once deployed, the AFE will ignite a solid rocket motor (SRM) and accelerate to a state that simulates a craft returning from GEO. The SRM casing will then be discarded and allowed to re-enter. The AFE vehicle will perform trim burns to properly position itself for atmospheric entry (approximately 400kft, called "entry interface" or "EI"). The atmospheric guidance will then assume control and guide the vehicle through the atmosphere while targeting a pre-selected exit orbit. During the aeropass, onboard experiments and instruments will sample the flow and record measurements. This data will be later used to verify computational fluid dynamics (CFD) codes. After exiting the atmosphere, and reaching apogee, orbital maneuvers will be performed to correct for errors and circularize the orbit for subsequent rendevouz and retrieval by the Shuttle. Figure 2.1-1 illustrates the basic mission profile.

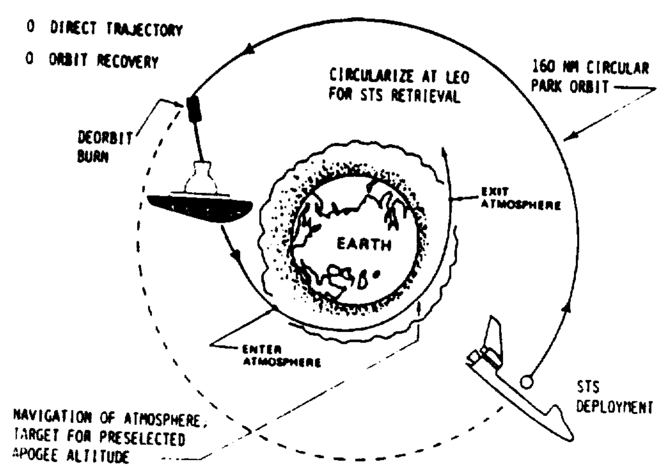

Figure 2.1-1 - Basic AFE Mission Profile

2.2 Vehicle Configuration & Characteristics

The basic design of the AFE vehicle consists of three components: the aerobrake, the carrier vehicle, and the main propulsion unit. Figure 2.2-1 shows a schematic of the AFE flight article.

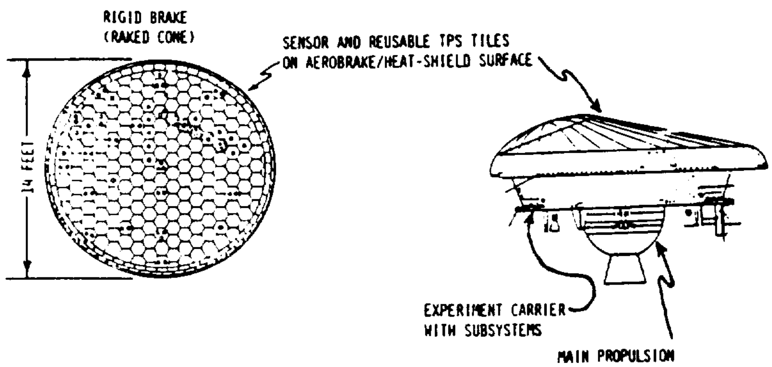

Figure 2.2-1 - AFE Schematic

The aerobrake is a raked cone which provides an aerodynamic component of lift during the aeropass (nominal L/D is 0.28) which can rotate about the velocity vector via reaction control system (RCS) jets. By rotating the lift vector, the vertical (or "in-plane") component of lift can be adjusted in flight so that the pre-selected exit apogee is attained. The position of the lift vector is measured in terms of the bank angle. T· horizontal (or "out-of-plane") component of lift is constantly causing the orbital plane to change. The diffe ce between the desired and actual orbital planes is called the "wedge angle." The wedge angle is controlled by iodically reversing the side of the vertical plane on which the bank angle is being modulated. This is done by simply changing the sign of the bank angle and is called a "roll-reversal." The brake is a fixed-geometry structure covered by thermal protection system (TPS) tiles like those on the Shuttle. Data-gathering sensors are positioned in the tiles to support the onboard experiments.

The primary structure of the system is the carrier vehicle. It is the link between the aerobrake and the propulsion system. It will house the computer systems as well as many experiment packages. The carrier vehicle will also contain a strapdown inertial measurement unit (IMU) for navigation.

The remanining component is the main propulsion system. It consists of a SRM that will deliver the vehicle to its simulated return-from-GEO conditions. The SRM is jettisoned prior to EI by way of a large spring system between the SRM casing and the carrier vehicle.

The atmospheric guidance to use for the mission is still undecided. Currently, several algorithms are undergoing testing. For this study, C. J. Cerimele's HYPAS guidance routine (Ref. 2) was used. The HYPAS guidance separates the aeropass into two phases: the equilibrium glide phase and the exit phase. During the first phase, the logic attempts to gradually null the altitude acceleration while controlling the loads the vehicle is experiencing and ensuring sufficient capture. Once a particular decelleration has occurred, control is transferred to the exit phase logic. The exit phase uses an analytic prediction/correction technique to attain a targeted exit apogee altitude.

3.0 TRAJECTORY SIMULATION TOOLS

The three degree-of-freedom (DOF) Descent Design System (DDS) simulation program, originally developed for the Space Shuttle program, was modified to simulate the AFE trajectories. A fourth DOF was added to model the balancing of the pitching moment. DDS is fast and efficient for performing nominal trajectory simulations.

For dispersion analyses, the3-DOF shuttle-based LAND montecarlo program was upgraded to 4-DOF and renamed the Aerobraking Montecarlo Analysis Program (AMAP) (Ref. 3). AMAP models dispersions in state, aeroynamic, atmospheric, and navigational parameters. Finally, dispersed atmosphere profiles (for use in AMAP) were created using the stand-alone version of the 1986 Global Reference Atmosphere Model (GRAM86) program (Ref. 4).

4.0 INVESTIGATION METHOD & RESULTS

McDonnell Douglas Space Systems Company (MDSSC) supports the Mission Planning & Analysis Division (MPAD) of NASA at the Johnson Space Center. MPAD directed MDSSC to optimize the AFE trajectory. The key parameters in the optimization were: (1) the peak heat rate experienced during the aeropass, and (2) the post-aeropass change in velocity (ΔV) required to circularize the orbit. In effect, the ability to control and manipulate the trajectory was examined (Ref. 5). The current contraints were that the mean (average) peak heat rate be under 40.3 Btu/ft^2 s and, if possible, the mean plus 3sigma peak heat rate to be under 40.3 Btu/ft^2 s. Also, the mean plus 3sigma post-aeropass ΔV had to be less than 400 fps.

4.1 Transfer Orbit Perigee and Guidance Gain Variation

The first step in the study was to vary guidance gains and the transfer orbit perigee. The gains altered were the equilibrium glide phase altitude rate and dynamic pressure terms: GHDOT and GQ respectively. Varying the gains simply alters the reaction of the guidance algorithm to different situations. For instance, increasing GHDOT increases the sensitivity of the guidance to altitude-rate variations. Varying the transfer orbit perigee translates into entering the atmosphere at a varied flight path angle (Gamma). Aside from perigee and gain variations, all other conditions were held constant and 100-case montecarlo trajectories flown using AMAP. This meant that the guidance was subjected to 100 sets of dispersion combinations for each gain and perigee adjustment. The statistical results were tabulated in terms of the mean and the mean plus 3sigma values. Figures 4.2-1 and 4.2-2 show plots of the statistical results of the mean peak heat rates and the mean plus 3sigma post-aeropass ΔV's for the gain and gamma combinations.

As expected, the region of mean plus 3-sigma ΔV of less than 400 fps (mission constraint) has a generally higher peak heat rate than do the regions of larger ΔV's. The figures show the nominal heat rate for lift-vector-up trajectories (i.e. the best possible heat rates) when ΔV constraints are ignored. The AFE heat rate constraint of 40.3 is also shown. It is clear that the mean heat rate constraint of 40.3 is possible to meet while maintaining a ΔV of less than 400 fps. However, meeting a mean plus 3sigma of 40.3 was not possible for perigee and gain variation alone.

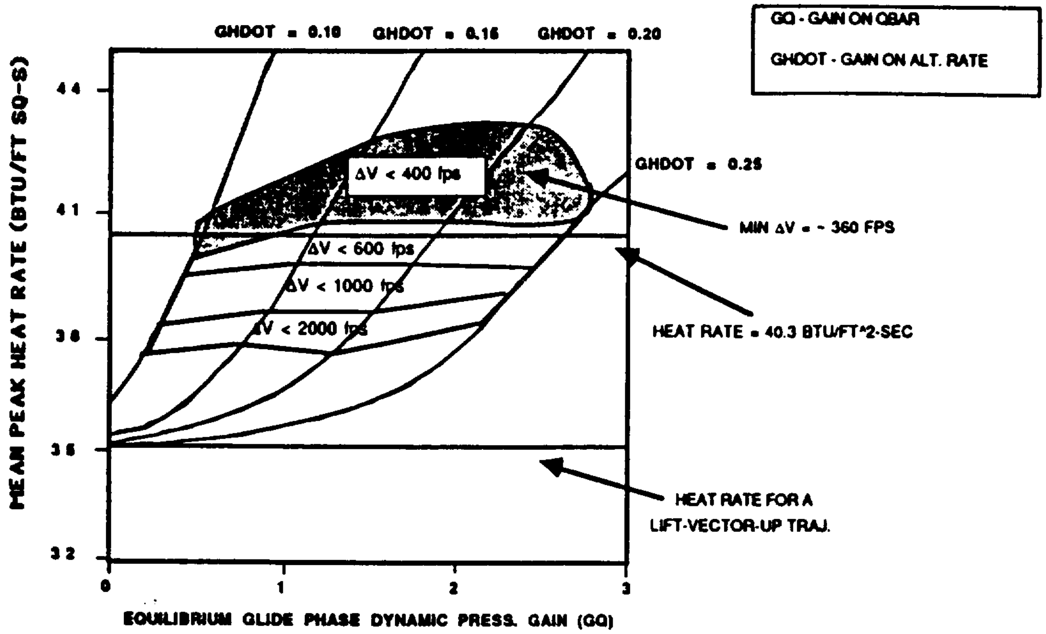

Figure 4.2-1 - Effects of Gain Variation on Mean Peak Heat Rate & ΔV for Gamma = -4.4 Degrees

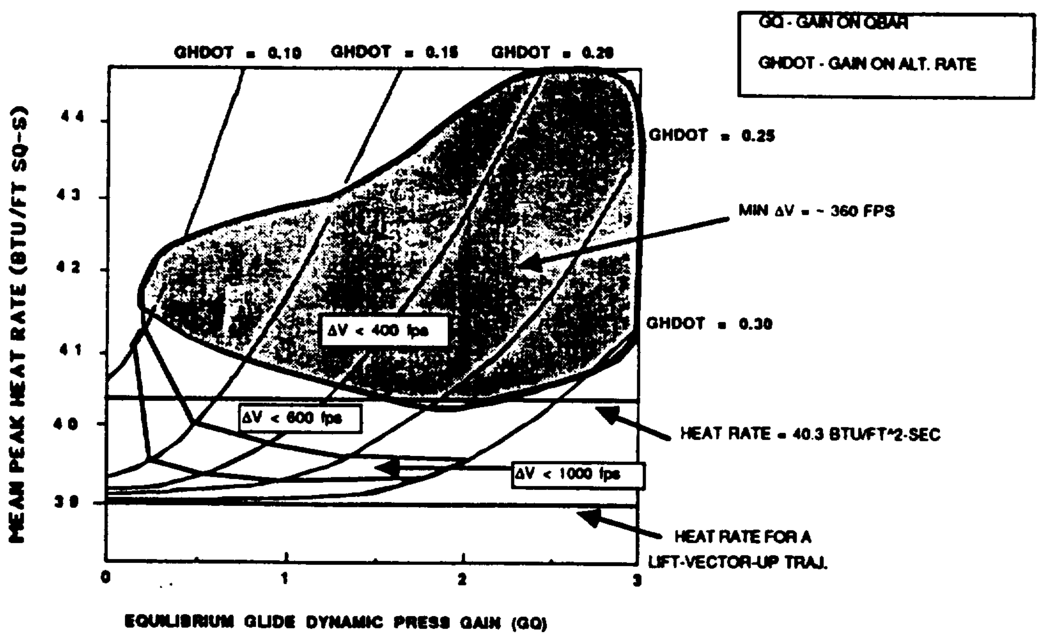

Figure 4.2-2 - Effects of Gain Variation on Mean Peak Heat Rate & ΔV for Gamma = -4.5 Degrees

Figures 4.2-3 and 4.2-4 show that gamma variation outside the -4.4 to -4.5 range results in increased peak heat rates and/or ΔV's.

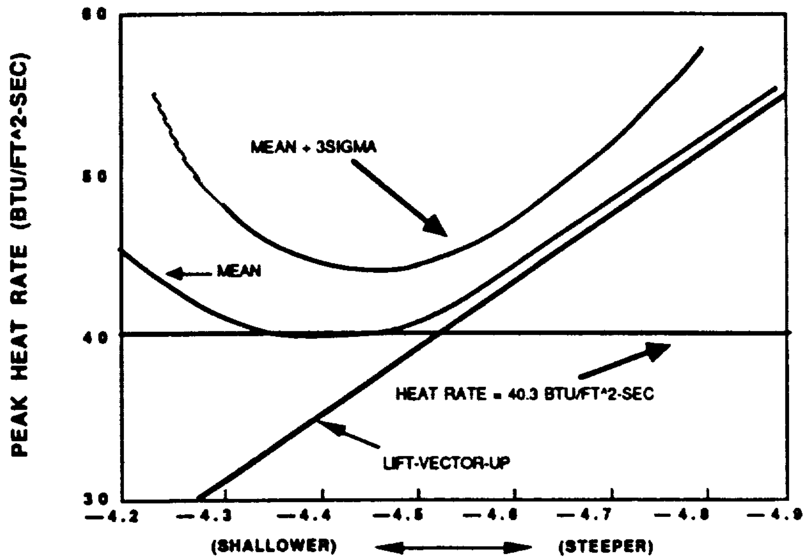

Figure 4.2-3 - Peak Heat Rate Vs. Gamma

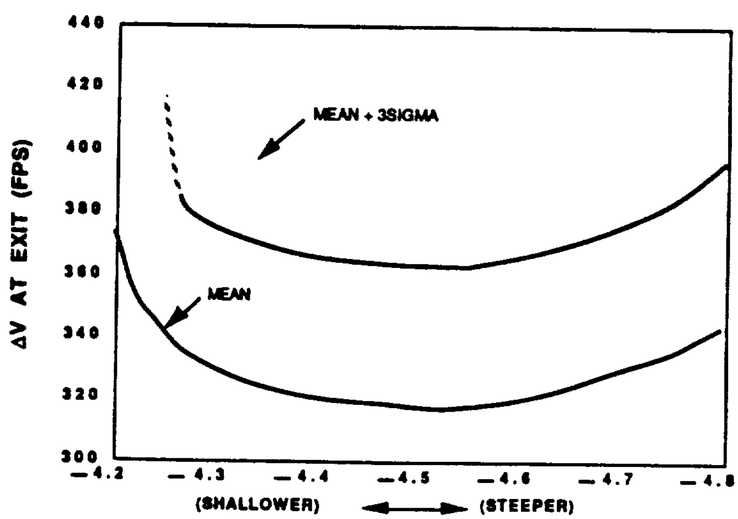

Figure 4.2-4 - Mean + 3-Sigma ΔV Vs. Gamma

4.2 Transfer Orbit Apogee Variation

The next step in the study was to vary the transfer orbit apogee to try to attain a mean plus 3sigma heat rate of less than 40.3 Btu/ft^2 s. The transfer orbit apogee was added to the list of parameters to be varied. This translates into altering the inertial velocity at EI. Of course, altering this parameter means deviating from the overall mission objective of simulating a GEO-return. For instance, lowering the transfer orbit apogee (i.e. lowering EI velocity) signifies returning from a lower-than-GEO. The optimal gains for each flight path angle (found from the previous section) were used while the transfer orbit apogee was scanned. Figures 4.3-1 and 4.3-2 show the results.

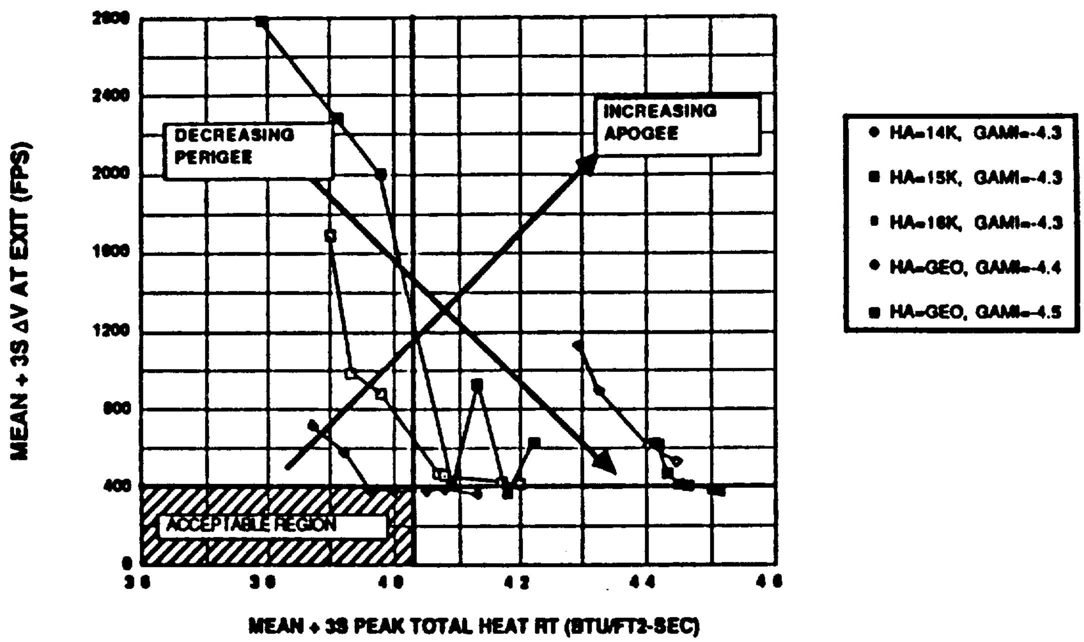

Figure 4.3-1 Heating Vs. ΔV for Varying Transfer Orbit Apogee & Perigee

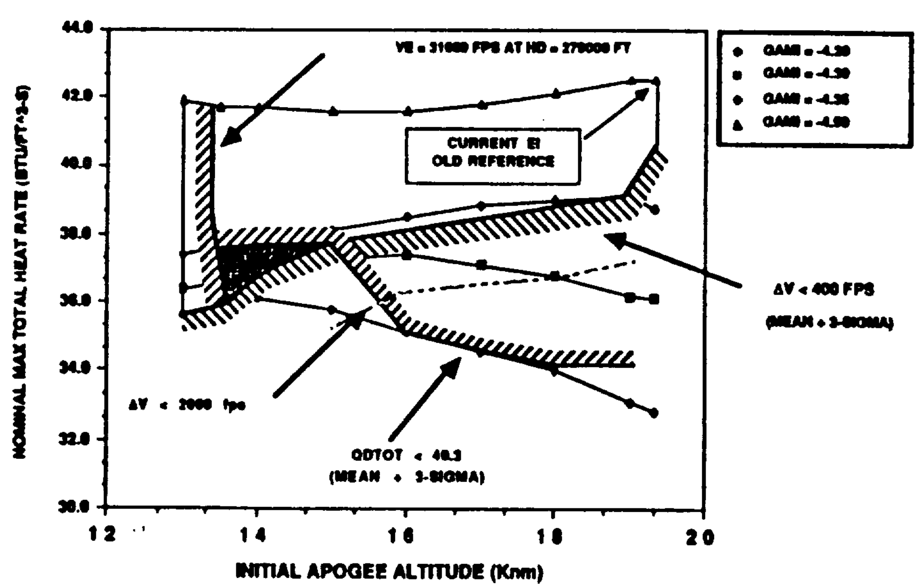

Figure 4.3-2 Heating Vs. Transfer Orbit Apogee Altitude

Both figures show that, in order to satisfy the ΔV and heat rate constraints, both the transfer orbit apogee and perigee had to be significantly altered. Also, when a constraint was added to satisfy the conditions necessary for the flow conditions to be sampled (relative velocity at 279000 ft > 31660 fps), Figure 4.3-2 revealed only a very small region of acceptability (shaded area).

4.4 Relative Contributions of Individual Dispersion Sources

Knowing that lowering the transfer orbit apogee is highly undesirable, the next step in in the study was to investigate the relative contributions of the individual dispersion sources in order to define which ones (if any) were dominating the controllability of the trajectory. Dispersion sources were all deactivated and only a single source re-activated. This was done for each dispersion source in turn so that the effects of a single source could be statistically analyzed. Figures 4.4-1 and 4.4-2 show the effects of the single dispersion sources on the 3-sigma peak total heat rate and post-aeropass ΔV.

In both figures, it is clear that the dominating factor influencing the peak heat rate and post-aeropass ΔV is the dispersed atmosphere set. When compared to the other dispersion sources, the effect of the atmospheres is completely dominant.

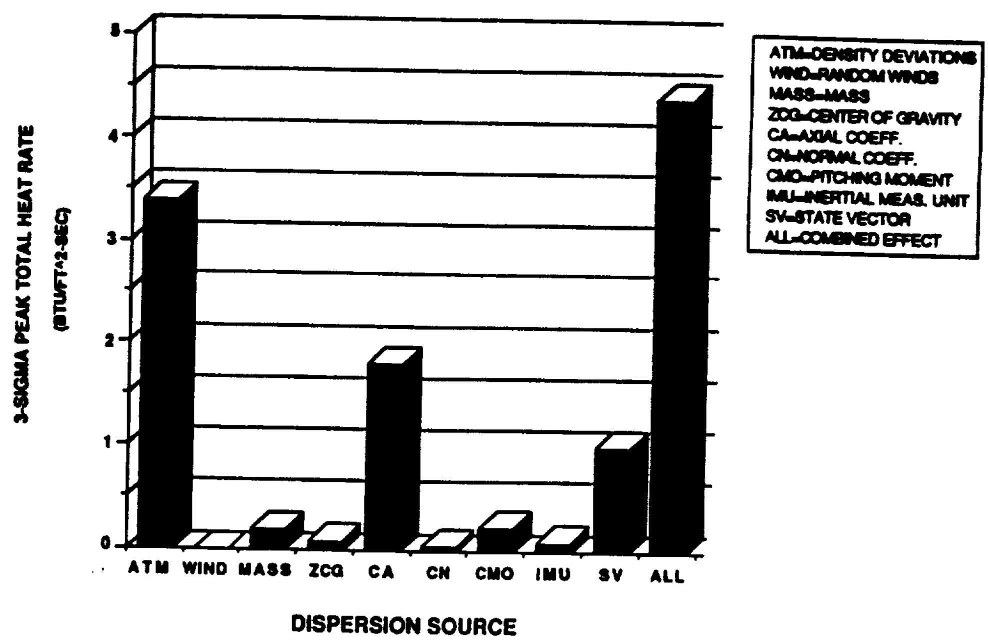

Figure 4.4-1 - Effects of Single Dispersion Sources on Peak Heat Rate

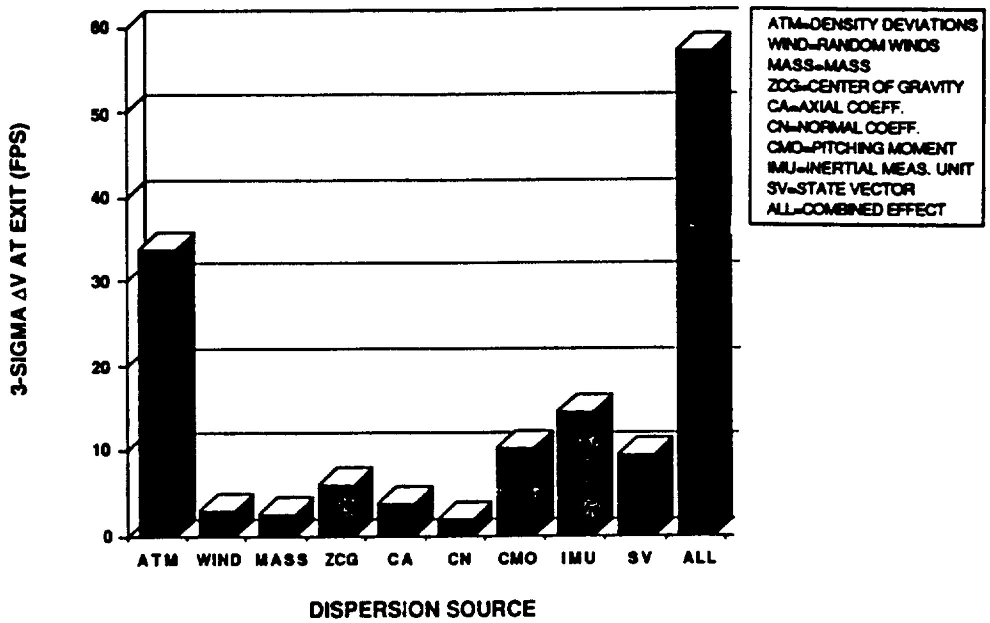

Figure 4.4-2 - Effects of Single Dispersion Sources on Post-Aeropass ΔV

The GRAM mean monthly atmosphere, as well as the plus/minus 3-sigma boundaries, is shown in Figure 4.4-3. The 0% horizontal line on the plot indicates no deviation from the '76 standard atmosphere. A density above the 0% line indicates a thicker atmosphere (at a certain altitude) than the '76 standard, while below the line indicates a thinner atmosphere than the '76 standard. It is clear that the GRAM mean and the '76 standard atmosphere profiles are not significantly different over the altitudes that the AFE vehicle will traverse (236kft to 400kft).

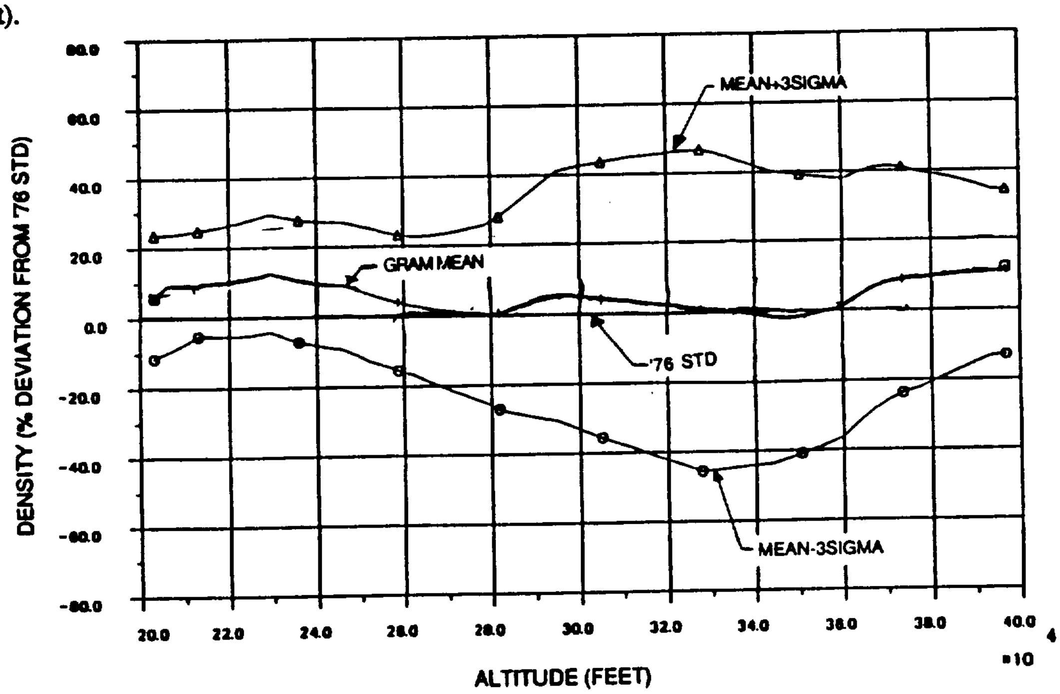

Figure 4.4-3 - GRAM Mean Atmosphere & +/- 3sigma Boundaries

In the AMAP montecarlo simulations however, the vehicle does not experience the mean atmosphere. Instead, the vehicle is subjected to GRAM-supplied deviations to the mean as a function of altitude. The deviations model density shears as well as overall thick and thin atmospheres. A sample dispersed atmosphere profile is shown in Figure 4.4-4.

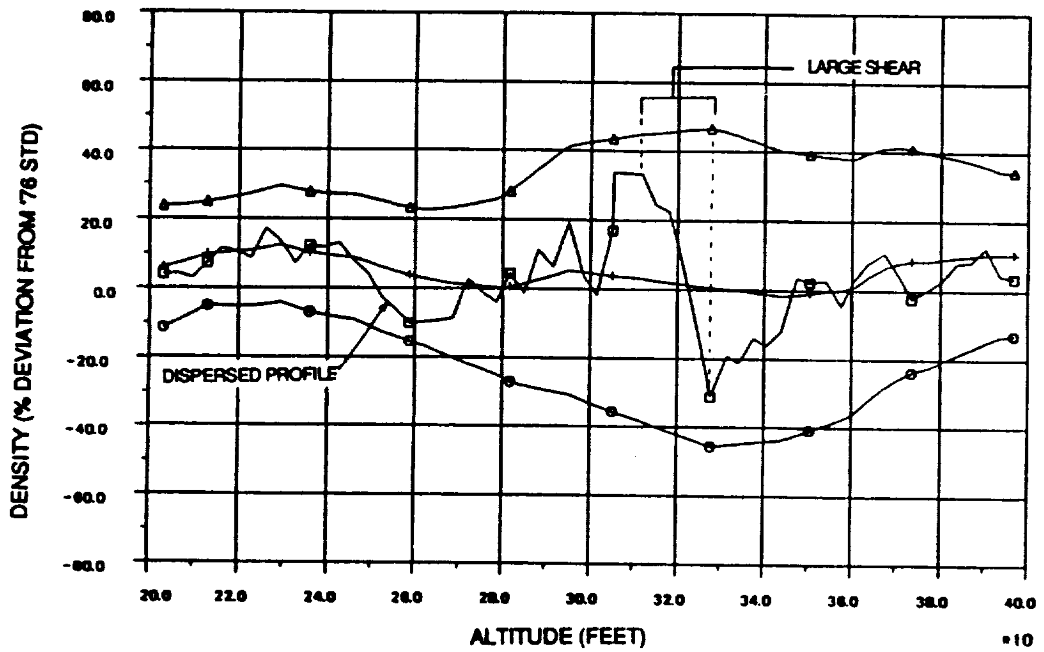

Figure 4.4-4 - Sample Dispersed Density Profile

The extremely jagged profile indicates the necessity of the guidance to react to density dispersions. It is important to realize that guidance has no way of predicting the atmospheric conditions it will encounter. In other words, the atmosphere is an "unknown" dispersion. Attempts are made during the flight to estimate the actual density (derived from navigation-supplied parameters such as drag acceleration and relative velocity), but the estimated density can be inaccurate. In addition, although knowing the current density is beneficial, it is not nearly as advantageous as knowing the upcoming density. In other words, guidance would like to prepare for a density shear or a completely thick or thin atmosphere prior to encountering it. Since guidance has no such knowledge, the effects of the corrections it does command (i.e. changes in bank angle) lag behind the actual density changes.

Currently, the guidance always predicts that the upcoming atmosphere it encounters will be the '76 standard. Indeed, if the density shears are short-period and relatively symmetric about the 0% line (See Fig. 4.4-5), then guidance's '76 standard model of the atmosphere will approximate the average of the dispersed profile and satisfactory trajectory performance is likely.

On the other hand, if the shears are long-period or the overall atmosphere is generally thick or thin, guidance's model becomes inaccurate and poor performance often results. It is especially critical that the guidance model is accurate during the region emcompassing minimum altitude. In this region, the vehicle is transitioning from a negative altitude rate to a positive one. This means that a pseudo-constant altitude is being held for a relatively long period of time (See Figure 4.4-6). Also, this phase of constant altitude is the most critical region for control. Since the dispersed density is a function of altitude only, the vehicle may experience a thicker or thinner-than-expected density for a long period of time and in the critical portion of the trajectory. Of course, inaccurate modeling of the atmosphere by guidance during this time often results in poor performance. An example of an atmosphere posessing a large density deviation (from '76 standard) during minimum altitude is shown in Figure 4.4-7. During testing, it has consistently caused significant difficulties for the guidance routine.

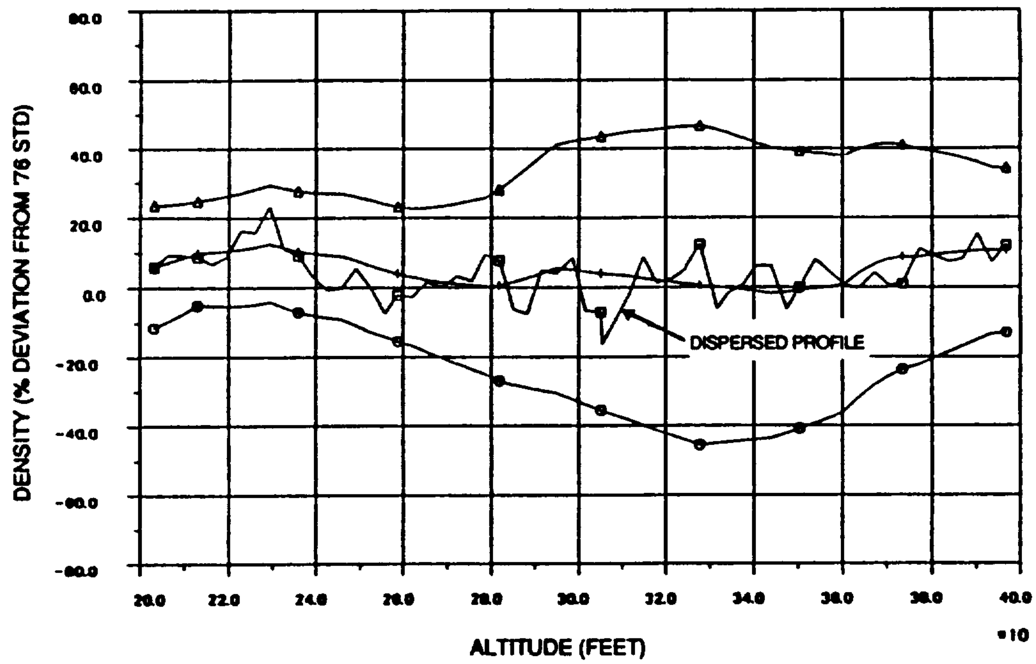

Figure 4.4-5 - "Mild-Case" Atmosphere Profile

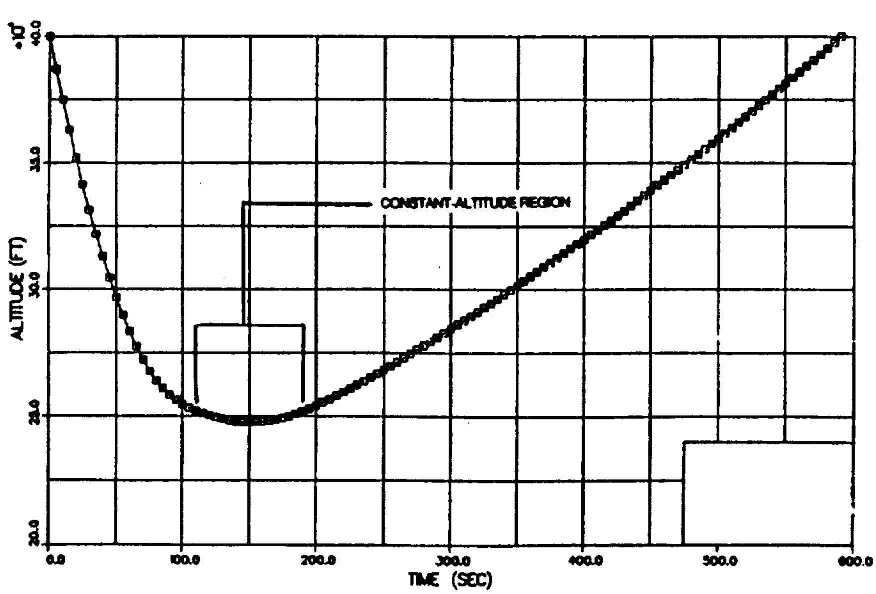

Figure 4.4-6 - Altitude Vs. Time for a Typical AFE Trajectory

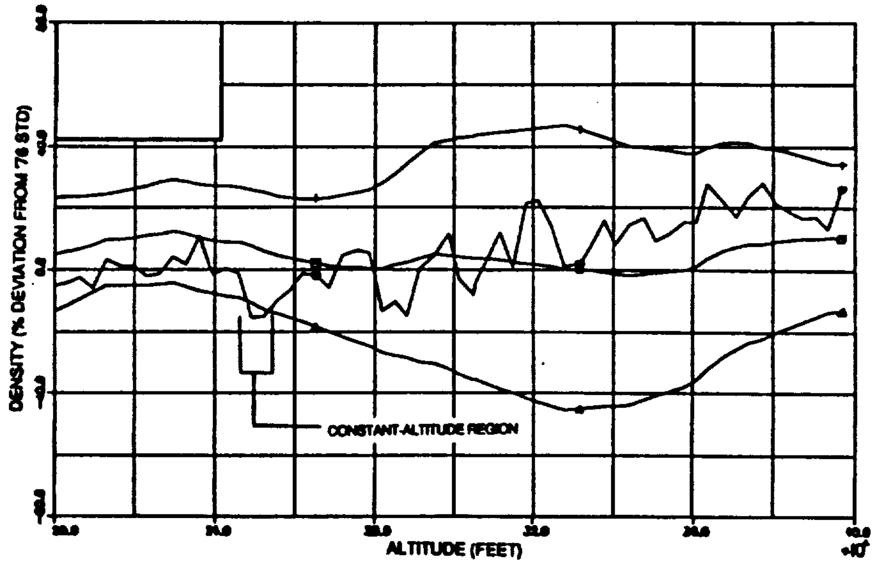

Figure 4.4-7 - "Bad-Case" Atmosphere Profile

5.0 CONCLUSIONS

Under the conditions of this study, the results indicate that mission constraints of a mean peak heat rate of 40.3 Btu/ft^2sec and a mean + 3sigma post-aeropass ΔV of less than 400 fps can be satisfied if the guidance gains and transfer orbit perigee are chosen properly. However, due to the sensitivity of the trajectory parameters to gain and perigee changes, the regions of constraint satisfaction are very small.

Attempting to further minimize the peak heating and attain a mean plus 3sigma peak total heat rate of 40.3 Btu/ft^2sec proved successful but only through large decreases in transfer orbit apogee. But, varying the transfer orbit apogee from GEO is inconsistent with mission objectives and is highly undesirable.

Investigation of the relative contribution of factors detrimental to control revealed the domination of the dispersed atmospheres in determining the regions of controllability (i.e. constraint satisfaction). Although decreasing the magnitude of other dispersion sources should improve performance, without advanced knowledge of the actual density profile or an accurate model of it, guidance has great difficulty compensating in real-time for atmospheric dispersions. These dispersions, especially during the constant-altitude phase, can be sufficiently deviated from guidance's atmosphere model that large errors result in the post-aeropass orbit. In general, a trade must be made between post-aeropass ΔV and the peak heat rate. To minimize the atmospheric dispersion effects on ΔV, the vehicle must "dig deeper" into the atmosphere. Doing this, however, results in an increased heat rate.

6.0 REFERENCES

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7.0 ACKNOWLEDGEMENTS

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