

Comparison of Return to Launch Site Options for a Reusable Booster Stage



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AE8900 MS Special Problems Report
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August 1, 2005

Table of Contents

Table of Contents	ii
List of Figures	iii
List of Tables	iv
Nomenclature	v
1.0 Introduction.....	1
2.0 Historical Background and Previous Work	2
2.1 Early Historical Look at Reusable Boosters	2
2.2 Previous RTLS Comparison Studies	4
2.3 Glideback Studies and Examples	4
2.4 Flyback Studies and Examples	5
2.5 Boostback Studies and Examples	6
3.0 Technical Approach.....	8
3.1 Branching Trajectory Problem.....	8
3.2 Contributing Analyses	9
3.2.1 Configuration	9
3.2.2 Aerodynamics	11
3.2.3 Rocket Propulsion.....	17
3.2.4 Airbreathing Propulsion.....	20
3.2.5 Trajectory Simulation	21
3.2.6 Weights and Sizing	23
3.3 Design Structure Matrix and MDO.....	25
4.0 Results.....	27
4.1 Optimal Staging Points	27
4.2 Trajectory plots	30
4.2.1 Glideback Trajectory	30
4.2.2 Flyback Trajectory	33
4.2.3 Boostback Trajectory	35
4.3 Mass Breakdown of Each RTLS Method	38
5.0 Discussion and Conclusions	40
6.0 Acknowledgements.....	43
References.....	44
Appendix A.....	A-1

List of Figures

Figure 1. Reusable Booster with Inflatable Drag-Cone.....	3
Figure 2. Reusable Booster with Paraglider.	3
Figure 3. Liquid Flyback Booster Configurations for the Space Shuttle.....	5
Figure 4. Trajectory of Tossback RTLS method.	6
Figure 5. Ascent and Boostback Trajectory for Kistler K-1.....	7
Figure 6. Notional Branching Trajectory.....	8
Figure 7. Notional 3-View of Baseline Configuration.....	10
Figure 8. Isometric View of Total Configuration in APAS.....	11
Figure 9. Isometric View of Booster in APAS.	12
Figure 10. Isometric View of Upper Stage in APAS.....	12
Figure 11. Aerodynamics for Total Configuration.	13
Figure 12. Aerodynamics for Booster without Base Drag.....	14
Figure 13. Aerodynamics for Booster with Base Drag.....	15
Figure 14. Aerodynamics for Upper Stage.	16
Figure 15. Vacuum Thrust to Weight for Booster Engine.....	18
Figure 16. Exit Area for Booster Engine.	18
Figure 17. Vacuum Thrust to Weight for Upper Stage Engine.	19
Figure 18. Exit Area for Upper Stage Engine.....	19
Figure 19. Airbreathing Isp vs. Cruise Mach for Engine Parameters in Table III.	21
Figure 20. TPS Area Density as a Function of Maximum Re-entry Mach Number.	25
Figure 21. DSM Used for Modeling of the RTLS Methods in this Study.....	26
Figure 22. Total Gross Mass of Booster and Upper Stage at Various Staging Points.....	27
Figure 23. Total Dry Mass of Booster and Upper Stage at Various Staging Points.....	28
Figure 24. Final Altitude Over Launch Site for Glideback at Various Staging Points....	28
Figure 25. Comparison of RTLS Methods When Optimized for Lowest Gross Mass....	29
Figure 26. Comparison of RTLS Methods When Optimized for Lowest Dry Mass.....	30
Figure 27. Altitude vs. Downrange for Glideback Trajectory.....	31
Figure 28. Ground Track for Glideback Trajectory.....	31
Figure 29. Dynamic Pressure, Normal Force, and Overall Acceleration vs. Time for Glideback Trajectory.	32
Figure 30. Mach Number and Aerodynamic Angles for Glideback Trajectory.	32
Figure 31. Altitude vs. Downrange for Flyback Trajectory.....	33
Figure 32. Ground Track for Flyback Trajectory.	34
Figure 33. Dynamic Pressure and Mach Number vs. Time for Flyback Trajectory.....	34
Figure 34. Normal Acceleration and Aerodynamic Angles for Flyback Trajectory.	35
Figure 35. Altitude vs. Downrange for Boostback Trajectory.....	36
Figure 36. Ground Track for Boostback Trajectory.	36
Figure 37. Dynamic Pressure and Normal Force vs. Time for Boostback Trajectory.....	37
Figure 38. Mach Number and Aerodynamic Angles for Boostback Trajectory.....	37

List of Tables

Table I. Baseline Configuration Parameters for RTLS Booster.	10
Table II. Rocket Engine Parameter Held Constant in this Study.....	17
Table III. Ranges of Inputs for Turbofan DOE.....	20
Table IV. Ranges for DOE Run in Flyback Deck in POST.....	23
Table V. Inputs for SESAW.	24
Table VI. Parameters that Result from Optimal Staging Points.	29
Table VII. Mass Breakdown for Each RTLS Booster.	38
Table VIII. Mass Breakdown for Upper Stage for Each RTLS Method.....	39

Nomenclature

APAS	Aerodynamic Preliminary Analysis Software
BPR	Bypass Ratio
CAD	Computer-Aided Drawing
DOE	Design of Experiments
DOF	Degree of Freedom
DSM	Design Structure Matrix
ΔV	Change in Velocity
ELV	Expendable Launch Vehicle
FPA	Flight Path Angle
FPI	Fixed Point Iteration
GUI	Graphical User Interface
HABP	Hypersonic Arbitrary Body Program
ISP	Specific Impulse
KSC	Kennedy Space Center
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MDO	Multi-Disciplinary Design Optimization
MER	Mass Estimating Relationship
MR	Mass Ratio
OBD	Optimizer Based Decomposition
POST	Program to Optimize Simulated Trajectories
RLV	Reusable Launch Vehicle
RP	Rocket Grade Kerosene
RSE	Response Surface Equation
RTLS	Return to Launch Site
SESAW	Simple Electrical Systems and Avionics Wizard
SSTO	Single Stage To Orbit
TSTO	Two Stage To Orbit
UDP	Unified Distributed Panel
USAF	United States Air Force

1.0 Introduction

Ever since the United States became involved in developing launch vehicles, there has been a desire to develop a vehicle that could place a payload in orbit, return to its launch site, and be reused quickly similar to a conventional airplane. The major deterrent to developing a RLV has been the large upfront development cost without the launch frequency necessary to justify that cost. The only partially reusable vehicle developed is the Space Shuttle which has shown to have large operation expenses and a long turn around time. Its solid rocket boosters must be extracted from the ocean and undergo long maintenance procedures to clean out the salt water.

All unmanned launches around the world currently make use of completely expendable launch vehicles which can run up to \$500 million a launch. Along with the current need in the USAF for responsive space lift and for long range strike and the growing space tourist market, there is now a growing desire to develop a partial or totally reusable TSTO launch vehicle to replace the current ELV's and the Shuttle.

A current trend in RLV development is to focus on reusing the booster while leaving the upper stage expendable. A vehicle like this can serve as a stepping stone to a totally reusable system by developing operational techniques, prove technologies, better determine economic benefits, and build public support for reusable launch architectures.

One of the main design decisions for a reusable booster is to determine the method it will use for RTLS. If the booster is unpowered after staging, then there is a limit as to how high the staging can occur so the booster will have enough margin to return and land safely. If the booster uses airbreathing engines, hardware for those engines needs to be added along with another fuel tank thereby increasing the complexity, mass, and cost of the booster. The airbreathing engines, however, will allow for a higher staging point, since it can return after turning around at a point farther downrange. Another possibility for a RTLS booster is to use the ascent rocket engines to provide the necessary acceleration for RTLS.

This study will compare the RTLS methods of boostback, flyback with an airbreathing engine (referred to as "flyback" in this study), and glideback and compare them based on the optimal staging point for both gross mass and dry mass. In order to find this, a multi-disciplinary model of the vehicles incorporating many different design tools was made to be able to find an optimal sized vehicle based on the staging point while keeping most other parameters constant.

2.0 Historical Background and Previous Work

2.1 Early Historical Look at Reusable Boosters

The desire to build a RLV has been around since the days of the space race to the moon. As with today, they were concerned with the cost of space access. It was believed that economics would limit space exploration and not technology¹. Many early studies focused on reusing the booster as the first method to lower the direct operating costs of placing a payload in orbit.

A study by Boeing² initially looked at the options of a RTLS booster and a booster that flies ballistically into the ocean and is then picked up by a boat. The biggest difference in development cost was the lifting surfaces and the associated modifications to a standard expendable booster, which would increase with staging altitude and Mach number. Also, adding wings would require flight testing for a manned system. Recovering the booster in the ocean, however, would need small modifications adding aerodynamic stabilization and deceleration devices such as parachutes. Overall, a higher research and development cost of almost 30 to 1 to build a RTLS booster gave a much more favorable outlook towards water recovery. The manufacturing cost to build each RTLS booster would cost about 3.5 times that of the ocean recovery.

The advantages of the RTLS booster show up when looking at the recurring costs. It was estimated that an individual RTLS booster could be used almost 5-6 times more than the ocean recovery.

In the early 1960's, the Douglas Aircraft Co. proposed using an inflatable drag-cone, shown in Figure 1, system to land the booster in the ocean that could be towed back to land¹. The cone would be inflated by the residual hydrogen and helium pressurant. The gases would provide air buoyancy at an altitude of about 2000 ft to help reduce impact velocity. Additionally, the cone would protect the booster from salt water, allowing for reduced maintenance concerns.

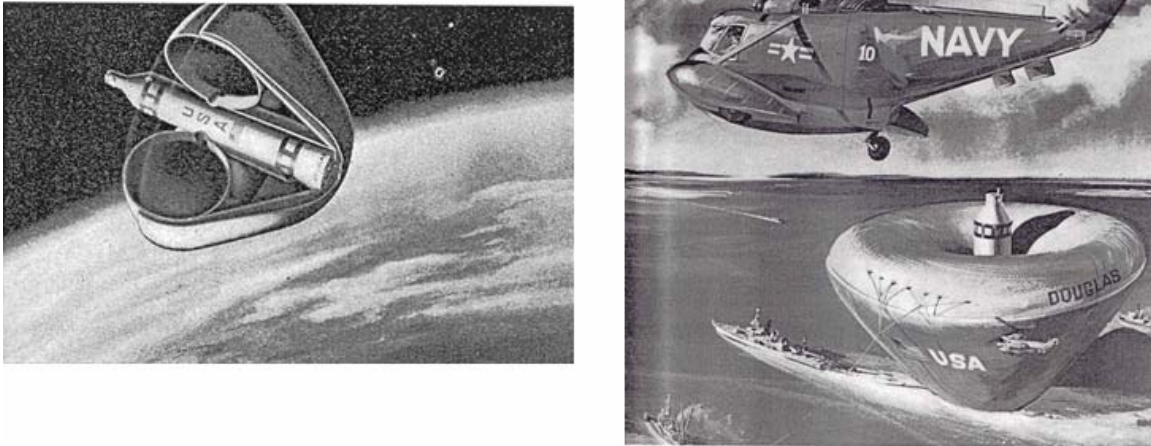


Figure 1. Reusable Booster with Inflatable Drag-Cone¹.

A method for gliding back was proposed at NASA Langley that would use a paraglider, shown in Figure 2, to glide back to the launch site. The paraglider would control the re-entry forces, provide necessary lateral turns, and land the booster at a very slow descent rate. The cost of implementing this type of system was expected to be very high.

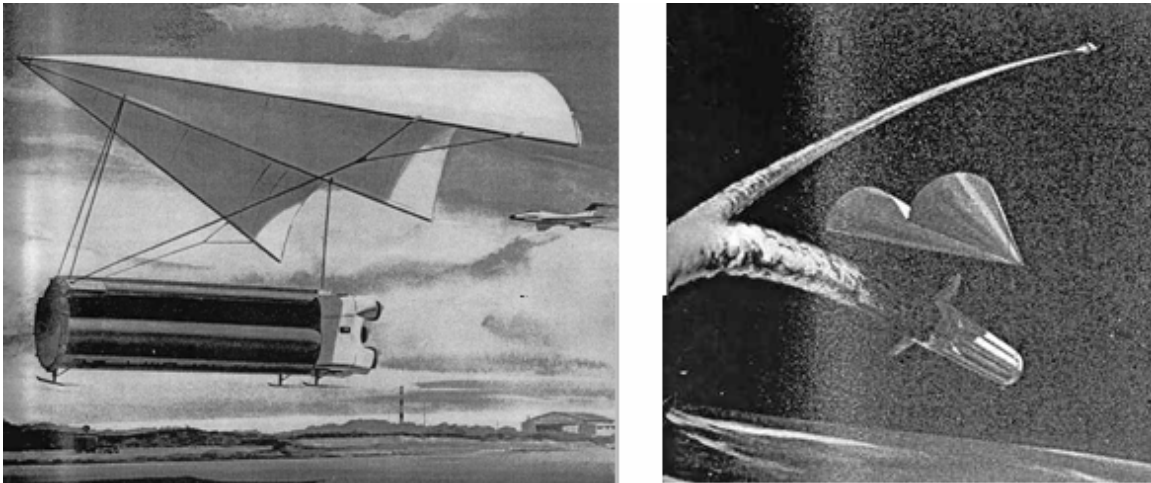


Figure 2. Reusable Booster with Paraglider¹.

Another method to allow for easier booster recovery from the ocean was to increase the amount of vertical rise of the booster before beginning to pitch over for orbit insertion³. This idea was based on the belief that it is advantageous to reduce the distance from the launch site to the point of atmospheric entry. The study showed that for a 50% increase in vertical rise time of the booster allowed for a 15% reduction in impact distance. The main motivation of this study of reducing the downrange distance of atmospheric entry is one motivation for the idea behind the boostback RTLS method.

2.2 Previous RTLS Comparison Studies

There are no widely known publicly published comparisons in which the boostback RTLS method is compared to other the other methods. The current comparison studies only focus on glideback vs. flyback.

One study conducted at Adelaide University in Australia and the University of Stuttgart looked at glideback and flyback launching out of the Woomera launch site in Australia⁴. In this study both stages were assumed to be reusable with both stages using LOX/RP propellants. Along with analyzing the RTLS methods, the study also noted that it is not optimal to perform high g-loading turns as the extra wing weight would not make up for additional payload. This study allowed for 3.6 g turns during the RTLS branch. The optimal staging point for glideback was at a velocity of about 3937 ft/sec at and altitude of about 16.2 nmi, while flyback staged at about 10,498 ft/sec at an altitude of about 34.5 nmi.

This study did not fix a payload but fixed a gross weight at liftoff. So mass differences between the two RTLS methods must focus on the payload. The flyback vehicle was shown to lift almost 50% more payload into LEO than glideback. Although adding extra engines for flyback, this study recommends using that method as it can lift significantly more payload to orbit.

Another comparison study conducted at Tokyo University compared flyback vs. glideback and also looked at the difference between different fuels, methane, LH2, RP, and densified LH2⁵. This study shows that in order for glideback to be able to occur, the mass ratio between the booster and the orbiter must be small. This study showed for the LOX/RP flyback booster, the dry weight is 17% less than LOX/LH2 but the gross mass is 48% higher. The LOX/Methane booster was heavier in both gross and dry mass than the other propellants. The only glideback boosters looked at in this study were LOX/LH2 showing that glideback had 92% more gross mass and 63% more dry mass, over flyback with LOX/LH2.

2.3 Glideback Studies and Examples

Although studies have shown that the powered flyback RTLS method can be advantageous when considering the gross and dry weight, glideback can make the booster a simpler vehicle without needing to add in extra hardware for the turbine engine and extra fuel tank. Even going back to the early days of spaceflight as shown above, there were many ideas to implement the simplicity of gliding back to the launch site after releasing an upper stage(s).

One example of fully reusable TSTO concept conceived at NASA Langley was the Future Space Transportation System to replace the Space Shuttle^{6,7,8}. This system was design to carry 150,000 lbs to LEO. The booster uses LOX/RP propellants and the upper stage uses LOX/LH2 propellants. Since the both stages burn simultaneously, the booster carries

extra LH2 in a separate tank for the upper stage. The booster would glideback after staging at Mach 3. The overall payload fraction estimated for this design is about 3%. The total dry weight is estimated to be about 456,000 pounds which is just over 3 times the weight of the payload. The wings were designed for a 2.5g normal acceleration limit. Due to the low staging Mach number, no TPS is required.

Another more recent study at NASA Langley looked at developing a small launch vehicle to go along with the current desire for responsive space lift. The vehicle proposed is has three-stages with a reusable booster and expendable upper stages capable of placing a 330 lb payload in polar orbit launched out of Vandenberg. The staging point was set at Mach 3. The glideback flight was limited to 2.5 g's of normal force and a maximum dynamic pressure of 1000 psf. The glideback trajectory was analyzed in POST with the objective function to maximize altitude over the launch site and to had be modified to avoid overflight of the coast.. The booster takes 356 seconds for RTLS. The estimated payload fraction is about 2.8% and the dry is about 100 times larger than the payload weight.

2.4 Flyback Studies and Examples

A major effort since the space shuttle began operating looked at replacing the solid rocket boosters with liquid flyback boosters. The configurations of dual boosters and catamaran booster are shown in Figure 3. The boosters would stage at about Mach 5.2 and an altitude of about 163,000 ft⁹. The boosters would coast to an apogee of about 270,000 ft, re-enter, perform a transonic turn and cruise back to KSC at about 18,500 ft and Mach 0.48. It was estimated that about 20,000 lb of fuel would be needed for the turbine engine¹⁰.

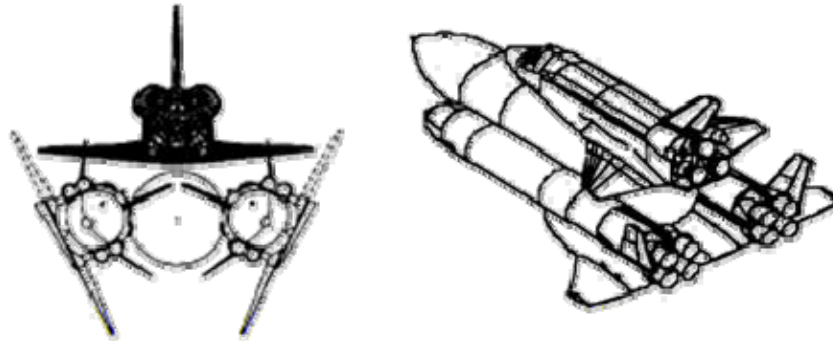


Figure 3. Liquid Flyback Booster Configurations for the Space Shuttle⁹.

The Europeans also looked at using a flyback booster for their Ariane launch vehicle. One study conducted by DLR in Germany¹¹ looked at different configurations including one booster, a double fuselage catamaran, two small boosters attached to the single upper stage, and a single booster inline with the upper stage. The analysis of the single booster using LOX/RP showed that four turbofans were needed for flyback. This study allowed for a maximum normal acceleration of 3.5 g's. The staging Mach number for the various

configurations range from 5.38 to 6.05. Each booster configuration reaches a peak altitude of about 328,000 ft. The maximum re-entry Mach number is about the same as the staging point.

2.5 Boostback Studies and Examples

In the mid 80's McDonnell Douglas proposed a "tossback" booster in which the booster is ballistically thrown back to the launch site¹². After staging and a 20 second reorientation period, the booster pitches back and executes a short rocket engine burn. Figure 4 shows the trajectory for this type of maneuver. This plot shows how ascent branches up until the staging point is elevated when compared to a normal optimized ascent trajectory with no tossback. This study attempted to maximize payload fraction and showed that with tossback a payload fraction of about 5% can be achieved with a staging point around 10,000 ft/sec ΔV at an altitude of about 237,000 ft. The recovery of the booster was proposed to happen in a fresh water pond after a brief terminal descent burn from the booster engines. There are no wings for this method of RTLS giving the booster a max L/D of about 0.25. This will still allow for 5-10 nmi crossrange control.

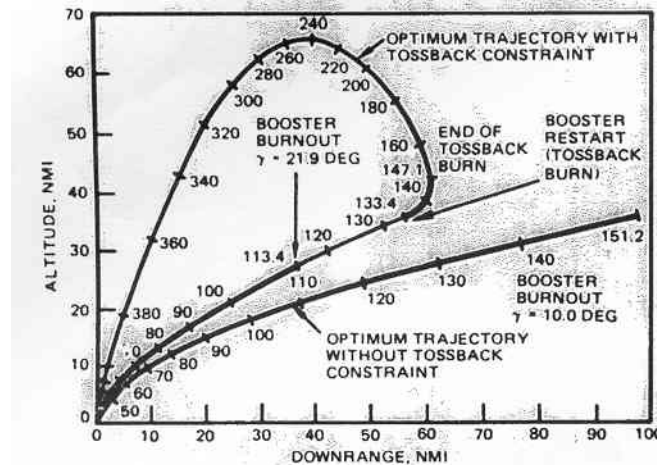


Fig. 2 Tossback constraint elevates trajectory

Figure 4. Trajectory of Tossback RTLS method¹².

A example of boostback in which hardware has actually been built but not yet flown is the Kistler K-1^{13,14,15,16}. This is a fully reusable launch vehicle in which the booster executes a burn similar to the tossback method discussed above, shown in Figure 5. This staging occurs at about Mach 4.4, around 135,000 – 140,000 ft., and 135 seconds into the flight. For the boostback burn, the center engine (out of 3) burns for 35 seconds. The booster uses parachutes to slowdown after re-entry and air bags for landing. The landing takes place at about 12 minutes after liftoff.

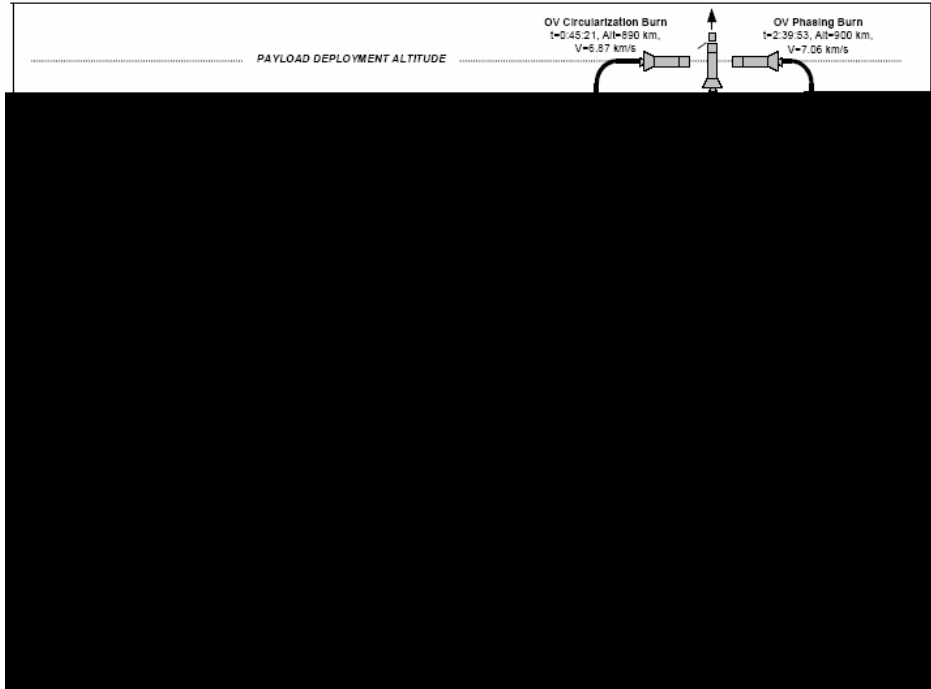


Figure 5. Ascent and Boostback Trajectory for Kistler K-1¹³.

3.0 Technical Approach

The main focus of this study is to compare the vehicle sizes required to complete a certain mission utilizing three different RTLS methods. The vehicles will be compared by the total amount of gross weight and dry weight. The mission requirements for this comparison are to launch a 15,000 lb payload to a 100 nmi circular orbit and a 28.5° inclination. The launch site is Kennedy Space Center (28.5°N latitude and 80.5°W longitude). To ensure enough margin to land back at the launch site, the booster must return to KSC with at least an altitude 15,000 ft. Both stages use LOX/RP-1 for propellant.

3.1 Branching Trajectory Problem

The use of a reusable booster poses an multi-disciplinary problem known as a branching trajectory¹⁷. For a TSTO vehicle, the overall flight path of both stages is broken up into three different branches. The ascent branch includes both stages mated together starting at the launch site and flying to a certain staging point. This staging point is selected based on a certain amount of ideal ΔV from the conditions at the launch site. The upper stage then flies along the orbital branch to orbit insertion. Figure 6 shows a notional branching trajectory. In this study, both the ascent and orbital branch were modeled in the same trajectory input file. The booster executes necessary maneuvers for the RTLS branch from the conditions at staging. A seven parameter state vector is used to identify the staging conditions: latitude, longitude, velocity, flight path angle, altitude, azimuth direction of the velocity vector, and the after staging weight of the booster.

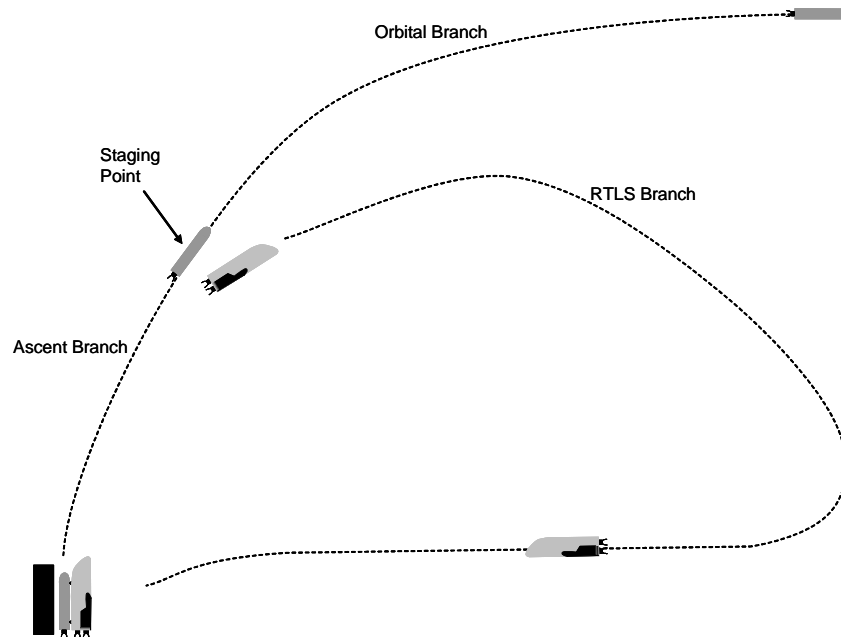


Figure 6. Notional Branching Trajectory.

The RTLS branch brings in a modeling problem of the booster when it requires additional propellant. The booster and upper stage without RTLS can easily be sized so the proper payload can be inserted into a desired orbit. Adding in extra propellant for the booster for RTLS, requires the booster to grow in size, thereby increasing the amount propellant needed to reach staging, and the problem becomes cyclical. Feedback is thus required in the vehicle model to ensure proper sizing. In order to model the TSTO vehicle with a reusable booster, MDO methods are needed to handle the feedback aspect of the problem.

3.2 Contributing Analyses

Modeling the TSTO vehicle with and RTLS booster is broken down into many different design disciplines that rely on information from other disciplines and assumptions to be made. This section describes each of the different disciplines or contributing analyses, what assumptions are made and what design tool is used.

3.2.1 Configuration

The shape of the booster is based off the shape of the SSTO RLV using the ACRE-92 designed for the NASA HRST study and further modeled by Spaceworks Engineering, Inc.¹⁸. The baseline booster fuselage for this study is cylindrical with a drooped nose section and a blunt end. The propellant tanks make up most of the fuselage with the forward dome of the fuel tank located inside the nose section. There is a 2 foot spacing between the propellant tanks and a 5 foot section in the rear. For the airbreathing RTLS booster, the rear section is assumed to be 10 feet to allow for a flyback fuel tank and extra hardware for the turbine engines, thereby lowering the packaging efficiency. The wing is a delta shape with vertical fins located at the wing tips. The rear of the booster has a body flap underneath the engines.

The upper stage is cylindrical body mounted on top of the booster. The diameter of the upper stage is set to 6 ft. The propellant tanks have domes with a 0.707 height to radius ratio and a 2 foot intertank adapter. The thrust structure is located on the rear dome of the oxidizer tank. The fairing has a 10 foot conical section on top of a cylindrical housing for the payload. A 2-D 3-View of the booster is shown in Figure 7. The baseline configuration parameters are listed in Table I.

Table I. Baseline Configuration Parameters for RTLS Booster.

Fuselage Length	165 ft
Total Fuselage Volume	94,676 ft ³
Packaging Efficiency (Glideback and Boostback)	79.55 %
Packaging Efficiency (Flyback)	74.55 %
Structural Span	110 ft
Wing Reference Area	6,000 ft ²
Maximum Wing Root Thickness	9 ft
Total Verticals Planform Area	425 ft ²
Body Flap Length	10 ft
Primary Structure Area	2758 ft ²
Secondary Structure Area	615.8 ft ²
Body Flap Planform Area	280 ft ²
TPS Planform Area	9,512.7 ft ²
TPS Total Wetted Area	23,579 ft ²

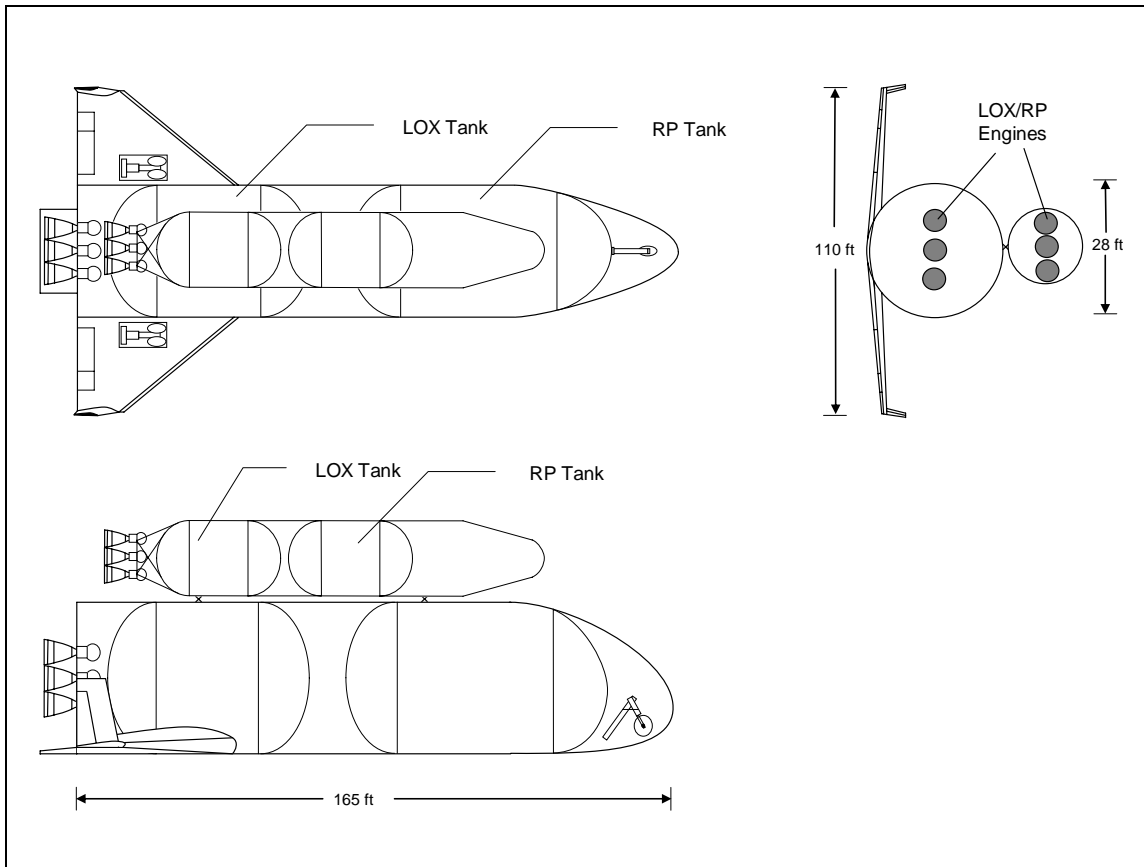


Figure 7. Notional 3-View of Baseline Configuration.

3.2.2 Aerodynamics

The aerodynamic model for the booster was calculated using the APAS code¹⁹. The vehicle inputted into the code had dimensions based on a 0.5 scale factor of the baseline configuration dimensions for the booster shown above. The upper stage was inputted with a 6 ft radius and 40 ft length. The vehicle shape was analyzed in UDP for low speed and transonic flight (Mach 0 – Mach 2) and HABP for the hypersonic flight (Mach 3+).

Screen shots of the booster with the upper stage attached, booster alone, and upper stage alone are shown in Figure 8 through Figure 10. The total configuration and upper stage alone were analyzed without base drag. Since the booster will at times be gliding, it was analyzed with and without base drag. Figure 11 through Figure 14 shows the drag polars and lift to drag trends for the aerodynamic model.

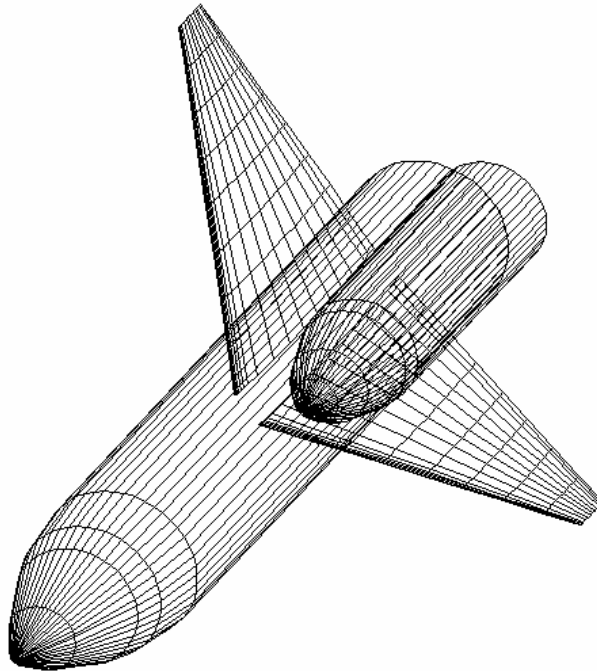


Figure 8. Isometric View of Total Configuration in APAS.

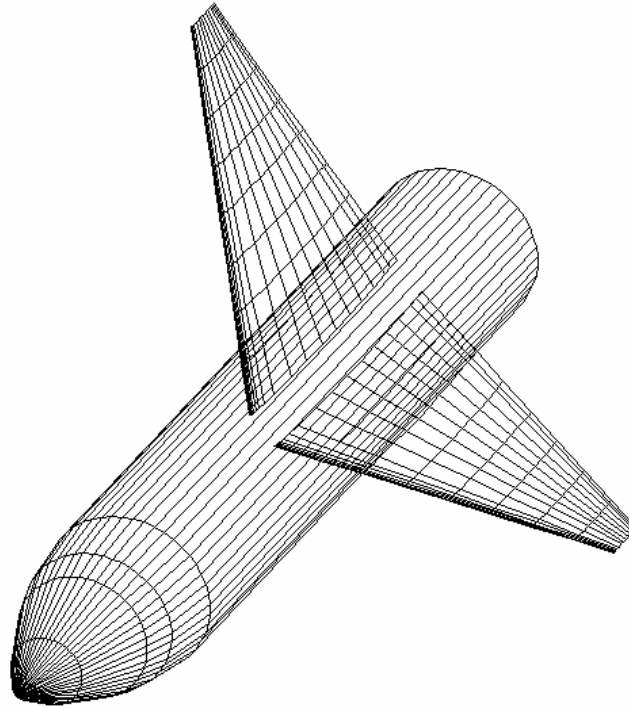


Figure 9. Isometric View of Booster in APAS.

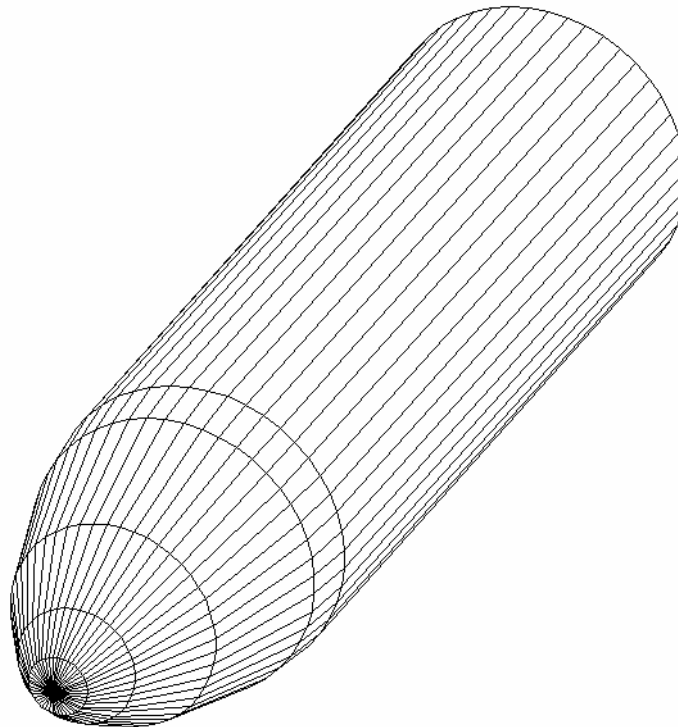


Figure 10. Isometric View of Upper Stage in APAS.

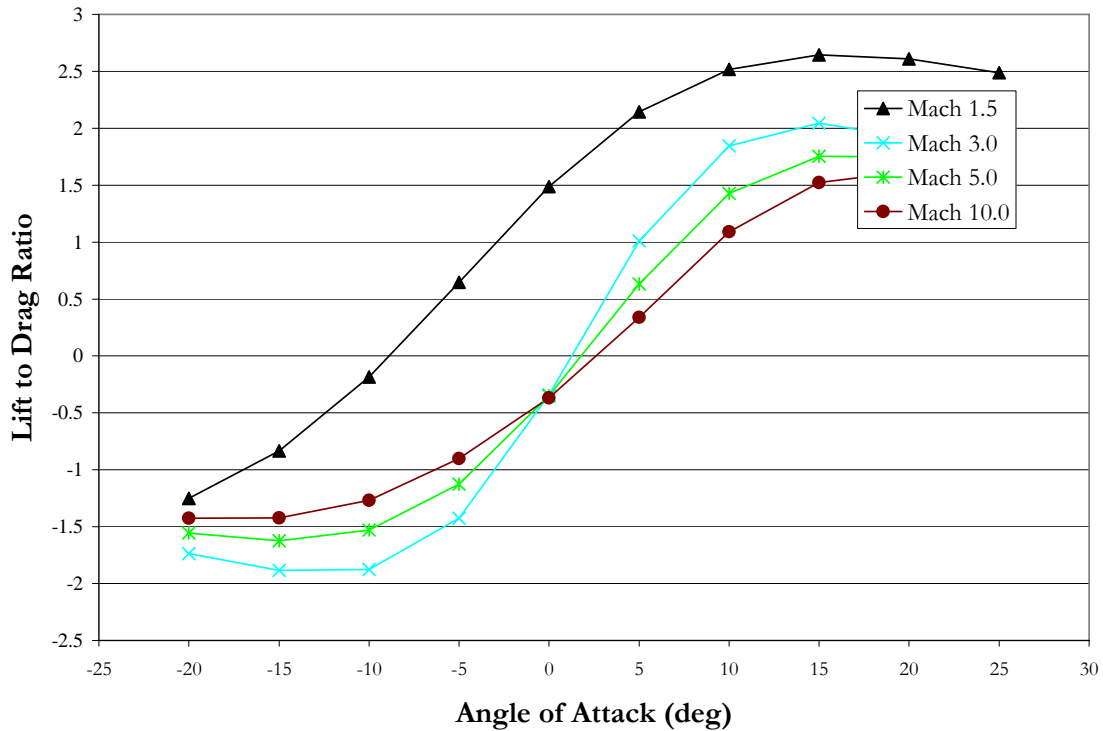
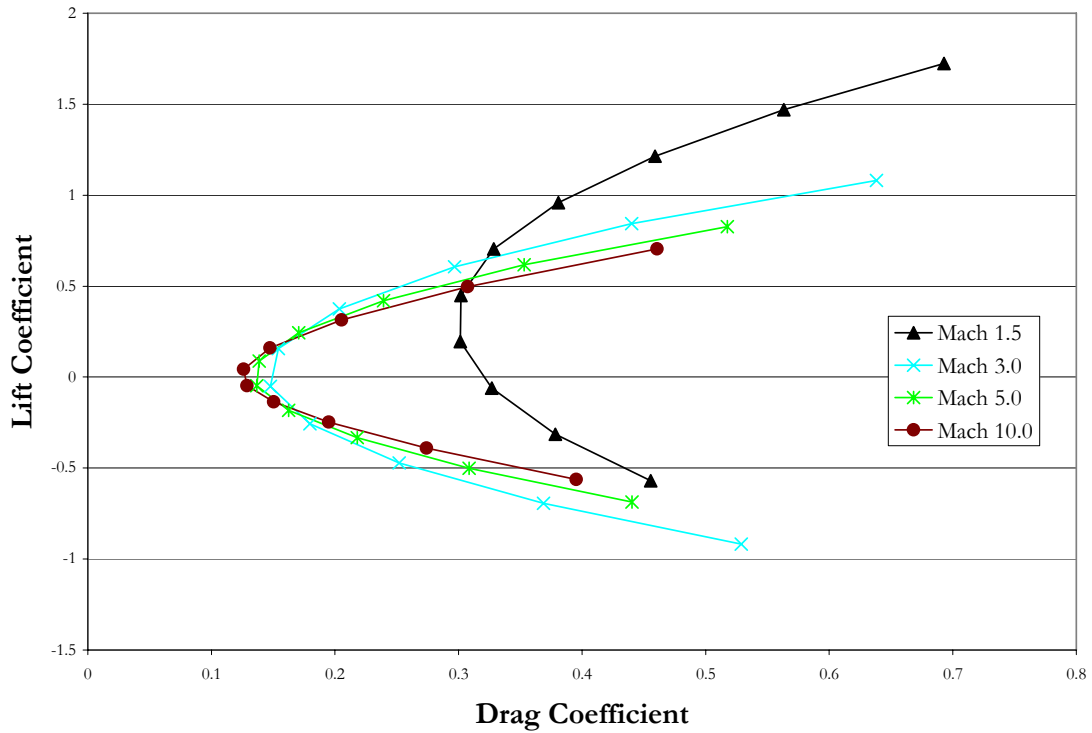


Figure 11. Aerodynamics for Total Configuration.

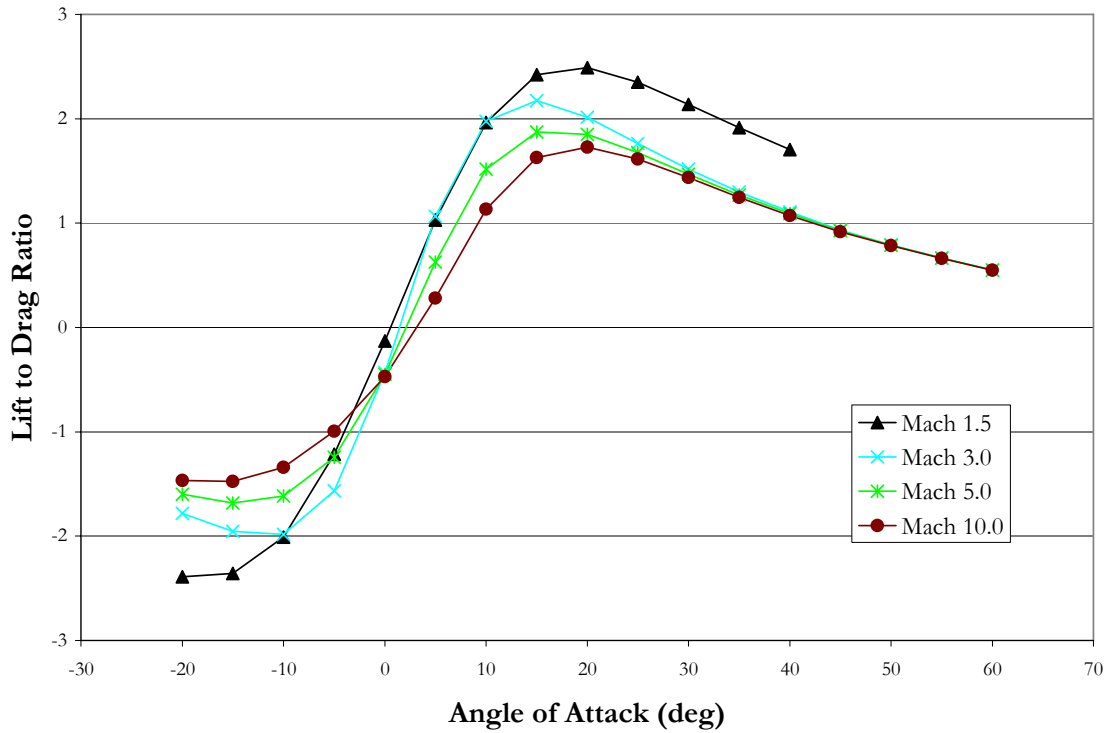
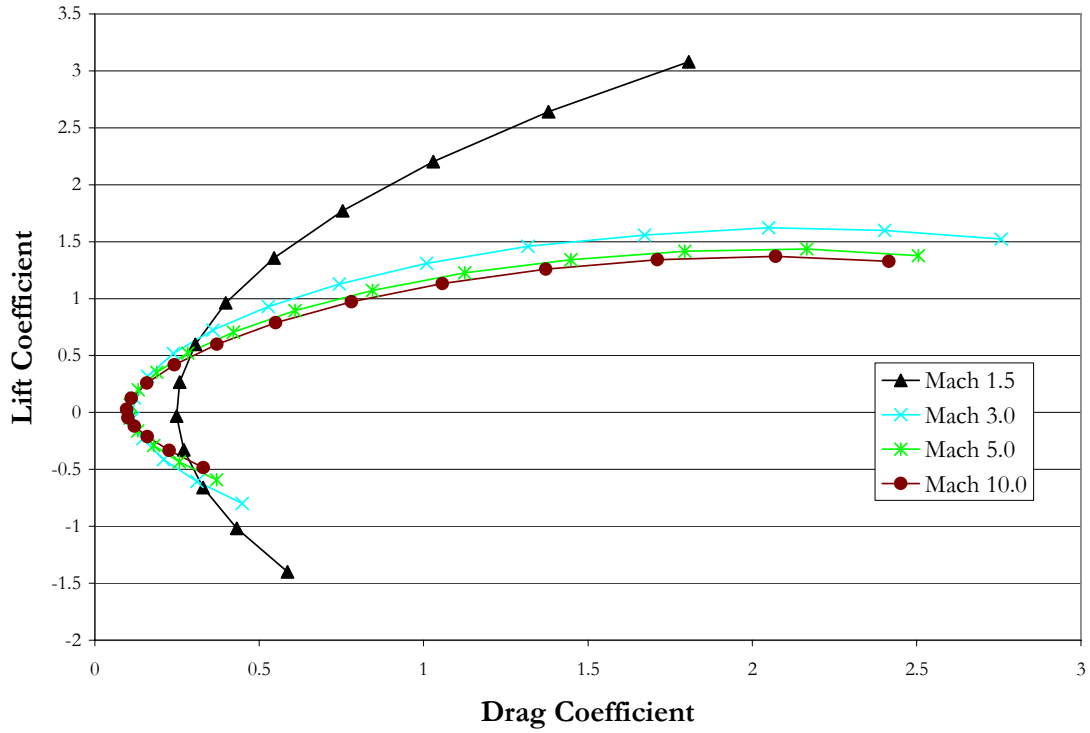


Figure 12. Aerodynamics for Booster without Base Drag.

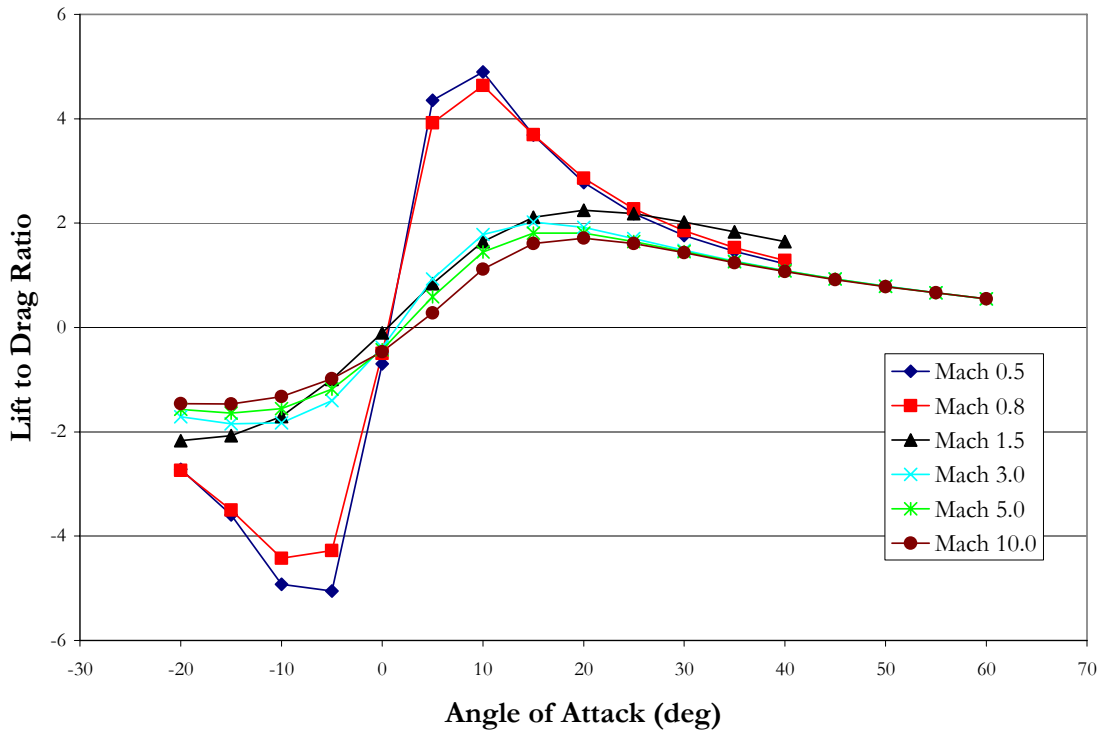
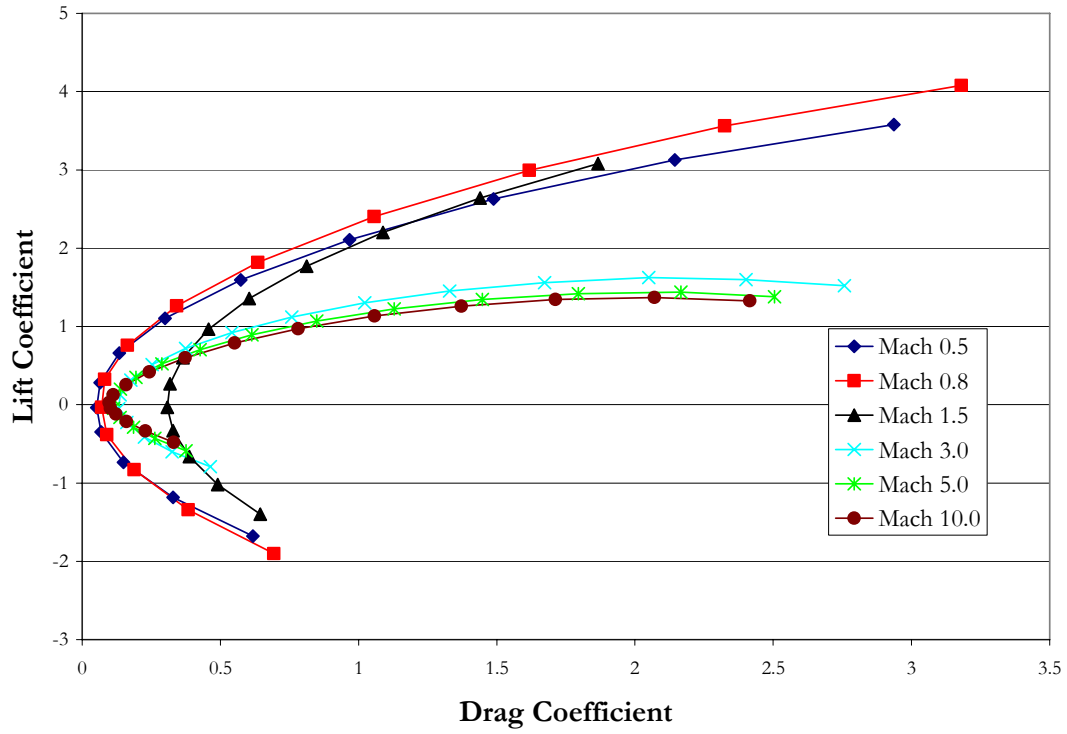
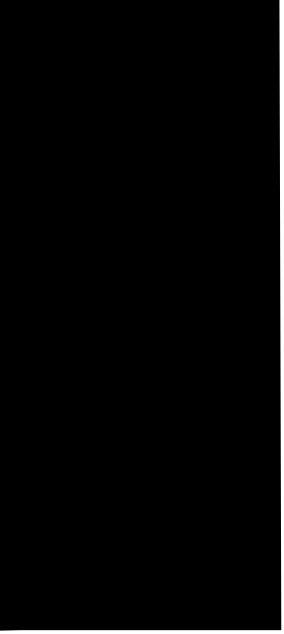


Figure 13. Aerodynamics for Booster with Base Drag.



3.2.3 Rocket Propulsion

Two different rubberized engine types were assumed for the booster and upper stage. Both engines types are single chamber, LOX/RP, gas-generator cycle, with a series flow sequence. The basic engine parameters, listed in

Table II, were assumed to be constant for both stages. Each engine has Engine Health Monitoring, double controller redundancy, gimbals, and no engine nacelle.

Table II. Rocket Engine Parameter Held Constant in this Study.

Oxidizer to Fuel Ratio	2.7
Booster Engine Expansion Ratio	30
Upper Stage Engine Expansion Ratio	60
Chamber Pressure	2500 psi
Gas Generator Oxidizer to Fuel Ratio	1.5

The only parameter that was allowed to vary for the engines in this study was the amount of vacuum thrust per engine. The vacuum thrust to weight (T_{vac}/W_e), exit area, and vacuum Isp were calculated using REDTOP-2 version 1.5²⁰. The 1-D curve fits used for T_{vac}/W_e and exit area in the overall vehicle model are shown in Figure 15 through Figure 18. The Vacuum Isp output did not show any trend to fit a curve so the average outputted Isp for engine type was used, 327.6 sec for the booster, and 338.5 sec for the upper stage. The number of engines can be selected so the engines are appropriately sized.

The amount thrust needed for the engines was taken from a given sea-level thrust to weight at liftoff of 1.2 and vacuum thrust to weight at staging of 1.0. The reason that the thrust to weight at staging was set to 1.0 was because for the Glideback RTLS option, the upper stage required more thrust at staging to reach orbit because of the low staging point.

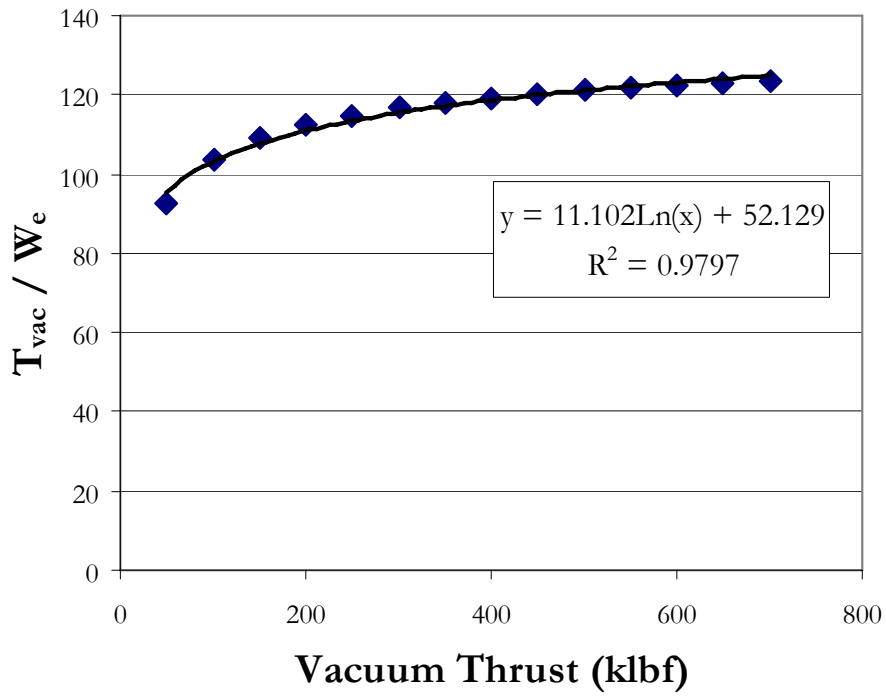


Figure 15. Vacuum Thrust to Weight for Booster Engine.

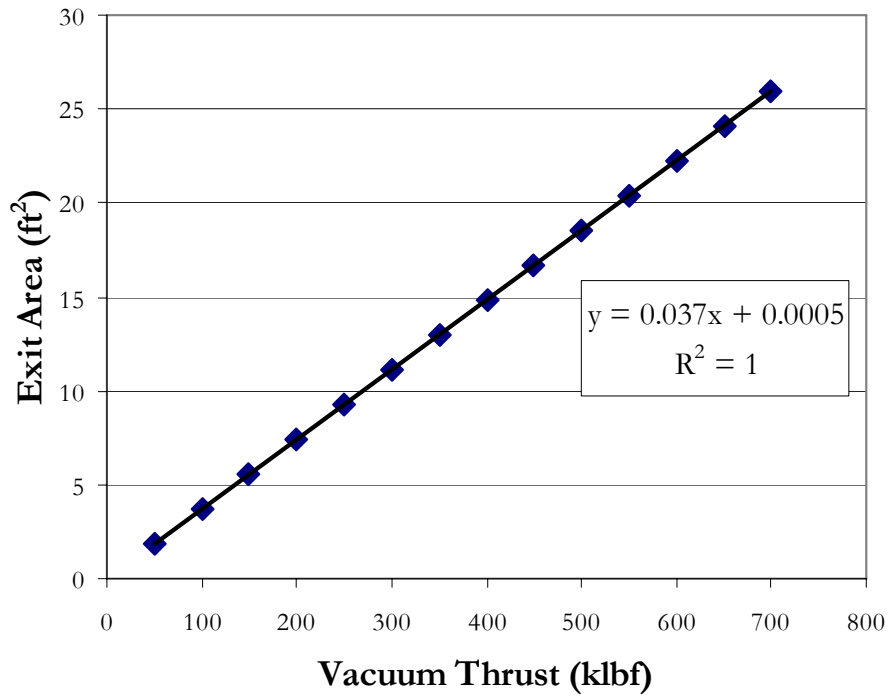


Figure 16. Exit Area for Booster Engine.

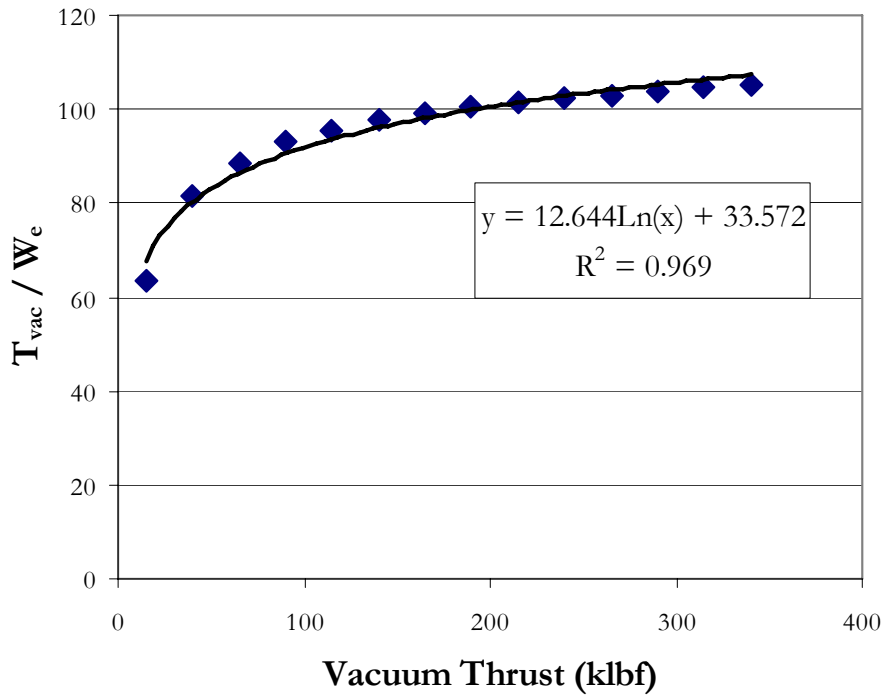


Figure 17. Vacuum Thrust to Weight for Upper Stage Engine.

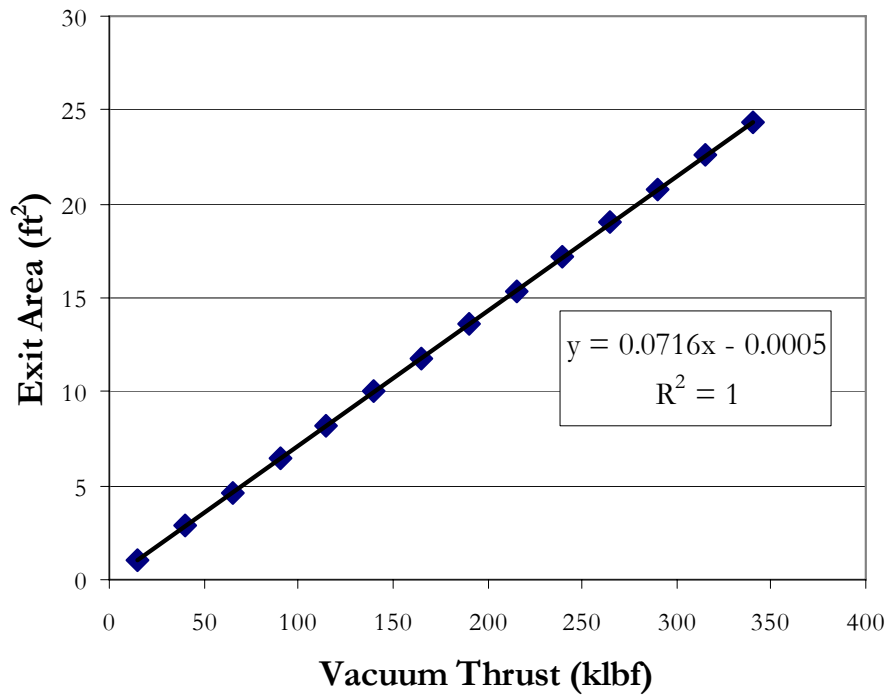


Figure 18. Exit Area for Upper Stage Engine.

3.2.4 Airbreathing Propulsion

The flyback RTLS option makes use of a turbofan engine to cruise back to the launch site after re-entering the atmosphere and turning around. The actual amount of thrust required for the engine at any given point during the cruise is calculated by POST to maintain a constant Mach number and altitude. The other input required for POST is the Isp of the engine at the cruising altitude. Sea-Level thrust, used for sizing the engine mass, was calculated based on the density ratio between cruising altitude and sea-level and the required cruising thrust at the beginning of the flyback cruise calculated by POST. The installed thrust to weight for the turbofan was estimated to be 3.0.

The engine performance code PARA version 4.015²¹ was used to calculate the SFC (then converted to Isp) of the turbofan based on five inputs, cruise altitude, compressor pressure ratio, fan pressure ratio, BPR, and cruise Mach number. Since this program is strictly a GUI interface and could not be integrated into ModelCenter very easily, a RSE based on the five inputs with ranges shown in Table III is used to rapidly calculate the SFC and then converted to Isp. The R^2 value for this RSE is 0.99755. The RSE was created using a 43 run DOE that is based on a Central Composite Design²². The airbreathing engine Isp at 15,000 ft calculated from the RSE is shown in Figure 19

Table III. Ranges of Inputs for Turbofan DOE.

Input Parameter	Lower Bound	Upper Bound	Value Used
Cruise Altitude	10,000 ft	35,000 ft	15,000 ft
Compressor Pressure Ratio	15	35	30
Fan Pressure Ratio	1.5	3.0	2.5
BPR	0.5	3.5	1.5
Mach Number	0.3	0.8	Output From POST

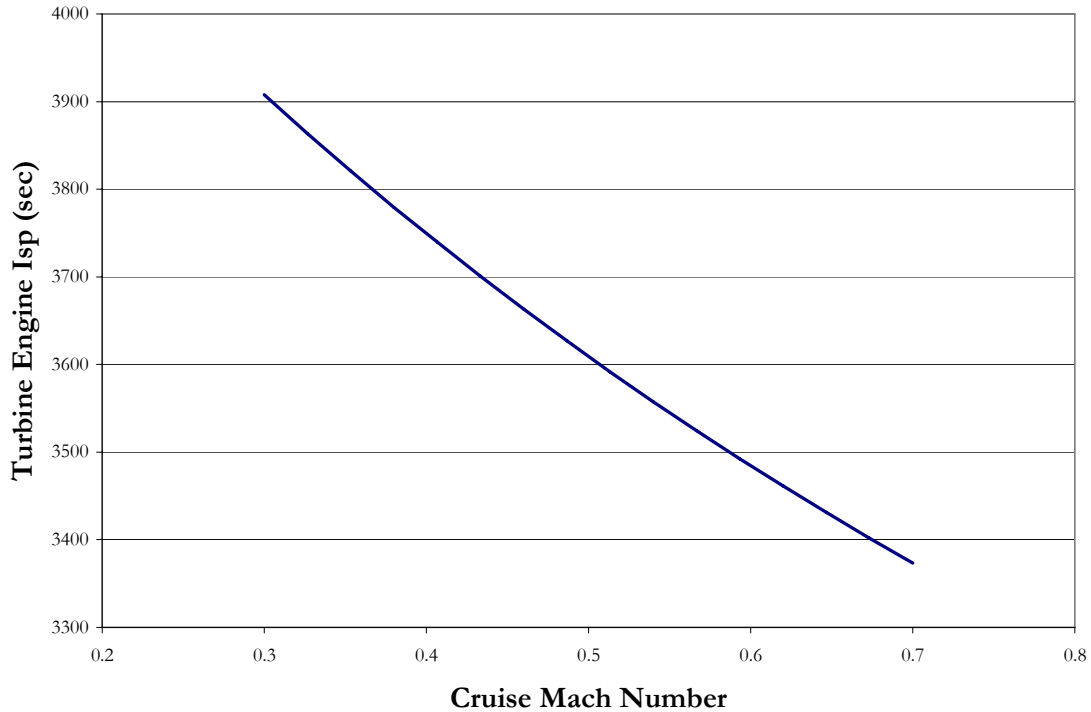


Figure 19. Airbreathing Isp vs. Cruise Mach for Engine Parameters in Table III.

3.2.5 Trajectory Simulation

The trajectory simulations were modeled using NASA’s 3 DOF Program to Optimize Simulated Trajectories. This is a FORTRAN 77 legacy code very highly used in the spacecraft and launch vehicle industries. The input deck of the trajectory is broken down into different events that begin at user defined triggers and incorporates all aspects of flight including aerodynamics, the curvature and oblateness of the earth, the orientation of the vehicle, velocity losses, etc. The program will integrate along the equations of motion for a given set of user defined input variables. On top of the trajectory analysis, POST can use 1 of 3 methods to optimize the input variables based on a set of user defined dependant variables to achieve a user defined objective function²³.

For the ascent branch and the three different RTLS branches, POST’s accelerated projected gradient optimizer was used. Projected Gradient is based on the Method of Feasible Directions optimization scheme in which the optimizer will find a feasible design point and “follow” the constraints to find the optimized value²⁴. The four POST decks used in this study are in Appendix A.

The Ascent Branch deck is common to all three RTLS options. Its objective function is to maximize the burnout weight at a circular 100nmi orbit at 28.5° inclination. The first event is the total configuration taking off vertically from KSC and beginning to pitch over. The pitch angles along the path are optimized based on a linearly interpolated

table of time steps. The staging point occurs at an inputted value of ideal change in velocity (ΔV). At this point, the weight of the booster is dropped and the upper stage coasts for 5 seconds before lighting the upper stage engines. The upper stage then flies along optimized pitch angles until reaching orbit velocity at 100 nmi and 0 flight path angle. The engine thrust is throttled to ensure a maximum acceleration of 6 g's. The vector of conditions at staging are wrapped into ModelCenter and passed onto the RTLS branch.

The glideback RTLS branch starts at the staging conditions from the ascent branch with the weight of the booster after staging. The booster flies at zero bank and angle of attack of 45°. The booster coasts to the peak of its trajectory and then re-enter the atmosphere. When the wind loading reaches 2.5 g's, the angle of attack is lowered using POST's generalized acceleration steering, until the dynamic pressure reaches its peak (change in dynamic pressure equals zero). At this point, the booster begins to turn at optimized angles of attack and bank angles. The booster turns until it reaches an optimized azimuth angle and then has 20 seconds to pull out of the turn to a zero bank and an angle of attack for best L/D based on the given aerodynamic model. The POST deck ends when the booster reaches the longitude of the launch site. The independent variables are the angles off attack, turning bank angles, and the azimuth angle to turn to. The constraints are the final latitude, max wing loading of 2.5 g's, and max dynamic pressure of 500 psf.

The flyback RTLS branch flies a constant angle of attack of 50 degrees from the staging point. When it reaches a wing loading of 2.3 g's, the angle of attack is lowered using generalized acceleration steering so as to keep the wing loading constant. Since the booster has not used any RTLS fuel and is heavier than the landing weight, the reduce g-load is used to account for the fact that normal force should be 2.5 times the landing weight and not the weight after staging. The total acceleration increases due to the drag in the axial direction. After the total acceleration drops back to 2.3 g's, which is after the booster phugoid mode altitude, the booster will begin to bank at optimized angles of attack and bank angles. It will keep turning until it reaches the appropriate optimized azimuth angle to fly back to the launch site, take 25 seconds to pull out of the turn, and then will fly at 10° angle of attack (the best L/D ratio for this aero model) and zero bank until it reaches about 16,000 ft. It will then start the engine and pullout to about 15,000 ft. The angle of attack, throttle, and bank angle are then varied using generalized acceleration steering to fly straight and level until reaching the longitude of the launch site. The independent variables are the angles of attack and bank angles during the turn and the azimuth angle to turn to. The constraints are the final longitude, wing loading, max angle of attack, and dynamic pressure during the turn.

The ascent trajectory for the flyback method was modified to set a staging flight path angle to control the maximum dynamic pressure during re-entry. The flight path angle at staging used to produce the results shown here was 20°.

A RSE was made from the POST model of the flyback branch. This was done in response to the difficulty of the total flyback RTLS model to converge to a point using FPI. The reason believed for the convergence difficulty is the occasional failure of POST's projected gradient optimizer to find a true optimum each time it was run thereby causing the RTLS required MR to fluctuate. The outputs of the RSE's are flyback propellant required (R^2 of 0.99896), maximum re-entry Mach number (R^2 of 1.0), cruise Mach number (R^2 of 0.9115), and cruise thrust (R^2 of 0.999157). The DOE used was an 8 variable Central Composite design²². The ranges for the DOE are listed in Table IV.

Table IV. Ranges for DOE Run in Flyback Deck in POST.

Staging Latitude	28.3 – 28.5 deg
Staging Longitude	279.5 – 281 deg
Staging Relative Velocity	4000 – 8800 ft/sec
Staging Relative Flight Path Angle	20 – 45 deg
Staging Azimuth Angle	90.5 – 91.3 deg
Staging Altitude	155,000 – 200,000 ft
Staging Weight	120,000 – 170,000 lb
Airbreathing Engine ISP	3000 – 4000 sec

The boostback RTLS branch begins with the booster pitching around to an angle of attack of 180° so that the thrust is opposite the velocity vector with the rocket engine off with in 10 seconds. One engine is then turned on and the booster flies to an optimal pitch angle and that. The criteria for shutting off the engine was selected to be the horizontal velocity towards the base (POST variable vxf). After shutting off the engine, the booster went to a 40° angle of attack and held that angle until the wing loading reached 2.5 g's, since the booster at this point has undergone the RTLS burn and is now at the landing weight. The angle of attack was then adjusted using generalized acceleration steering to maintain that normal force until the altitude leveled off before the phugoid mode altitude rise. Then the booster glided at optimal pitch and bank angles until reaching the longitude of KSC. The independent variables are inertial pitch angles while the engine is running, and the angle of attack and bank angles during the gliding portion of flight. The constraints are the maximum number of normal g's while gliding, maximum dynamic pressure, a minimum altitude of 15,000 ft at the end of the flight, the final latitude, and a maximum angle of attack of 40° during gliding flight.

3.2.6 Weights and Sizing

Weights and Sizing was set up in Microsoft Excel and was done by breaking up the vehicle into MERs for the booster and upper stage and sizing each stage separately²⁵. The MR for each of the three branches is used to properly size the two stages. The upper stage is first sized by varying the total amount of propellant in the vehicle. The booster is then sized

adding in the gross weight of the upper stage by varying the scaling parameter of the baseline dimensions and the total amount of propellant required for the RTLS branch. The sizing parameters are set using Microsoft Excel's Solver so that all required MR and calculated MR are equal. There are no technology reduction factors added to these MERs so that the mass estimation is based on the current state of the technology.

The Simple Electrical Systems and Avionics Wizard²⁶ is used to estimate the weight of the avionics required for the booster and the upper stage. Table V shows the settings used in SESAW for each stage. An Excel spreadsheet was made to give the same results from the same relationships²⁷ in the SESAW program so that it could be integrated into ModelCenter.

Table V. Inputs for SESAW.

Input Parameter	Booster Value	Upper Stage Value
System Redundancy	2	2
Program Development Year	2005	2005
Stage Length	Current Value	Current Value
Guided Landing?	Yes	No
Takeoff Vertically?	Yes	Yes
Crew on Board?	No	No
Piloted by Crew?	No	No
At Least 1 Other Stage Reusable?	No	Yes
Altitude Other Reusable Stages are Dropped	N/A	50 nmi
Is This Stage Expendable?	No	Yes
Upper or Only Stage?	No	Yes
Highest Altitude for this Stage	Suborbital	LEO
Time in Orbit (days)	0.2	1

The propulsion weight sizing is based on thrust to weight ratios discussed above. The rocket engines thrust to weight ratios comes from the REDTOP-2 design tool. The airbreathing engine weight was calculated based on an assumed thrust to weight of 3 based on the sea level thrust.

The thermal protection MER used for the booster requires an input of surface area density. The chart shown in Figure 20 shows the surface area density used as a function of maximum re-entry Mach number that occurs after the booster reaches the peak of its trajectory. Below Mach 3, no TPS is needed.

A 15% propellant reserve was used flyback and 1.5% propellant was reserve was used for boostback. The residuals for RTLS were 0.5%. There were 1% propellant reserves and residuals for ascent on each stage. Each stage assumed a 1% startup amount of propellant.

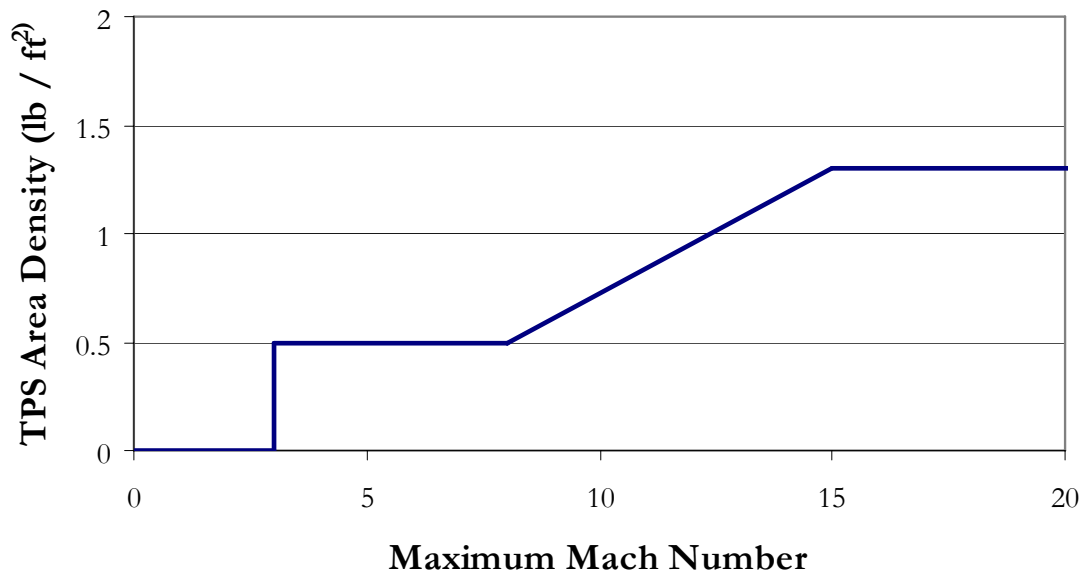


Figure 20. TPS Area Density as a Function of Maximum Re-entry Mach Number.

3.3 Design Structure Matrix and MDO

Each of the contributing analyses fit into a design structure matrix shown in Figure 21. The links on the top right of the CA's are known as the feed forwards and the links on the bottom left are known as the feedbacks. Since it is very difficult, often impossible, to make a computer model with the feedback loops directly, a MDO technique must be utilized to “break” the feedback links. While this DSM encompasses any possible aspect of an launch system with a RTLS booster, not all of the links are needed for each method, i.e. airbreathing engine is only needed for the flyback method.

The MDO technique known as Fixed Point Iteration was used in ModelCenter to handle the feedback. In FPI, guesses are made for the variables that are feedback. All CA and feed forward links are then ran. The outputs from the model are then logged and put back into the model as the new guesses. When the difference between the guesses and the outputs are within some appropriate tolerance, then system is assumed to be converged.

The only system variable in this study was the staging ideal ΔV . Relaxation was used were appropriate to dampen out convergence oscillations.

The glideback RTLS branch was taken outside of the overall system loop because it does not give any output to the rest of the model because it only tries to maximize the final altitude over the landing site based on the staging conditions. For glideback, the booster and upper stage are sized based on the staging point and the glideback RTLS branch is then run to determine what altitude it will reach over the launch site.

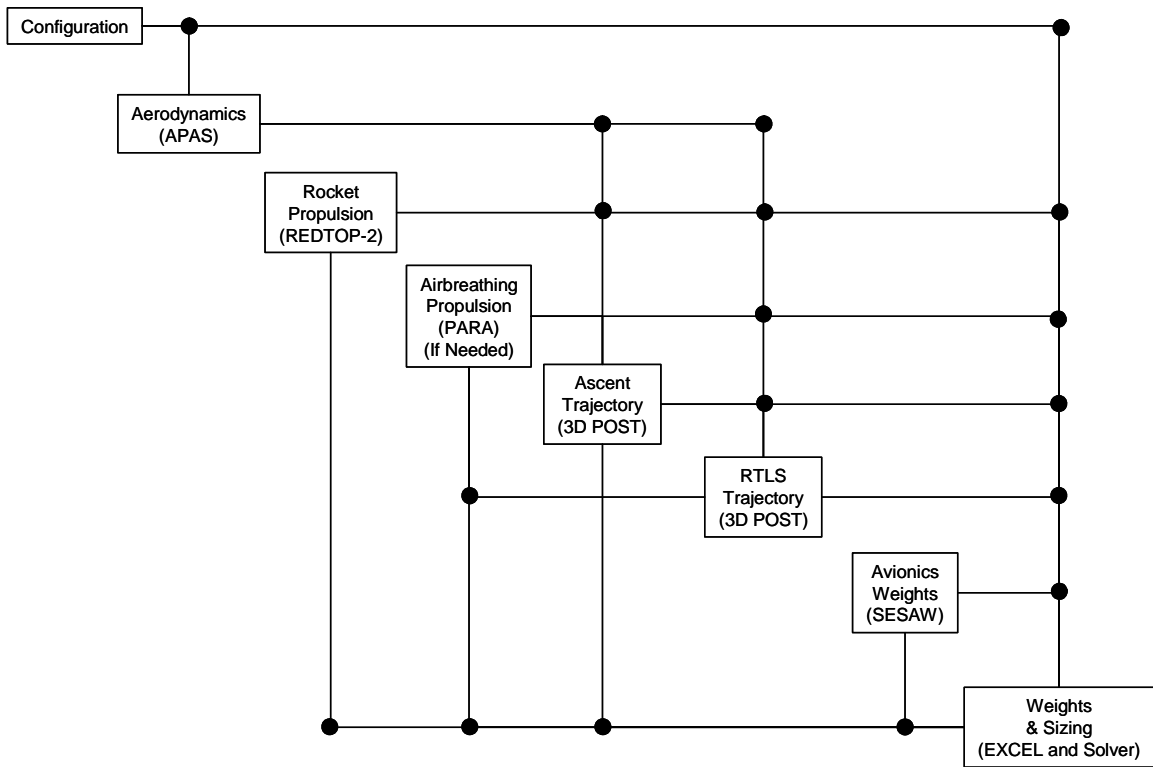


Figure 21. DSM Used for Modeling of the RTLS Methods in this Study.

4.0 Results

4.1 Optimal Staging Points

For the boostback and flyback RTLS methods, a sweep of staging points was run to show where the staging point occurs for lowest gross mass and for lowest dry mass. For glideback, a sweep of staging points was done to find the final altitude after gliding back to the launch site. The sweeps of staging points for gross and dry mass are shown in Figure 22 and Figure 23. Figure 24 shows the final altitude at various staging points of the booster after gliding back to the launch site. For both boostback and flyback, the sweep of staging points show a bucket shape for gross and dry mass show that there is an optimal staging point for minimum mass. For glideback, no optimal point can be selected because there is a cutoff point where the booster can't make it back with the required altitude margin.

Table VI shows the conditions at the optimal staging point for each of the RTLS methods and the vehicle parameters that results from that staging point. Figure 22 and Figure 26 show direct comparisons for the optimal gross and dry mass, for each RTLS method.

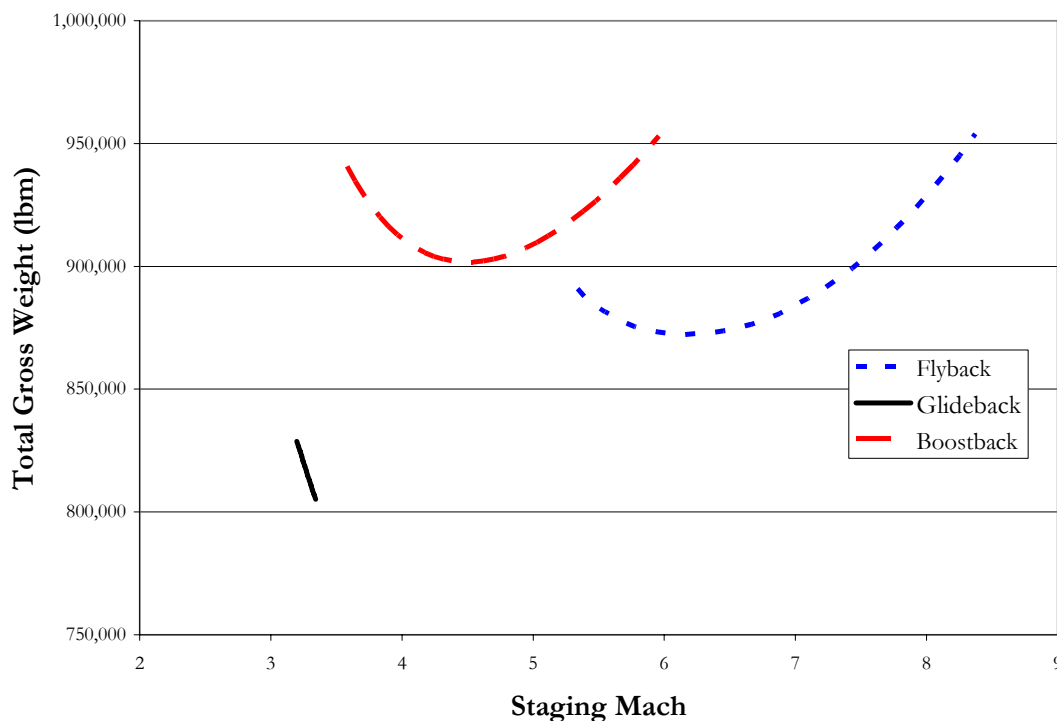


Figure 22. Total Gross Mass of Booster and Upper Stage at Various Staging Points.

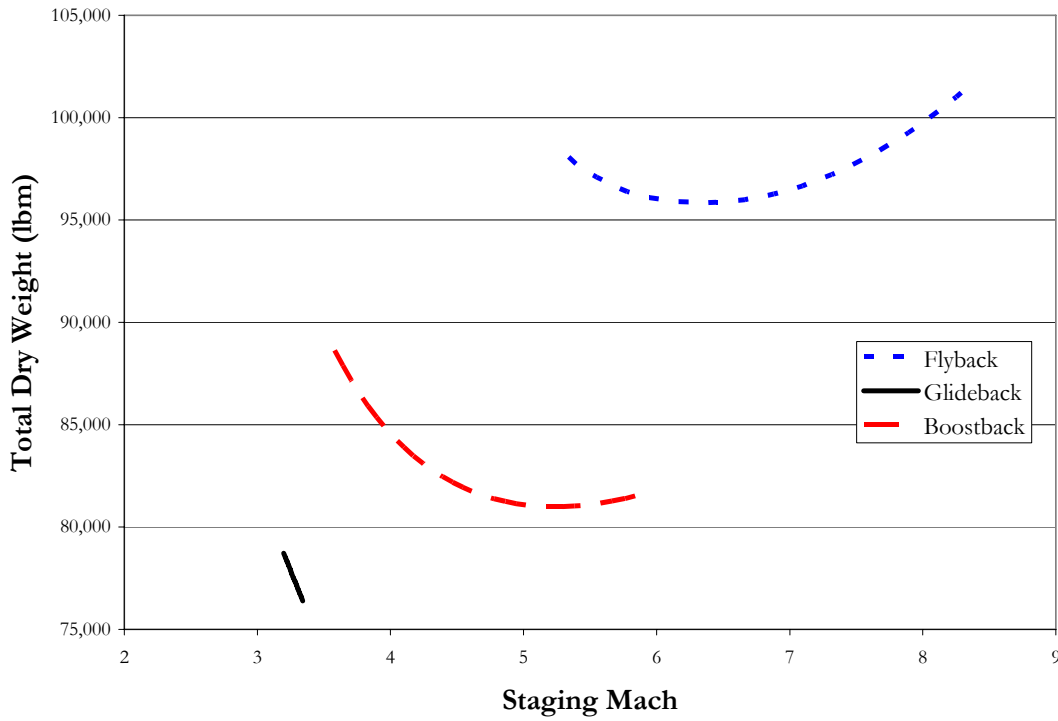


Figure 23. Total Dry Mass of Booster and Upper Stage at Various Staging Points.

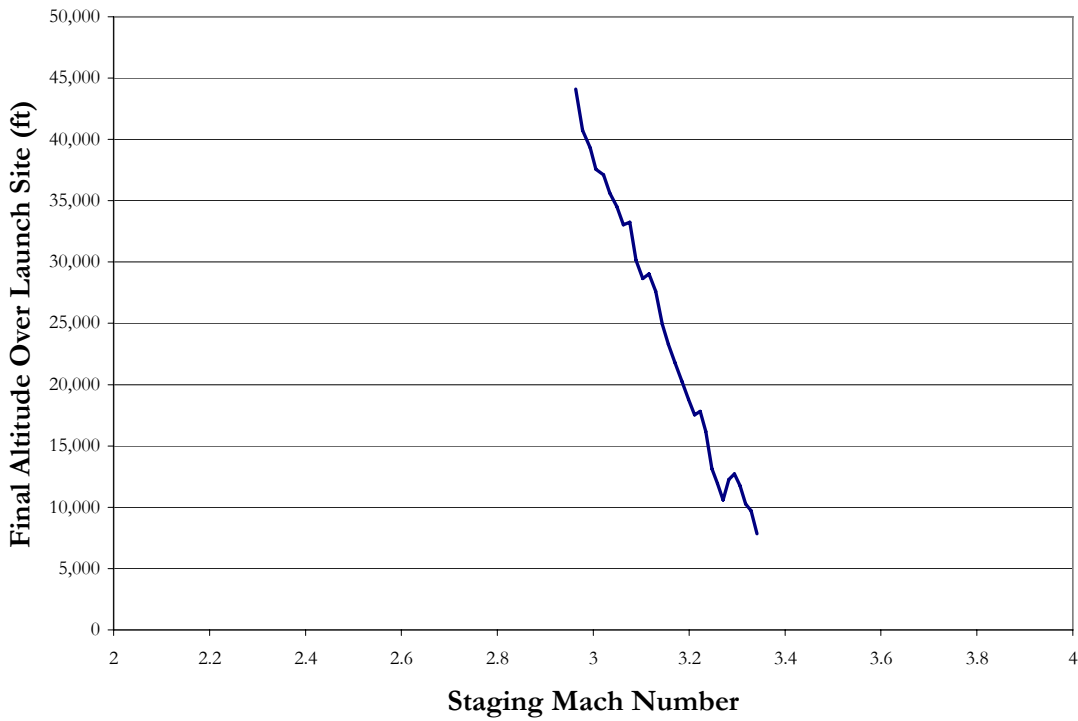


Figure 24. Final Altitude Over Launch Site for Glideback at Various Staging Points.

Result from Optimal Staging Points.

Back (Lowest Gross Mass)	Boostback (Lowest Gross Mass)	Flyback (Lowest Dry Mass)	Boostback (Lowest Dry Mass)
--------------------------------	-------------------------------------	---------------------------------	-----------------------------------

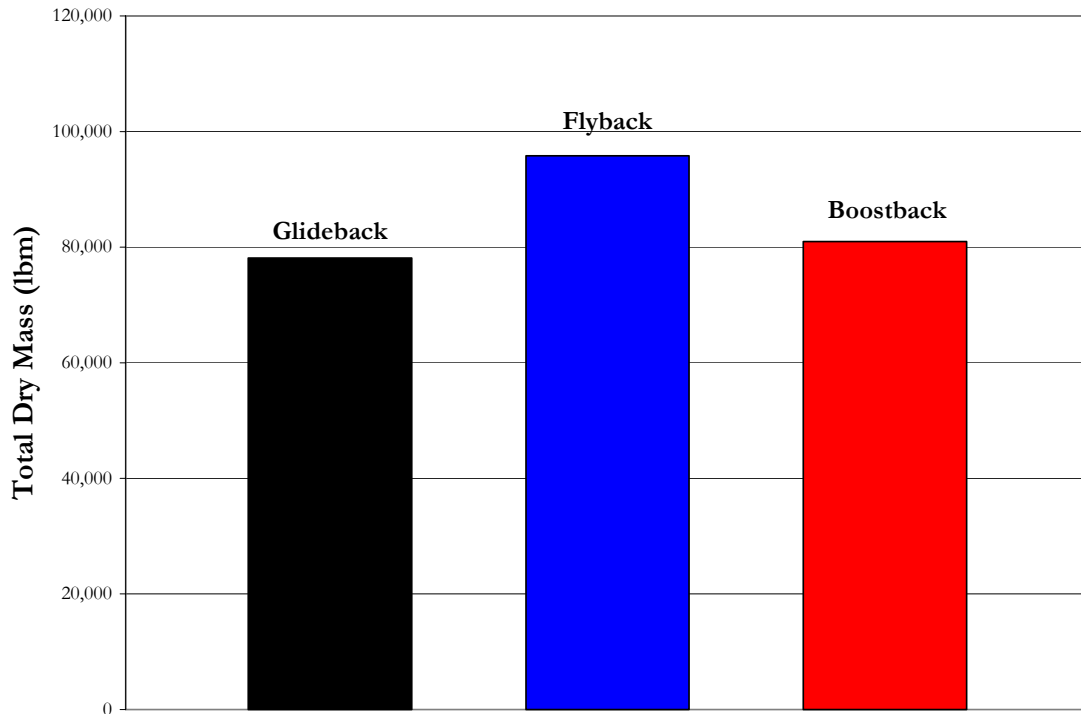


Figure 26. Comparison of RTLS Methods When Optimized for Lowest Dry Mass.

4.2 Trajectory plots

4.2.1 Glideback Trajectory

As shown above, the staging condition that allows for the booster to have a final altitude of 15,000 ft above the launch site occurs at about Mach 3.1. The altitude vs. downrange plot of the trajectory is shown in Figure 27 with the ground shown in Figure 28. The booster reaches a peak altitude of about 31 nmi, re-enters the atmosphere, and then turns south for returning. The turn begins when the booster is supersonic and ends after it has dropped below Mach 1. During its turn, it reaches a maximum downrange distance of about 52 nmi. It begins the straight glide under Mach 0.8 and decelerates until it reaches the launch site. Since the peak re-entry Mach number of 1.86 (the peak in Figure 30) is well below Mach 3, no TPS is required for this method. The ground track for glideback and the other RTLS methods below show that when launch out of KSC, there is no need to modify the trajectory to avoid over-flight issues. The booster returns about 14 minutes after staging.

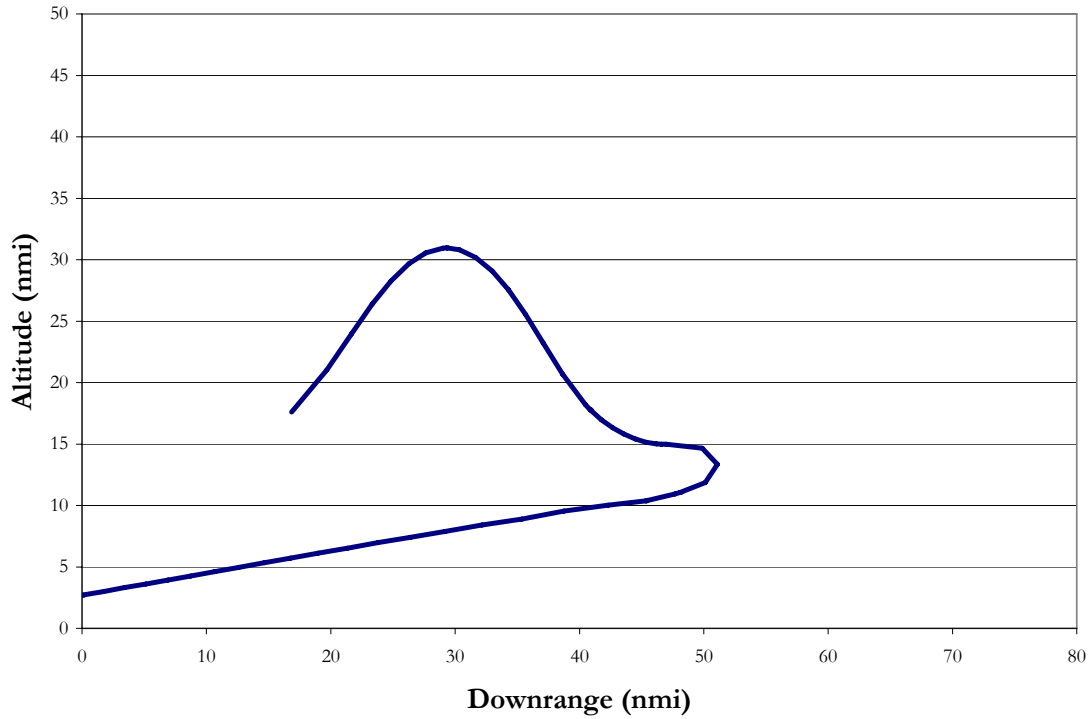


Figure 27. Altitude vs. Downrange for Glideback Trajectory.

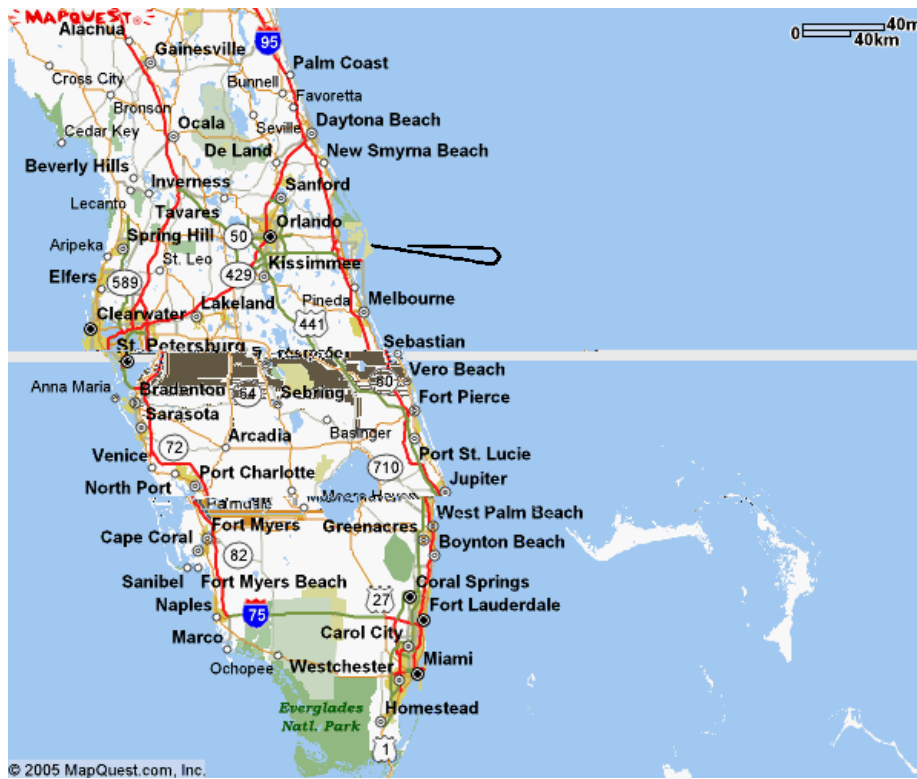


Figure 28. Ground Track for Glideback Trajectory.

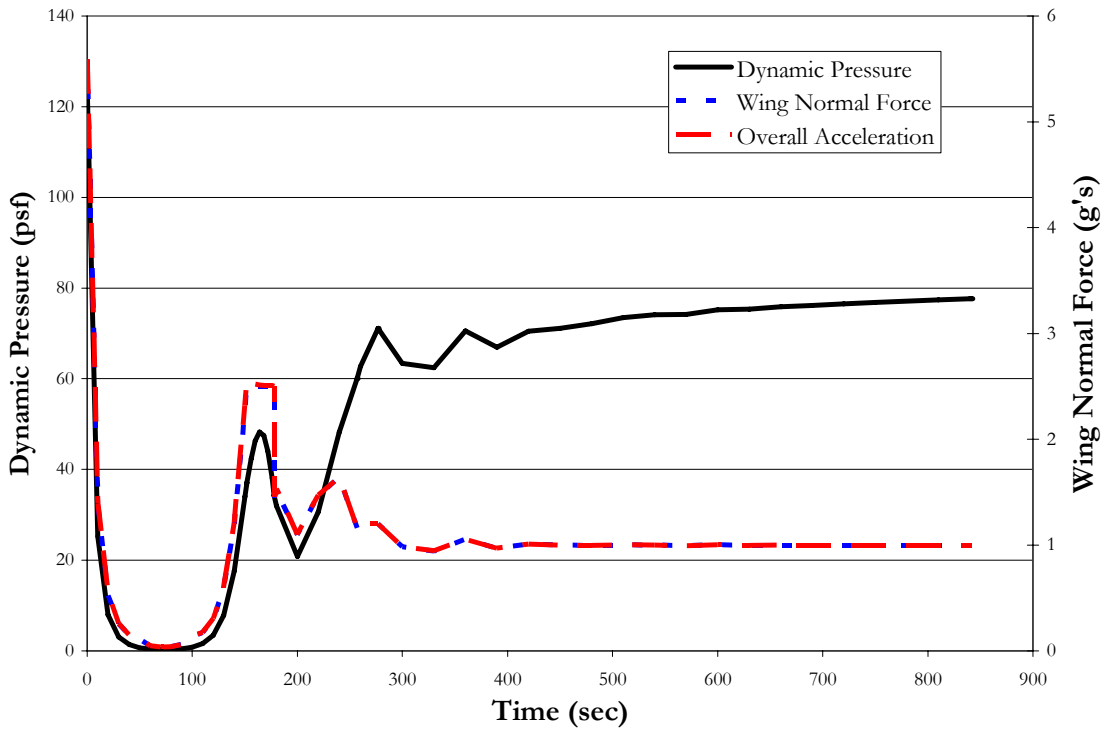


Figure 29. Dynamic Pressure, Normal Force, and Overall Acceleration vs. Time for Glideback Trajectory.

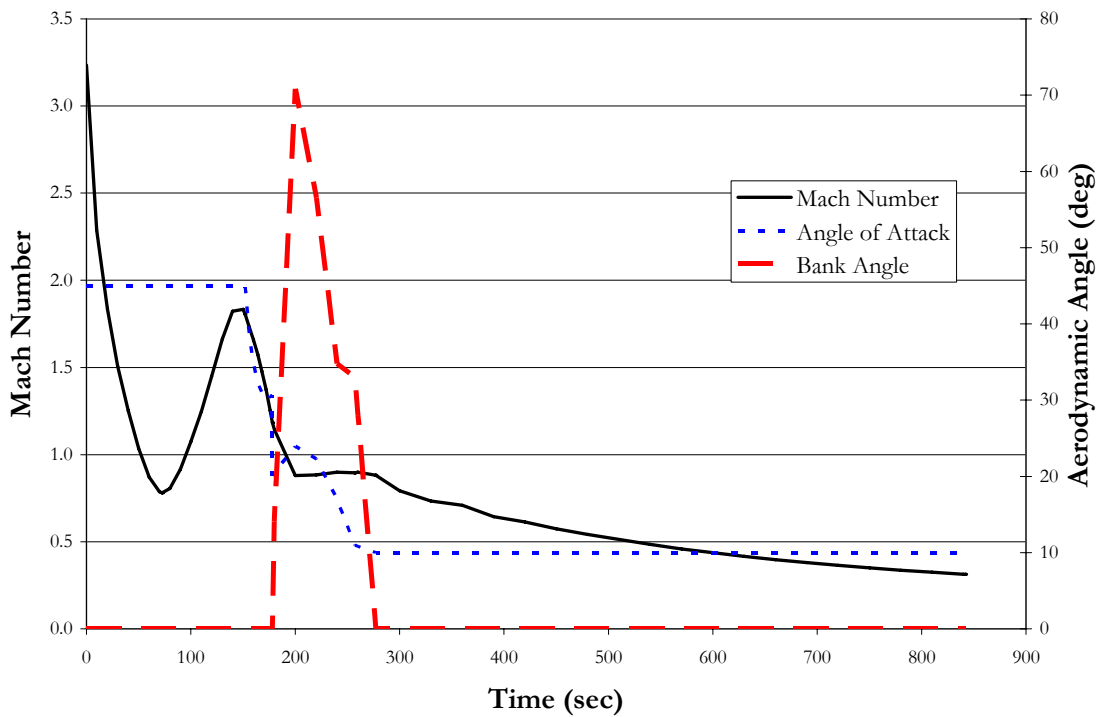


Figure 30. Mach Number and Aerodynamic Angles for Glideback Trajectory.

4.2.2 Flyback Trajectory

Figure 31 through Figure 34 shows the booster's trajectory for the optimal dry weight flyback method. The booster holds a constant angle of attack reaching a peak altitude of about 48 nmi. As it re-enters the atmosphere, the angle of attack is dropped rapidly and then is increased to hold the required normal force until the phugoid mode altitude rise occurs. At the peak of the altitude rise, the booster begins its gliding turn in which the booster's speed is subsonic. The booster reaches a maximum downrange of about 350 nmi. After gliding about 30 nmi (which is about the max downrange distance for the glideback booster), the airbreathing engine must be turned on to hold an altitude of about 15,000 ft. The engine's Isp is about 3610 sec requiring about 8,000 lbf of thrust for each engine at the beginning of the cruise. The RTLS branch takes about 77 minutes. Also, the ground track out of KSC reaches beyond the Bahamas which could possibly be used as an emergency landing site. The peak re-entry Mach number is about 6.93, requiring TPS.

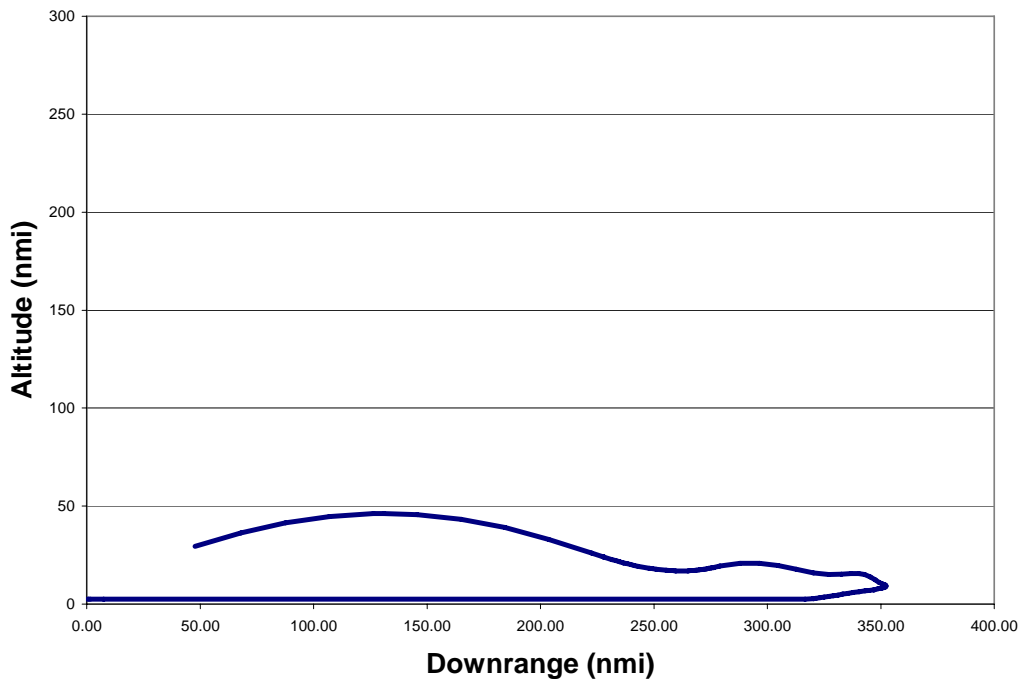


Figure 31. Altitude vs. Downrange for Flyback Trajectory.

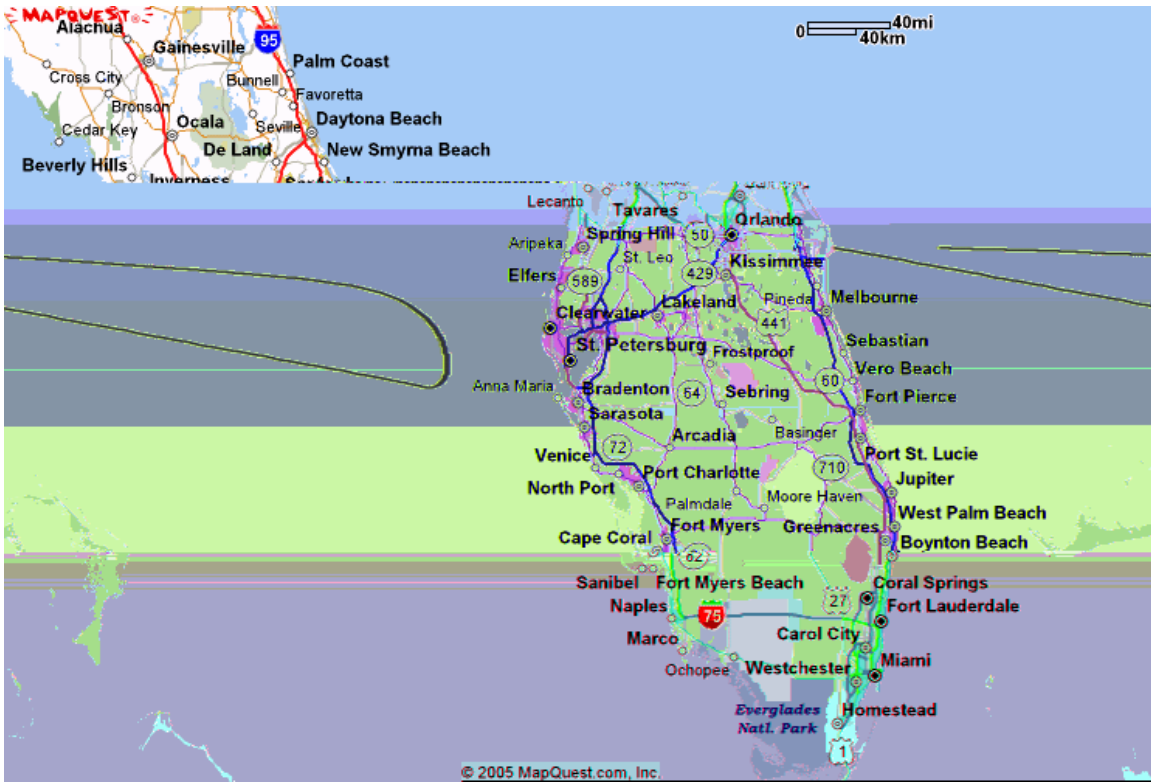


Figure 32. Ground Track for Flyback Trajectory.

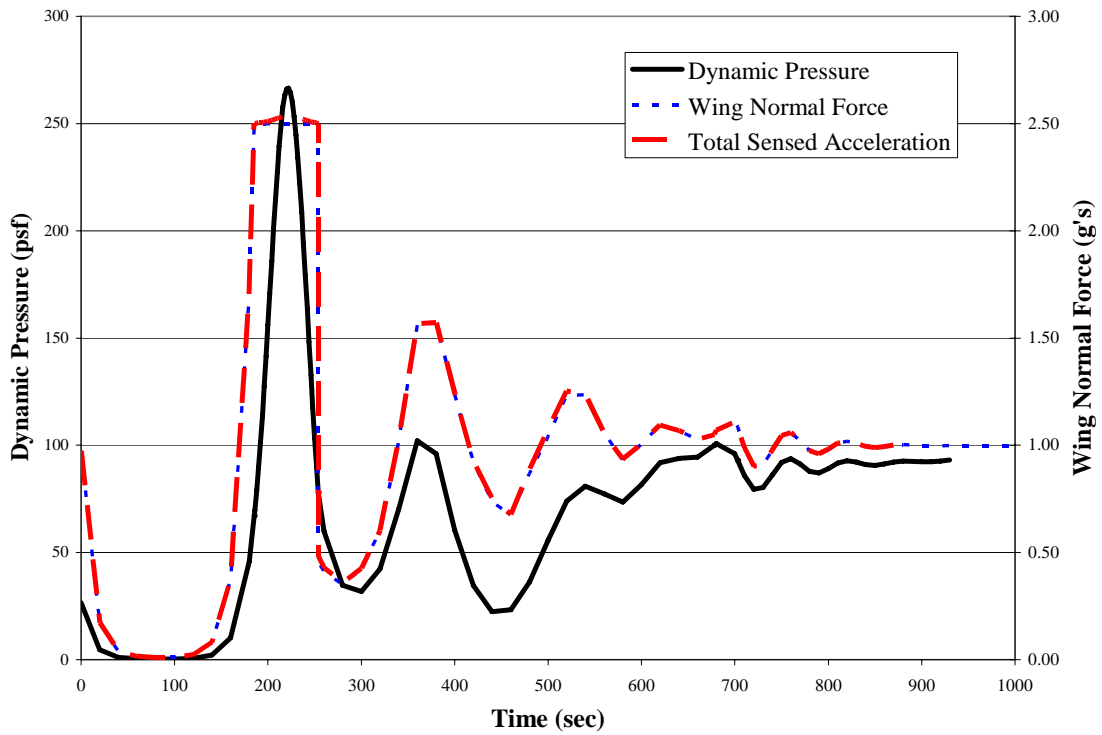


Figure 33. Dynamic Pressure and Mach Number vs. Time for Flyback Trajectory.

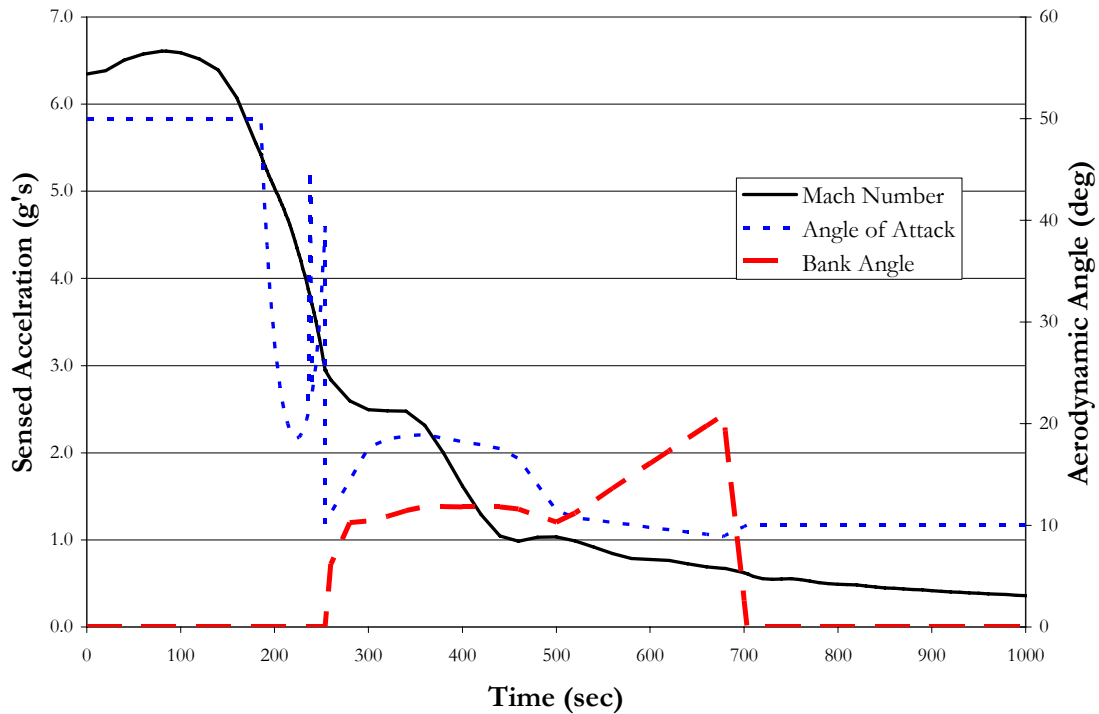


Figure 34. Normal Acceleration and Aerodynamic Angles for Flyback Trajectory.

4.2.3 Boostback Trajectory

The trajectory of the optimal dry weight booster using the boostback RTLS method is shown in Figure 35 through Figure 38. The booster maximum downrange is about 24 nmi which is less than the glideback trajectory. This effect is due mostly to the reverse engine thrust providing more deceleration than and aerodynamic turn. Also the deceleration can start occurring above the atmosphere, which a glideback maneuver cannot due. The peak of the trajectory is at 28 nmi. During the engine burn, the angle of attack is very high to allow for the thrust vector to be opposite the velocity vector. After the engine burn, the booster is a dive like state when re-entering, and levels off after the peak deceleration. The maximum re-entry Mach number is below 3 so no TPS is required. After the phugoid mode altitude rise, a mild amount of banking is required to line up the booster with the launch site. The time of flight for the boostback RTLS branch is about 3 minutes. When the booster reaches the launch site, it is well over 15,000 ft in altitude giving plenty of margin to land.

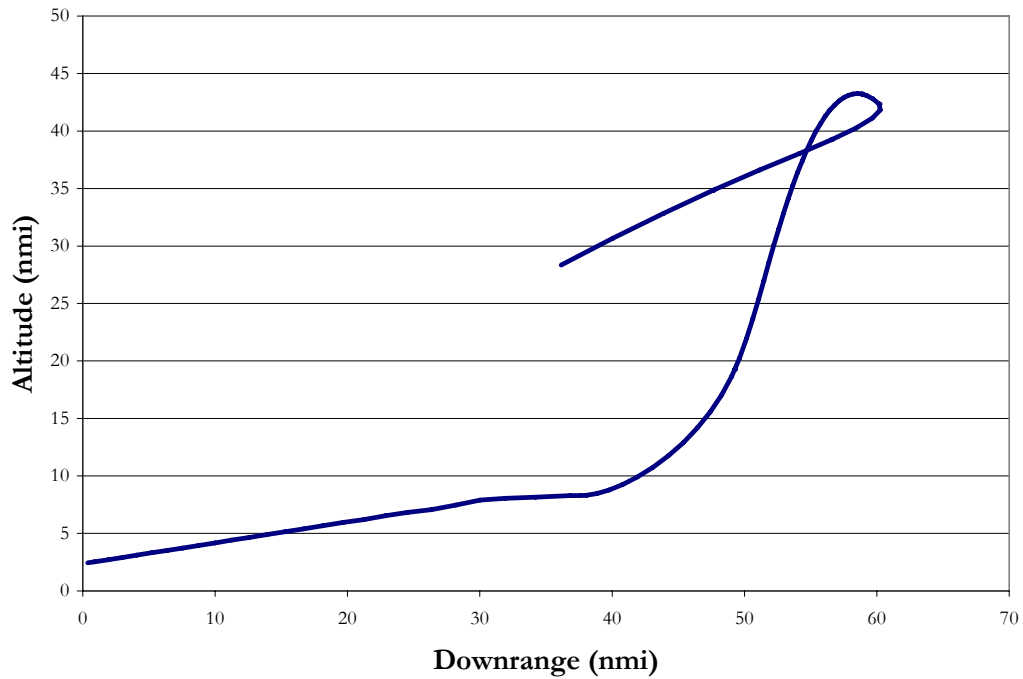


Figure 35. Altitude vs. Downrange for Boostback Trajectory.

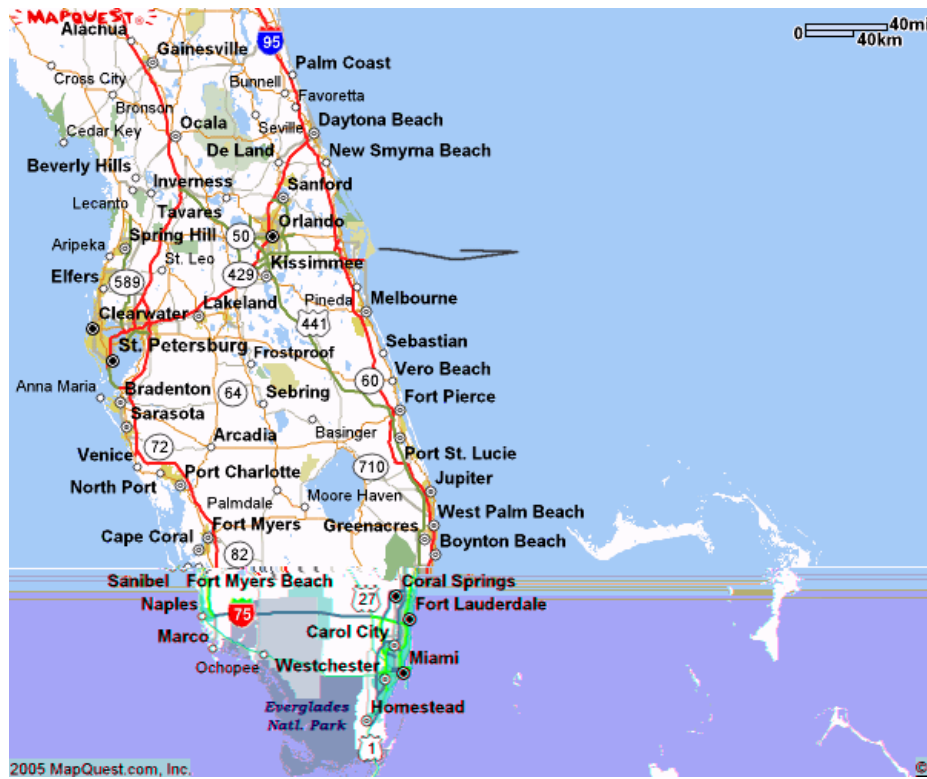


Figure 36. Ground Track for Boostback Trajectory.

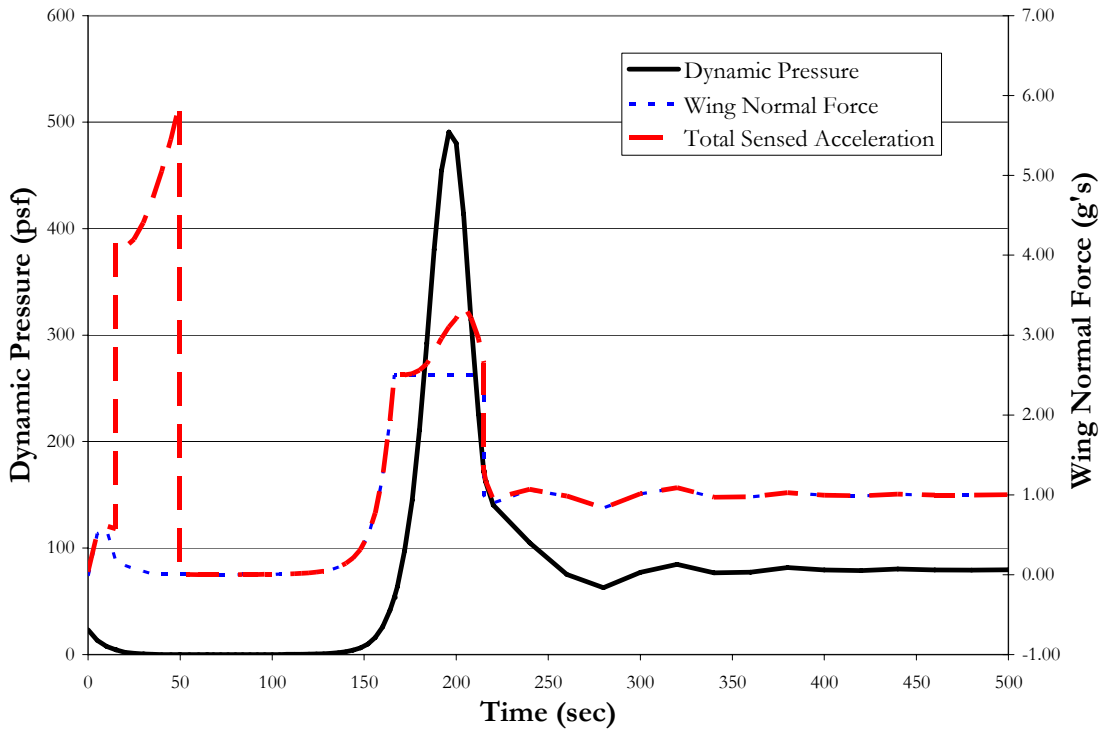


Figure 37. Dynamic Pressure and Normal Force vs. Time for Boostback Trajectory.

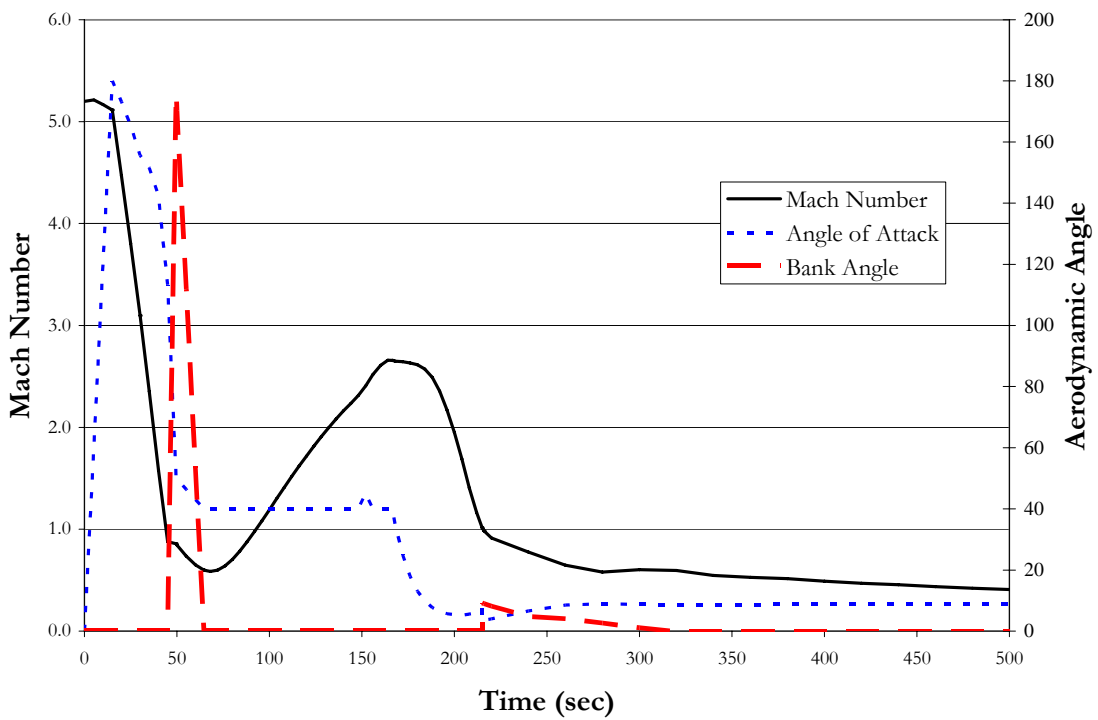


Figure 38. Mach Number and Aerodynamic Angles for Boostback Trajectory.

4.3 Mass Breakdown of Each RTLS Method

Table VII. Mass Breakdown for Each RTLS Booster.

Mass Component	Glideback	Flyback	Boostback
Wing Group	4,848	7,600	5,950
Tail Group	423	600	590
Body Group	9,541	12,680	12,880
<i>Primary Structure</i>			
<i>Secondary Structure</i>			
<i>Crew Cabin (w/ escape system)</i>			
<i>Body Flap</i>			
<i>Thrust Structure</i>			
<i>Oxidizer Tank</i>			
<i>Fuel Tank</i>			
<i>Airbreathing Flyback Fuel Tank</i>			
Thermal Protection	0	6,910	0
Landing Gear	1,982	2,760	2,180
Propulsion Hardware	14,483	19,800	15,790
<i>Rocket</i>			
<i>Rocket Feedlines, Pressurization, etc.</i>			
<i>Airbreathing</i>			
RCS Propulsion	850	1,380	930
Primary Power	991	990	990
Electrical Conversion & Dist	3,595	4,870	3,870
Hydraulic Systems	0	0	0
Surface Control Actuation	291	470	320
Avionics	1,150	1,260	1,250
Environmental Control	2,652	2,650	2,650
Personnel Equipment	0	0	0
Piggyback Structure	8,480	4,830	5,610
<i>Thrust Structure</i>			
<i>Link Structure</i>			
Dry Weight Margin (15%)	8,697	11,790	9,350
Dry Weight	57,983	78,610	62,350
Crew and Gear	0	0	0
Payload Provisions	0	0	0
Residual Propellants	2,087	2,980	3,110
<i>Ascent Residuals</i>			
<i>RTLS Residuals</i>			
RTLS Reserve Propellants	0	2,110	640
Landed Weight	60,069	83,690	66,100
RTLS Propellant Weight	0	14,040	42,700
RCS Propellant Weight	632	1,030	1,150
After Staging Weight (Entry Weight)	60,702	98,760	109,950
Upper Stage	353,323	201,150	233,710
Ascent Reserve Propellants	2,087	2,910	2,900
In-flight Losses and Vents	4,203	3,060	3,500
Before Staging Weight	420,314	305,880	350,060
Ascent Propellants	417,317	581,890	580,250
<i>Oxidizer</i>			
<i>Fuel</i>			
Gross Liftoff Weight	837,632	887,770	930,320
Startup Losses	4,173	5,820	5,800
Maximum Pre-launch Weight	841,805	893,590	936,120

Table VIII. Mass Breakdown for Upper Stage for Each RTLS Method.

Mass Component	Glideback	Flyback	Boostback
Structure	7,300	7,980	8,430
<i>Primary Structure (intertank)</i>			
<i>Fuel Tank (RP)</i>			
<i>Oxidizer Tank (LOX)</i>			
<i>Thrust Structure</i>			
<i>Payload Support</i>			
<i>Secondary Structure (Payload Fairing)</i>			
Aero Surfaces	0	0	0
Propulsion Hardware	5,510	3,340	3,810
<i>Main Engines</i>			
<i>Plumbing, Feed, and Pressurization</i>			
Power	500	500	500
Reaction Control	1,010	860	930
Avionics and Controls	670	760	760
Piggyback Structure	2,120	1,210	1,400
<i>Shear Structure</i>			
<i>Link Structure</i>			
Growth Margin (15%)	3,020	2,580	2,800
Dry Weight	20,130	17,230	18,630
Residuals and Reserves	3,180	1,690	2,000
Circulization Propellant	0	0	0
Payload	15,000	15,000	15,000
Burnout Weight	38,320	33,920	35,630
Main Propellants	313,420	166,380	197,080
<i>Fuel</i>			
<i>Oxidizer</i>			
Gross Weight	351,730	200,310	232,710
<i>Startup Losses</i>		840	1,000
Maximum Weight	353,320	201,150	233,710

5.0 Discussion and Conclusions

The booster used in this study is a simple design consisting of a circular fuselage with a dropped nose, integral propellant tanks, and wing with vertical fins attached to the wing tips. The upper stage is expendable and mounted on top of the fuselage. This winged structure for the booster allows for large amounts of crossrange control that are needed to for turning and landing back at the launch site. The wings are also necessary to decelerate and provide lift during the steep angle re-entry that result from a ballistic trajectory after the staging point. Even though this type of booster is necessary to execute the RTLS methods analyzed in this study, it will weigh more than an expendable booster with the same mass ratio, resulting in higher development and manufacturing costs. The additional weight comes with the extra systems required for RTLS such as wings, landing gear, and TPS if required. Even though the upfront costs for a reusable booster will be higher than an expendable one, the recurring costs should make the investment worth while, assuming that the launch frequency is high enough.

The glideback RTLS method is the simplest method and doesn't require any additionally propellant after staging. After re-entering the atmosphere, it turns more than 180° and is able to reach the landing site with enough altitude margin without any additional energy. The highest staging point is about Mach 3.1, which gives a low enough re-entry Mach number thereby removing the need for TPS and a very large recurring maintenance cost. This low staging Mach number causes the upper stage to have a longer fuselage than the booster, which is consistent with previous studies⁵. During re-entry the overall acceleration of the booster doesn't get much higher than that in the normal direction, possibly allowing lighter wings. Since there is no extra propellant on board, it re-enters at the same weight it lands with. Although the vehicle is not able to control the downrange distance of re-entry, the low staging point allows for maximum downrange point of less than 55 nmi and only requires 14 minutes to reach KSC after staging. As was also shown, the final altitude that glideback booster can reach over the launch site drops very rapidly over with only small increases in staging Mach number. In order to maintain proper altitude margin, the glideback trajectory has very little margin. Minor adverse weather condition may limit the number of launch opportunities available. Furthermore, the vehicle may have more limited capabilities at other launch sites due to overflight limitations. The staging point for glideback is similar to what was estimated in other studies.

The flyback RTLS method requires the most change and complexity to the baseline booster presented. It requires an additional fuel tank and hardware for turbofan engines that add to the dry weight and reduce the packaging efficiency. Its optimal

staging point is the highest of the methods analyzed. After staging it has no control over the downrange distance for re-entry and reaches about 350 nmi during its turn. This method must re-enter with a higher weight than when it lands due to the fuel needed for flyback; thus, preventing the booster from allowing the full 2.5 normal g's. The re-entry Mach number requires some modest TPS that adds to dry weight and requires maintenance. During re-entry, the booster only experiences a brief 3 g's of overall acceleration. After turning the booster glides for about 35 nmi (a little less than glideback) before turning on the engine. The 15% fuel reserves it carries can help in adverse weather conditions. Since the boosters take about an hour to return, this margin is needed since weather concerns must be addressed. The staging point in this study is lower than most previous studies.

The boostback RTLS method utilizes one of the ascent engines on the booster to slow down near at apogee and start the booster gliding in a direction pointing near the launch site. This prevents the need for extra hardware or an extra fuel tank, keeping the packaging efficiency the same as glideback. The propellant needed for the boostback burn comes from the same tanks as what was used for ascent. The optimal staging point occurs slightly higher than glideback and lower than the Kister K-1. After staging, the booster pitched around so that thrust vector points opposite the velocity vector. The engine must be relit. The booster flies above the ascent trajectory before beginning the glide. The booster enters at its landing weight and at a Mach number low enough to avoid the need for TPS. A small amount of banking is necessary to get back to the launch site's latitude. Out of the three methods, it stays the closest to land with a max downrange distance of about 25 nmi. It also ends with a huge altitude margin, much more than the minimum constraint of 15,000 ft for this study. More analysis needs to be done to show how much margin is available for engine restart when beginning the boostback maneuver. Also, a look into the separation dynamics and the next few moments of flight is needed to ensure that the boostback maneuver doesn't cross the upper stage's path.

Some basic similarities arise between modeling these three RTLS methods. First, they all need very detailed control of the angle of attack during re-entry to ensure that the limit of normal g's is maintained. POST's generalized acceleration steering accomplished this requirement. Also during each RTLS trajectory branch, the most difficult constraint to satisfy was the normal acceleration limit during any gliding portion of the flight.

This study showed that glideback method results in the lowest total gross and dry mass when compared to the others, which is in contrast to the other comparison studies presented. The main reason behind this inconsistent result is that the upper stage in the previous two studies was reusable as opposed to being expendable. Reusable vehicles require significantly more dry mass especially if it reaches orbit, requiring TPS. This extra weight in upper stage caused the booster to grow more and leading to glideback becoming the less

preferred method. Thus glideback is only projected to be advantageous on weight criteria if the upper stage is sized only to place the payload into orbit. If a glideback system like the one presented here was built, the same architecture might not be able to be used if the upper stage become reusable.

The boostback method was shown to have an optimal dry lower than the flyback method but a higher optimal gross mass. This can be attributed to a number of reasons. First, flyback requires more hardware for the turbofan engine and fuel tank. The packaging efficiency is also lower with flyback. Boostback, requires a large amount of propellant for the RTLS maneuver which causes the high gross weight. Finally, another reason that boostback is more attractive with the criteria of weight is that no TPS is needed.

For a RTLS booster, boostback provides some distinct advantages in addition to the lower mass. First, it is a much simpler design as it uses the same hardware for ascent as for RTLS maneuvers. It also provides a huge altitude margin over the launch site to ensure a safe landing. Its downrange distance is very short allowing it to return quickly before the conditions at the launch site become more difficult for landing.

In order to better understand which RTLS method is better, an optimization of other design variables such as upper stage diameter and engine parameters needs to be done. Also, a look at the separation dynamics for each method will help improve the overall trajectory modeling. Lastly, another area that needs to be addressed in the minimum cost for each RTLS method. The total dry weight cannot accurately estimate the life cycle cost of a hybrid system to the uniqueness of the architecture. The upper stage for TSTO hybrid system is thrown away every launch while the booster is reused. The development cost of the booster will be higher than the upper stage but it is amortized over the number of flights it will be flown. Taking these cost aspects into account will most likely lead to a higher staging point so the upper stage can be made smaller as it expendable.

6.0 Acknowledgements

I first would like to thank my beautiful wife Debra Vinar for helping me when I had stressful moments throughout my graduate school career and always being there for me. Being newly weds with someone in an engineering graduate school is not an easy way to start off but she was able to help keep our relationship strong.

I am very grateful to the Department of the Air Force for creating the PALACE Acquire program to allow me to remain a full time employee while only having to focus on my graduate school work. I am also very grateful for my colleagues in the Aerospace Design and Analysis Branch at Wright Patterson AFB for being supportive during my first two years of employment. I specifically want to thank John Livingston for being a terrific mentor and providing much needed advice for this project.

I finally want to thank the members of the Georgia Tech Space Systems Design Lab. Most significantly was Dr. John Olds who allowed me to be a member of this design group and is always there to answer questions and provide advice. I have come across very few other professors who care so much about the success of their students. Other students who have me out are Tim Kokan with helping to set the modeling of this project, David Young helping me with POST, and Virgil Hutchinson with his advice about APAS.

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Appendix A

Ascent Branch POST Deck

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c Simple 3-D POST ascent trajectory for first branch of RTLS booster launch
c This trajectory file is common to all types of flyback missions
c
c Modified for RTLS Study by Barry Hellman
c Reaching 100% of Velocity
c This file uses ideal Delta V's as points where to drop stages
c
c written by: John R. Olds (Georgia Tech)
c December, 1999
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c set up optimization inputs
c
!$search
ioflag = 0,          / english input, english output units/
opt = 1,            / optimizer should maximize/
maxitr = 30,        / Maximum number of iterations/
ipro = -1,          / print only the final, optimized trajectory /
c
c *** optimization variable ***
c
optvar = 'weight',   / maximize burnout weight/
optph = 900,         / optimize at the end of booster stage/
c
c *** constraint variables ***
c
ndepv = 5,
depvr = 'xmax1','xmax2', 'gdalt', 'gamma1', 'inc', 'xmin7', /names of dependent variables/
depval = 850, 20, 607998.7, 0.0, 28.5, 0, /target values/
depth = 1, 0.1, 50, 0.01, 0.01, 0.01, /targeting criteria(allowable errors)/
depph = 1000, 1000, 1000, 1000, 1000, 1000, /phase where constraint is applied/
idepvr = 1, 1, 0, 0, 0, -1, /Max(1), Min(-1), or Exact(0) Constraint/
c
c
c *** simulation control variables (u's) ***
c
nindv = 11,
tabl = 5*'pitt',5*'pitt',
tably = 3,4,5,6,7,1,2,3,4,5
indvr = 'tab1','tab2','tab3','tab4','tab5',
        'tab6','tab7','tab8','tab9','tab10',
        'azl',
indph = 5*1,5*500,1,
c
c *** initial guesses for u's ***
c
c
u(1) = -10, /pitch angle at 25 seconds after liftoff/
u(2) = -25, /pitch angle at 50 seconds after liftoff/
u(3) = -35, /pitch angle at 75 seconds after liftoff/
u(4) = -45, /pitch angle at 100 seconds after liftoff/
u(5) = -55, /pitch angle at 150 seconds after liftoff/
u(6) = -65, /pitch angle at 0 seconds after staging and 5 second coast/
u(7) = -75, /pitch angle at 50 seconds after staging and 5 second coast/
u(8) = -80, /pitch angle at 100 seconds after staging and 5 second coast/
u(9) = -85, /pitch angle at 200 seconds after staging and 5 second coast/
u(10) = -90, /pitch angle at 300 seconds after staging and 5 second coast/
u(11) = 90,
c

```

```

c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c Projected Gradient Options
c (comment out this block if using npsol)
c
c srchm = 5, / use accelerated projected gradient /
c modew = 0, / use manual weighting for u's /
c wvu = 1e-3,2*2e-2,3e2,5*2e-01,1e-02,
  pert = 11*1e-5,
c conepts = 89.99,0,0,0,0, / tighten optimality criteria/
  pctcc = .5, / limit maximum change in u's for targeting /
  npad(1) = 0, / ignore requirements on pert precision /
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c NPSOL Options
c (comment out this block if using projected gradient)
c
c srchm = 6, / use npsol
c depvub = 6.080e5, 0, 10000, 0,
c depvub = 6.080e5, 0, 0, 0,
c deptl = 100, .005, 2, 1,
c indpub = 1000,0,0,0,0,0,
c indplb = 0,-70,-90,-90,-90,-100,-150,
c wopty = 100,
c wvnlc = 10000,1,10,
c wvu = 100,20,100,100,100,100,100,
c isens = 3, / automatic pert control from npsol
c isens = 1, / user selected central differences
c pert = 1e-6,6*1e-7,
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c
c $
c *** trajectory simulation inputs ***
c ccccccccc Begin Phase 1.000 ccccccccccccccccccccc
!$gendat
  title = 0h*Ascent Branch*,
  event = 1, / Calculate Keplerian Conics at end of each integration step/
  fesn = 1000, / final event number/
  npc(1) = 3,
  npc(2) = 1, / fourth order runge-kutta/
  dt = 5, / integration step size (in sec)/
c lref = 170.0, / body length/
  pinc = 10, / print interval (in sec)/
  prnc = 0,
c *** initial conditions ***
  npc(3) = 4, / earth relative velocity components/
c azl = 90, / rotate L coordinates so that Z points due east/
  npc(4) = 2, / geocentric position components/
  gdalt = 20.0, / initial altitude - feet/
  gdlat = 28.5, / Kennedy Space Center/
  long = 279.5,
  velr = 0.0, / Initial Relative Velocity/
  npc(5) = 5, / 1976 standard atmosphere/
  npc(7) = 1, / limit acceleration using etal /
  asmax = 6, / asmax is the maximum number of g's allowed/
  npc(8) = 2, / cl and cd aero inputs/
  sref = 1000.0, / aero reference area/
  npc(9) = 1, / use thrusting engines (rather than delta V's)/
  npc(12) = 1, / calculate relative downrange and crossrange distances/
  npc(15) = 1, / calculate heating using Chapman's equation/
  npc(16) = 1, / use spherical planet for gravity model/
  npc(21) = 1, / Calc prop brun/
  npc(25) = 2, / calculate velocity losses/
  npc(27) = 1, / integrate to find prop flow rates/
  npc(30) = 3, / use enhanced weight model (divided into steps)/

```

```

c
c *** enhanced weight model
c
c Define Engines
c
ispv = 331.0,340, / Vacuum Isp of each engines/
iengmf= 1,0,    / which engines are on/
ienga = 1,1,   / use engine throttle to limit acceleration/
iwdf = 2,2,    / calculate flowrate from engine's Vacuum Isp and thrust/
iwpf = 1,1,    / include engine in flowrate calculations/
nengl = 1,     / Lowest Engine Number/
nengh = 2,     / Highest Engine Number/
c
c Define Vehicle Steps
c
nstpl = 1,     / Lowest Step Number/
nstph = 3,     / Highest Step Number/
wstpd(1)= 500000, / Step 1 Gross Weight (Booster)/
wstpd(2)= 250000, / Step 2 Gross Weight (Upper Stage)/
wstpd(3)= 15000, / Step 3 Gross Weight (Payload)/
c
menstp = 1,2,  / map each engine to a specific step/
mentnk = 1,2,  / map each engine to a specific tank/
istepf = 1,1,  / include all steps in calculation of dry weight/
c
c
c *** guidance inputs ***
c
iguid(1) = 1,0,
iguid(4) = 2, / inertial Euler angles with table look up/
c
c Define Monitor Variables
c
monx(1) = 'dynp', /Dynamic pressure/
mony(1) = 'mach',
monx(2) = 'alpha', /Angle of Attack/
mony(2) = 'mach',
monx(3) = 'heatrt', /Aerodynamic Heating Rate/
mony(3) = 'mach',
monx(4) = 'asmg', /Sensed Acceleration/
mony(4) = 'mach',
monx(5) = 'fazb', /wing normal force/
mony(5) = 'mach',
monx(6) = 'gdalt', /altitude/
monx(7) = 'dprng2',
c
maxtim = 2000, /Maximum time of Flight/
altmax = 10000000, /Maximum Altitude/
altmin = -100, /Minimum Altitude/
c
c
c *** print block ***
print(97)='wprus1','wprus2',
        'wpru1','wpru2',
        'thr1','thr2',
        'isp1','isp2',
        'dynpdt',
        'xmin1','xmax1',
        'xmin2','xmax2',
        'xmin3','xmax3',
        'xmin4','xmax4',
        'xmin5','xmax5',
        'xmin6','xmax6',
        'xmin7','xmax7',
        'netisp',
        'timrf1','timrf2',
        'videal',
        'pstop',
$
!$tblmlt tvc1m = 1.0,

```



```

$
c inertial pitch angle table includes vertical rise segment/
l$tab
table= 'pitt',1,'time',7,1,1,1,
0, 0,
5, 0, /Forced to be vertical for 5 seconds/
20, 0,
50, 0,
100, 0,
150, 0,
220, 0,
$
c include APAS aerodynamic coefficients table
*include 'booster_upper.aero'
l$tab
c Thrust at liftoff
table = 'tvc1t',0, 1000000, /Vacuum thrust of 1st stage engine/
$
l$tab
c exit area for engine 1 (ft^2)
table = 'ae1t',0, 59.2,
endphs = 1, /End of Phase 1/
$
c cccccccc Begin Phase 400.000 cccccccccccccccccccc
l$gendat
c Step 1 burns out
event = 400, critr='videal', value = 6, /Staging ideal delta V/
wsjtd(1) = 38840.77, /Dry weight of Step 1/
iengmf = 0,0, /Turn off Main Engine/
nengl = 2,
nengh = 2,
nstpl = 2,
nstph = 3,
endphs = 1, /End of Phase 400/
$
c cccccccc Begin Phase 500.000 cccccccccccccccccccc
l$gendat
c Coast for 5 Seconds and Startup 2nd Stage Engine
event = 500, critr= 'tdurp',value = 5,
iengmf = 0, 1,
dtimr(1) = 1, /Turn on time for second pitch table and thrust table/
sref = 1000, /aero reference data is max cross sectional area/
$
l$tblmlt tvc2m = 1.0,
$
c include APAS aerodynamic coefficients table
*include 'upper_stage.aero'
c start new pitch angle steering table
l$tab
table= 'pitt',1,'timrf1',5,1,1,1,
0, 0,
50, 0,
100, 0,
200, 0,
300, 0,
$
l$tab
c step 2 uses the LOX/LH2 Engine
table = 'tvc2t',0, 250000, /vacuum thrust of 2nd stage engine/
$
l$tab
c exit area for LOX/LH@ Engine
table = 'ae2t',0, 14.18,
endphs = 1,
$
c cccccccc Begin Phase 900.000 cccccccccccccccccccc
l$gendat
c Step 1 burns out
event = 900, critr='vel', value = 25567.7, /This is total Orbit Velocity at 100 nmi/
wsjtd(2) = 25000, /Dry weight of Step 2/

```

```
iengmf = 0,0, /Turn off Upper Stage Engine/  
nstpl = 3,  
nstph = 3,  
endphs = 1, /End of Phase 900/  
$  
c cccccccc Begin Phase 1000.000 ccccccccccccccccccc  
l$gendat  
c this is the final event  
event = 1000,critr='tdurp',value= 0.0,  
endphs = 1,  
endjob = 1,  
endprb = 1,  
$
```

Glideback Branch POST Deck

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c Simple 3-D POST glideback trajectory for RTLS booster
c
c Modified for RTLS Study by Barry Hellman
c This file optimizes to minimize time after separation
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c set up optimization inputs
c
!$search
ioflag = 0,           / english input, english output units/
opt = 1,             / optimizer should maximize/
maxitr = 40,         / Maximum number of iterations/
ipro = -1,           / print only the final, optimized trajectory /
c
c *** optimization variable ***
c
optvar = 'gdalt',     / maximize altitude/
optph = 1000,         / optimize at the end of booster stage/
c
c *** constraint variables ***
c
ndepv = 5,
depvr = 'xmin5', 'xmax1', 'gdlat', 'xmax2', 'xmax8', /names of dependent variables/
depval = -80.4, 800, 28.5, 50, 70, /target values/
depl = 0.1, 1, 0.01, 0.1, 1, /targeting criteria(allowable errors)/
depph = 1000, 1000, 1000, 1000, 1000, /phase where constraint is applied/
idepvr = -1, 1, 0, 1, 1, /Max(1), Min(-1), or Exact(0) Constraint/
c
c
c *** simulation control variables (u's) ***
c
nindv = 13,
tabl = 6*'alphan',6*'bankt',
tably = 1,2,3,4,5,6,2,3,4,5,6,7,
indvr = 'tabl1','tabl2','tabl3','tabl4','tabl5','tabl6',
        'tabl7','tabl8','tabl9','tabl10','tabl11','tabl12',
        'critr',
indph = 6*300,6*300,400,
c
c *** initial guesses for u's ***
c
u(1) = 10,
u(2) = 25,
u(3) = 20,
u(4) = 15,
u(5) = 10,
u(6) = 10,
u(7) = 50,
u(8) = 50,
u(9) = 40,
u(10) = 30,
u(11) = 20,
u(12) = 10,
u(13) = 260,
c
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c Projected Gradient Options
c (comment out this block if using npsol)
c
srchm = 5,           / use accelerated projected gradient /
modew = 0,           / use manual weighting for u's /

```

```

c wvu = 1e-3,2*2e-2,3e2,5*2e-01,1e-02,
  pert = 6*0.001,6*0.001,0.001,
c coneps = 89.99,0,0,0,0, / tighten optimality criteria/
  pctcc = 0.5, / limit maximum change in u's for targeting /
  npad(1) = 0, / ignore requirements on pert precision /
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c NPSOL Options
c (comment out this block if using projected gradient)
c
c srchm = 6, / use npsol
c depvub = 6.080e5, 0, 10000, 0,
c depvlb = 6.080e5, 0, 0, 0,
c deptl = 100, .005, 2, 1,
c indpub = 1000,0,0,0,0,0,
c indplb = 0,-70,-90,-90,-90,-100,-150,
c wopt = 100,
c wvnlc = 10000,1,10,
c wvu = 100,20,100,100,100,100,100,
c isens = 3, / automatic pert control from npsol
c isens = 1, / user selected central differences
c pert = 1e-6,6*1e-7,
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c $
c *** trajectory simulation inputs ***
c cccccccc Begin Phase 1.000 cccccccccccccccccccc
!$gendat
  title = 0h*Glideback Branch*,
  event = 1,
  fesn = 1000, / final event number/
  npc(1) = 0, / Do not calculate Conic Parameters/
  npc(2) = 1, / fourth order runge-kutta/
  dt = 1, / integration step size (in sec)/
c lref = 170.0, / body length/
  pinc = 10, / print interval (in sec)/
  prnc = 0,
  npc(3) = 4, / earth relative velocity components/
  npc(4) = 2, / geocentric position components/
  npc(5) = 5, / 1976 standard atmosphere/
  npc(7) = 1, / limit acceleration using etal /
  asmax = 6, / asmax is the maximum number of g's allowed/
  npc(8) = 2, / cl and cd aero inputs/
  sref = 1219.577, / aero reference area/
  npc(9) = 0, / no thrust/
  npc(12) = 1, / calculate relative downrange and crossrange distances/
  npc(15) = 1, / calculate heating using Chapman's equation/
  npc(16) = 1, / use spherical planet for gravity model/
  npc(21) = 1, / Calc prop brun/
  npc(25) = 2, / calculate velocity losses/
  npc(27) = 1, / integrate to find prop flow rates/
  npc(30) = 3, / use enhanced weight model (divided into steps)/
c
c *** initial conditions ***
c
  azl = 90, / rotate L coordinates so that Z points due east/
  gdalt = 106943.8, / Initial altitude - feet/
  gdlat = 28.4974, / Initial Position in lat and long/
  long = 279.81888,
  velr = 3225.62307, / Initial Relative Velocity/
  gammar = 44.6427, / Initial relative flight path angle/
  azvelr = 90.6371, / Initial relative velocity aximuth angle/
c
c Use KSC as reference location
c
  latrefgd = 28.5,

```

```

lonref = 279.5,
c
c *** enhanced weight model
c
c
c *** Define Vehicle Steps
c
nstpl = 1, / Lowest Step Number/
nstph = 1, / Highest Step Number/
wstpd(1)= 60701.698, / Step 1 Gross Weight (Booster)/
istepf = 1, / include all steps in calculation of dry weight/
c
c *** guidance inputs ***
c
iguid(1)= 0,0,1,
alppc(1)= 45,
c
c Define Monitor Variables
c
monx(1) = 'dynp', /Dynamic pressure/
mony(1) = 'mach',
monx(2) = 'alpha', /Angle of Attack/
mony(2) = 'mach',
monx(3) = 'heatrt', /Aerodynamic Heating Rate/
mony(3) = 'mach',
monx(4) = 'asmg', /Sensed Accelration/
mony(4) = 'mach',
monx(5) = 'azb', /wing normal force/
mony(5) = 'mach',
monx(6) = 'gdalt', /altitude/
monx(7) = 'mach',
monx(8) = 'bnkang',
monx(9) = 'dynp',
c
maxtim = 1e5, /Maximum time of Flight/
altmax = 1e8, /Maximum Altitude/
altmin = -50000, /Minimum Altitude/
c
c
c *** print block ***
prnt(97)='dynpdt',
'xmin1','xmax1',
'xmin2','xmax2',
'xmin3','xmax3',
'xmin4','xmax4',
'xmin5','xmax5',
'xmin6','xmax6',
'xmin7','xmax7',
'xmin8','xmax8',
'xmin9','xmax9',
'fazb','fayb','faxb',
'azl','dynpdt',
'timrf1','timrf2','timrf3',
'pstop',
dtimr(1) = 1,
$
!$tblmlt tvc1m = 1.0,
$
c include APAS aerodynamic coefficients table
*include 'booster_BD.aero'
!$tblmlt tvc1m = 1.0, $
!$tab endphs = 1, $
c cccccccc Begin Phase 100.000 cccccccccccccccccccc
!$gendat
c Peak of trajectory
c Reset Max Mach Number monitoring for max re-entry mach number
event = 100, critr ='altdot', value =0,
xmax(7) = 0, /Reset Mach number monitoring/
endphs = 1,
$

```

```

c cccccccc Begin Phase 150.000 cccccccccccccccccccc
I$gendat
event = 150, critr='azb', value = -80.4,
ndepvs = 1,
dt = 2,
pinc = 4,
maxits = 10,
iguid(1)= 0,0,1,
depvrs = 'azb',
depvls = -80.4,
depts = 0.1,
indvrs = 'alppc1',
igsai(1)= 0,
perts = 1e-4,
us = 30,
endphs = 1,
$
c cccccccc Begin Phase 300.000 cccccccccccccccccccc
I$gendat
event = 300, critr='asmg', value = 2.5,
mdl = 3,
dt = 5,
pinc = 20,
ndepvs = 0,
dtimr(2) = 1,
xmin(5) = 0,
xmax(1) = 0, /Reset Max q monitoring/
xmax(2) = 0, /Reset Max Alpha monitoring/
iguid(1) = 0,1,0,
iguid(6) = 2,0,2, / Table lookup of alphas and bank/
$
I$tblmlt $
I$tab
table= 'alpha',1,'timrf2',6,1,1,1,
0, 0,
30, 0,
60, 0,
90, 0,
150, 0,
200, 0,
$
I$tab
table= 'bank',1,'timrf2',7,1,1,1,
0, 0, /Initial Bank Angle of 0deg/
10, 0,
30, 0,
60, 0,
90, 0,
150, 0,
200, 0,
endphs = 1, /End of Phase 300/
$
c cccccccc Begin Phase 400.000 cccccccccccccccccccc
c pull out of turn to level flight
c Straight gliding portion begins with bank of 0 and alpha of 10 deg
c pull out lasts 20 seconds
I$gendat
event = 400, critr='azvelr',value = 255,
mdl = 1,
iguid = 0,1,0,
iguid(6) = 3,1,3,
dbank = 0,
dalpha = 10,
endphs = 1,
$
c cccccccc Begin Phase 500.000 cccccccccccccccccccc
I$gendat
event = 500, critr='tdurp',value = 20,
dtimr(3) = 1, /Turn on timer for second pitch table and thrust table/
dt = 5,

```

```
pinc = 30,
iguid(1) = 0,1,0,
iguid(6) = 2,0,2, / Table lookup of alphas and bank/
c start new pitch angle steering table
$
!$tblmlt $
!$tab
table= 'alpha',1,'timrf3',2,1,1,1,
0, 10,
600, 10,
$
!$tab
table= 'bank',1,'timrf3',2,1,1,1,
0, 0,
600, 0,
endpchs = 1,
$
c cccccccc Begin Phase 900.000 cccccccccccccccccccc
!$gendat
event = 900,critr='long',value= 279.5, /Longitude at Launch Site/
endpchs = 1,
$
c cccccccc Begin Phase 1000.000 cccccccccccccccccccc
!$gendat
c this is the final event
event = 1000,critr='tdurp',value= 0.0,
endpchs = 1,
endjob = 1,
endprb = 1,
$
```

Flyback Branch POST Deck

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c Simple 3-D POST glideback trajectory for RTLS booster
c
c Modified for RTLS Study by Barry Hellman
c This file optimizes to minimize time after separation
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c set up optimization inputs
c
!$search
  ioflag = 0,          / english input, english output units/
  opt = 1,            / optimizer should maximize/
  maxitr = 60,        / Maximum number of iterations/
  ipro = -1,          / print only the final, optimized trajectory /
c
c *** optimization variable ***
c
  optvar = 'weight',  / maximize final weight/
  optph = 1000,        / optimize at the end of booster stage/
c
c *** constraint variables ***
c
  ndepv = 3,
  depvr = 'xmin5', 'gdlat', 'xmax2', /names of dependent variables/
  depval = -80.4, 28.50, 50.00, /target values/
  deptl = 1, 0.01, 0.1, /targeting criteria(allowable errors)/
  depvh = 1000, 1000, 1000, /phase where constraint is applied/
  idepvr = -1, 0, 1, /Max(1), Min(-1), or Exact(0) Constraint/
c
c
c *** simulation control variables (u's) ***
c
  nindv = 13,
  tabl = 6*'alphan',6*'bankt',
  tably = 1,2,3,4,5,6, 2,3,4,5,6,7,
  indvr = 'tabl1','tabl2','tabl3','tabl4','tabl5','tabl6',
         'tabl7','tabl8','tabl9','tabl10','tabl11','tabl12',
         'critr',
  indph = 6*300,6*300,400,
c
c *** initial guesses for u's ***
c
c
c
u(1) = 10.0000000,
u(2) = 20.0000000,
u(3) = 20.0000000,
u(4) = 15.0000000,
u(5) = 10.0000000,
u(6) = 10.0000000,
u(7) = 10.0000000,
u(8) = 10.0000000,
u(9) = 10.0000000,
u(10) = 10.0000000,
u(11) = 10.0000000,
u(12) = 10.0000000,
u(13) = 270.0000000,
c
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c Projected Gradient Options
c (comment out this block if using npsol)
c

```



```

srchm = 5,          / use accelerated projected gradient /
c modew = 0,        / use manual weighting for u's /
c wvu = 1e-3,2*2e-2,3e2,5*2e-01,1e-02,
  pert = 6*0.001,6*0.001,0.001,
c conepts = 89.99,0,0,0,0,0, / tighten optimality criteria/
  pctcc = .5,        / limit maximum change in u's for targeting /
  npad(1) = 0,       / ignore requirements on pert precision /
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c NPSOL Options
c (comment out this block if using projected gradient)
c
c srchm = 6,          / use npsol
c depvub = 6.080e5, 0, 10000, 0,
c depvlb = 6.080e5, 0, 0, 0,
c deptl = 100, .005, 2, 1,
c indpub = 1000,0,0,0,0,0,
c indplb = 0,-70,-90,-90,-90,-100,-150,
c wopty = 100,
c wvnlc = 10000,1,10,
c wvu = 100,20,100,100,100,100,100,
c isens = 3,         / automatic pert control from npsol
c isens = 1,         / user selected central differences
c pert = 1e-6,6*1e-7,
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c $
c *** trajectory simulation inputs ***
c ccccccccc Begin Phase 1.000 ccccccccccccccccccccccccccccccccc
!$gendat
  title = 0h*Flyback Branch*,
  event = 1,          / Calculate Keplerian Conics at end of each integration step/
  fesn = 1000,        / final event number/
  npc(1) = 3,
  npc(2) = 1,         / fourth order runge-kutta/
  dt = 5,             / integration step size (in sec)/
c lref = 170.0,       / body length/
  pinc = 20,          / print interval (in sec)/
  prnc = 0,
  npc(3) = 4,         / earth relative velocity components/
  npc(4) = 2,         / geocentric position components/
  npc(5) = 5,         / 1976 standard atmosphere/
  npc(7) = 1,         / limit acceleration using etal /
  asmax = 6,          / asmax is the maximum number of g's allowed/
  npc(8) = 2,         / cl and cd aero inputs/
  sref = 1619.41,     / aero reference area/
  npc(9) = 1,         / assume rocket engine model/
  npc(12) = 1,        / calculate relative downrange and crossrange distances/
  npc(15) = 1,        / calculate heating using Chapman's equation/
  npc(16) = 1,        / use spherical planet for gravity model/
  npc(21) = 1,        / Calc prop brun/
  npc(22) = 2,        / Vary eta using etapc1/
  npc(25) = 2,        / calculate velocity losses/
  npc(27) = 1,        / integrate to find prop flow rates/
  npc(30) = 3,        / use enhanced weight model (divided into steps)/
c
c *** initial conditions***
c
  azl = 90,           / rotate L coordinates so that Z points due east/
  gdalt = 178937.9,   / Initial altitude - feet/
  gdlat = 28.49073,   / Initial Position in lat and long/
  long = 280.4047,
  velr = 6758.72,     / Initial Relative Velocity/
  gammar = 20,        / Initial relative flight path angle/
  azvelr = 90.92126, / Initial relative velocity azimuth angle/
c

```

```

c Use KSC as referenc location
c
latrefgd = 28.50,
lonref = 279.50,
c
c *** enhanced weight model
c
c Define Airbreathing Engine
c
ispv = 3609.5, /Isp of Turbine Engine/
iengmf= 0, /which engines are on/
ienga = 0, /throttle engine according to npc(22)/
iwdf = 2, /calculate flowrate from engine's Vaccum Isp and thrust/
iwpf = 1, /include engine in flowrate calculations/
nengl = 1, /Lowest Engine Number/
nengh = 1, /Highest Engine Number/
c
c Define Vehicle Steps
c
nstpl = 1, / Lowest Step Number/
nstph = 1, / Highest Step Number/
wstpd(1)= 98758.99, / Step 1 Gross Weight (Booster)/
c
menstp = 1, / map each engine to a specific step/
mentnk = 1, / map each engine to a specific tank/
istepf = 1, / include all steps in calculation of dry weight/
c
c
c *** guidance inputs ***
c
iguid(1) = 0,0,1,
alppc(1) = 50,
bnkpc(1) = 0,
c Define Monitor Variables
c
monx(1) = 'dynp', /Dynamic pressure/
mony(1) = 'mach',
monx(2) = 'alpha', /Angle of Attack/
mony(2) = 'mach',
monx(3) = 'heatrt', /Aerodynamic Heating Rate/
mony(3) = 'mach',
monx(4) = 'asmg', /Sensed Acceleration/
mony(4) = 'mach',
monx(5) = 'azb', /wing normal force/
mony(5) = 'mach',
monx(6) = 'gdalt', /altitude/
monx(7) = 'mach',
monx(8) = 'thrust',
monx(9) = 'dynp',
c
maxtim = 1e5, /Maximum time of Flight/
altmax = 1e10, /Maximum Altitude/
altmin = -1000, /Minimum Altitude/
c
c
c *** print block ***
c
prnt(97)='dynpdt',
'xmin1','xmax1',
'xmin2','xmax2',
'xmin3','xmax3',
'xmin4','xmax4',
'xmin5','xmax5',
'xmin6','xmax6',
'xmin7','xmax7',
'xmin8','xmax8',
'xmin9','xmax9',
'fazb','fayb','faxb',
'dynpdt',
'altdot','machdt','gamad',
'timrf1','timrf2','timrf3',

```

```

        'netisp','isp1','ispv1','wprus1',
        'pstop',
dtime(1) = 1,
$
!$tblmlt $
c include APAS aerodynamic coefficients table with base drag
*include 'booster_BD.aero'
c !$tab
c table= 'alpat',1,'timrf1',4,1,1,1,
c 0, 0,
c 200, 0,
c 400, 0,
c 600, 0,
!$tab
endphs = 1, /End of Phase 1/
$
c cccccccc Begin Phase 100.000 cccccccccccccccccccc
!$gendat
c Peak of trajectory
c Reset Max Mach Number monitoring for max re-entry mach number
event = 100, critr ='altdot', value =0,
xmax(7) = 0, /Reset Mach number monitoring/
endphs = 1,
$
c cccccccc Begin Phase 150.000 cccccccccccccccccccc
!$gendat
event = 150, critr ='azb', value = -80.4,
ndepvs = 1,
dt = 1,
pinc = 2,
maxits = 10,
iguid(1)= 0,0,1,
depvrs = 'azb',
depvls = -80.4,
depts = 0.1,
indvrs = 'alppc1',
igsai(1)= 0,
perts = 1e-4,
us = 30,
endphs = 1,
$
c cccccccc Begin Phase 300.000 cccccccccccccccccccc
!$gendat
event = 300, critr ='asmg', value = 2.5,
mdl = 3,
dt = 5,
pinc = 20,
ndepvs = 0,
dtime(2) = 1,
xmin(5) = 0,
xmax(1) = 0, /reset dynp monitoring/
xmax(2) = 0,
iguid(1) = 0,1,0,
iguid(6) = 2,0,2, / Table lookup of alpat and bankt/
$
!$tblmlt $
!$tab
table= 'alpat',1,'timrf2',6,1,1,1,
0, 10,
50, 20,
100, 20,
200, 15,
250, 10,
300, 10,
$
!$tab
table= 'bankt',1,'timrf2',7,1,1,1,
0, 0, /Inital Bank Angle of 0deg/
10, 10,
50, 10,

```

```

100, 10,
200, 10,
250, 10,
300, 10,
endphs = 1, /End of Phase 200/
$
c ccccccc Begin Phase 400.000 ccccccccccccccccccc
c pull out of turn to level flight (lasts 25 seconds)
l$gendat
event = 400, critr= 'azvelr',value = 270,
mdl = 1,
iguid = 0,1,0,
iguid(6) = 3,1,3,
dbank = 0,
dalpha = 10,
endphs = 1,
$
c ccccccc Begin Phase 500.000 ccccccccccccccccccc
l$gendat
event = 500, critr= 'tdurp',value = 25,
dtimr(3) = 1,
dt = 10,
pinc = 10,
iguid(1) = 0,1,0,
iguid(6) = 2,0,2, / Table lookup of alphas and bank/
$
l$tblmlt $
l$tab
table= 'alpha',1,'timrf3',2,1,1,1,
0, 10,
600, 10,
$
l$tab
table= 'bank',1,'timrf3',2,1,1,1,
0, 0,
600, 0,
endphs = 1,
$
c ccccccc Begin Phase 700.000 ccccccccccccccccccc
l$gendat
event = 700,critr='gdalt',value= 16000.0,
npc(22) = 2,
iengmf = 1, /Turn on Airbreathing Engine/
dt = 20,
pinc = 100,
iguid(1)= 0,0,1,
iguid(6)= 0,0,0,
ndepvs = 3,
maxits = 10,
depvrs = 'gamad','velad','azvad',
depvls = 0,0,0,
depts = 0.001,0.0001,0.0001,
dusmax = 1,0.35,0.1,
igsai = 2,0,0,
indvrs = 'alppc1','etapc1','bnkpc1',
perts = 1e-4,1e-4,1e-4,
us = 5,0.5,0,
$
l$tblmlt tvc1m= 1,$
c include APAS aerodynamic coefficients table without base drag
*include 'booster_noBD.aero'
l$tab
c Thrust of Airbreathing Engine
table = 'tvc1t',0, 32664.92,
c endphs = 1,
$
c gamad is a function of altdot
l$tab table='depvls1t',1,'altdot',2,3*1,
-10, 0.1,
10, -0.1,

```

```
endphs = 1,  
$  
c cccccccc Begin Phase 900.000 ccccccccccccccccccc  
l$gendat  
event = 900,critr='long',value= 279.50, /Longitude at Launch Site/  
iengmf = 0,  
ndepvs = 0,  
endphs = 1,  
$  
c cccccccc Begin Phase 1000.000 ccccccccccccccccccc  
l$gendat  
c this is the final event  
event = 1000,critr='tdurp',value= 0.0,  
endphs = 1,  
endjob = 1,  
endprb = 1,  
$
```

Boostback Branch POST Deck

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c Simple 3-D POST boostback trajectory for RTLS booster
c
c Modified for RTLS Study by Barry Hellman
c This file optimizes final weight over the launch site
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c set up optimization inputs
c
l$search
ioflag = 0, / english input, english output units/
opt = 1, / optimizer should maximize/
maxitr = 10, / Maximum number of iterations/
ipro = -1, / print only the final, optimized trajectory/
c
c *** optimization variable ***
c
optvar = 'weight', / maximize final weight/
optph = 900, / optimize at the end of booster stage/
c
c *** constraint variables ***
c
ndepv = 4,
depvr = 'xmin5', 'xmax1', 'gdlat', 'long', 'xmax2', /names of dependent variables/
depval = -80.4, 800.0, 28.50, 279.5, 50.00, /target values/
depth = 1, 70, 0.1, 0.1, 1, /targeting criteria(allowable errors)/
depph = 900, 900, 900, 900, 900, /phase where constraint is applied/
idepvr = -1, 1, 0, 1, 1, /Max(1), Min(-1), or Exact(0) Constraint/
c
c
c *** simulation control variables (u's) ***
c
nindv = 12,
tabl = 5*'alphan',5*'bankt',
tably = 1,2,3,4,5,1,2,3,4,5,
indvr = 'tabl1','tabl2','tabl3','tabl4','tabl5',
'tabl6','tabl7','tabl8','tabl9','tabl10',
'critr','dpitch',
indph = 5*451,5*451,400,200,
c
c *** initial guesses for u's ***
c
c
u(1) = 10.3050294,
u(2) = 6.0347148,
u(3) = 9.0950628,
u(4) = 9.5665349,
u(5) = 9.6824041,
u(6) = 8.2438597,
u(7) = 5.0624181,
u(8) = 2.1679668,
u(9) = 0.0132919,
u(10) = 0.0044566,
u(11) = -1000.3640390,
u(12) = 90,
c
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c Projected Gradient Options
c (comment out this block if using npsol)
c
srchm = 5, / use accelerated projected gradient /
modew = 0, / use manual weighting for u's /

```

```

c wvu = 1e-3,2*2e-2,3e2,5*2e-01,1e-02,
pert = 5*0.0001,5*0.0001,0.0001,0.001,
coneps = 89.99,0,0,0,0, / tighten optimality criteria/
pctcc = 0.1, / limit maximum change in u's for targeting /
npad(1) = 0, / ignore requirements on pert precision /
c wopt = 0.00001,
IDEB = 0,
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c NPSOL Options
c (comment out this block if using projected gradient)
c
c srchm = 6, / use npsol
c depvub = 6.080e5, 0, 10000, 0,
c depvlb = 6.080e5, 0, 0, 0,
c deptl = 100, .005, 2, 1,
c indpub = 1000,0,0,0,0,0,
c indplb = 0,-70,-90,-90,-90,-100,-150,
c wopt = 100,
c wvnlc = 10000,1,10,
c wvu = 100,20,100,100,100,100,100,
c isens = 3, / automatic pert control from npsol
c isens = 1, / user selected central differences
c pert = 1e-6,6*1e-7,
c
c ccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c
c
c
c
c $
c *** trajectory simulation inputs ***
c ccccccccc Begin Phase 1.000 ccccccccccccccccccccc
!$gendat
title = 0h*Boostback Branch*,
event = 1, / Calculate Keplerian Conics at end of each integration step/
fesn = 900, / final event number/
npc(1) = 3,
npc(2) = 1, / fourth order runge-kutta/
dt = 1, / integration step size (in sec)/
pinc = 5, / print interval (in sec)/
prnc = 0,
npc(3) = 4, / earth relative velocity components/
npc(4) = 2, / geocentric position components/
npc(5) = 5, / 1976 standard atmosphere/
npc(7) = 1, / limit acceleration using etal /
asmax = 6.0, / asmax is the maximum number of g's allowed/
npc(8) = 2, / cl and cd aero inputs/
sref = 1588, / aero reference area/
npc(9) = 1, / assume rocket engine model/
npc(12) = 1, / calculate relative downrange and crossrange distances/
npc(15) = 1, / calculate heating using Chapman's equation/
npc(16) = 1, / use spherical planet for gravity model/
npc(21) = 1, / Calc prop brun/
npc(25) = 2, / calculate velocity losses/
npc(27) = 1, / integrate to find prop flow rates/
npc(30) = 3, / use enhanced weight model (divided into steps)/
c
c F frame origin
c
altf = 20,
gdlatf = 28.5,
longf = 279.5,
irngsf = 1, /Calculate the F frame/
c
c *** initial conditions***
c
azl = 90, / rotate L coordinates so that Z points due east/
gdalt = 172224.4, / Initial altitude - feet/
gdlat = 28.49348, / Initial Position in lat and long/

```

```

long = 280.184,
velr = 5593.984, / Initial Relative Velocity/
gammar = 30.992, / Initial relative flight path angle/
azvelr = 90.81667, / Initial relative velocity aximuth angle/
c
c Use KSC as referenc location
c
latrefgd = 28.50,
lonref = 279.50,
c
c *** enhanced weight model
c
c Define Airbreathing Engine
c
ispv = 326.7, /Isp of Turbine Engine/
iengmf= 0, /which engines are on/
ienga = 1, /throttle engine according to npc(22)/
iwdf = 2, /calculate flowrate from engine's Vaccum Isp and thrust/
iwpf = 1, /include engine in flowrate calculations/
nengl = 1, /Lowest Engine Number/
nengh = 1, /Highest Engine Number/
c
c Define Vehicle Steps
c
nstpl = 1, / Lowest Step Number/
nstph = 1, / Highest Step Number/
wstpd(1)= 109946.3, / Step 1 Gross Weight (Booster)/
c
menstp = 1, / map each engine to a specific step/
mentnk = 1, / map each engine to a specific tank/
istepf = 1, / include all steps in calculation of dry weight/
c
c
c *** guidance inputs ***
c Piecewise Linear Steering Using dalpha
iguid(1) = 0,1,
iguid(6) = 3,3,3, / Table lookup of alphas and bank/
dalpha = 180,
c bnkpc(1) = 180,
c dbank = 180,
c dbeta = 180,
c
c Define Monitor Variables
c
monx(1) = 'dynp', /Dynamic pressure/
mony(1) = 'mach',
monx(2) = 'alpha', /Angle of Attack/
mony(2) = 'mach',
monx(3) = 'heatrt', /Aerodynamic Heating Rate/
mony(3) = 'mach',
monx(4) = 'asmg', /Sensed Accelration/
mony(4) = 'mach',
monx(5) = 'azb', /wing normal force/
mony(5) = 'mach',
monx(6) = 'gdalt', /altitude/
monx(7) = 'mach', /Mach number/
monx(8) = 'thrust', /Thrust/
monx(9) = 'dprng1',
monx(10) = 'bnkang',
c
maxtim = 10000, /Maximum time of Flight/
altmax = 1e10, /Maximum Altitude/
altmin = 0, /Minimum Altitude/
c
c
c
c *** print block ***
prnt(97)='dynpdt',
'xmin1',xmax1',
'xmin2',xmax2',

```



```

    'xmin3','xmax3',
    'xmin4','xmax4',
    'xmin5','xmax5',
    'xmin6','xmax6',
    'xmax7','xmax8','xmin8','xmax10','xmin10',
    'altdot','machdt',
    'timrf1','timrf2','timrf3',
    'rgenv',
    'netisp','isp1','ispv1','wprus1','velad',
    'xmax9','genv1','genv2','dgenv','rgenv',
    'vxf','vyf','vzf','xf','yf','zf','dlong',
    'alpha','beta','banki','dprng1',
    'pstop',
$
!$tblmt $
c include APAS aerodynamic coefficients table with base drag
*include 'booster_BD.aero'
!$tab
c Thrust of Engine
table = 'tvc1t',0, 403751,
$
!$tab
table ='genv2t',1,'xmax9',2,1,1,1,
0, 0,
100, 100,
$
!$tab
table ='genv1t',1,'dprng1',2,1,1,1,
0, 0,
100, 100,
$
!$tab
table = 'ae1t',0, 5.1,
endphs = 1,
$
c cccccccc Begin Phase 200.000 cccccccccccccccccccc
!$gendat
c Turn on Engine
event = 200, critr ='tdurp', value = 15,
dt = 1,
pinc = 5,
iengmf = 1,
dtimr(1) = 1,
iguid(1) = 1,0,
iguid(4) = 3,
dpitch = 60,
c iguid(11)= 0, /roli is set to present value/
endphs = 1, /End of Phase 200/
$
c cccccccc Begin Phase 300.000 cccccccccccccccccccc
!$gendat
event = 300, critr ='tdurp', value = 15,
iguid(1) = 1,0,0,
endphs = 1, /End of Phase 300/
$
c cccccccc Begin Phase 400.000 cccccccccccccccccccc
!$gendat
event = 400, critr= 'vxf',value = 0,
mdl = 1,
pinc = 5,
xmax(7) = 0, /Reset max mach number monitoring to zero/
iengmf = 0, /Turn engine off/
iguid(1) = 0,0,
iguid(3) = 3,
dalpha = 40,
$
!$tblmt $
!$tab
table ='genv2t',1,'fazb',2,1,1,1,
0, 0,

```

```

100, 100,
$
l$tab
table ='genvt',1,'weight',2,1,1,1,
0, 0,
100, 100,
endphs = 1,
$
c cccccccc Begin Phase 430.000 cccccccccccccccccccc
l$gendat
event = 430, critr= 'tdurp',value = 15,
iguid(1) = 0,0,
iguid(3) = 0,
pinc = 4,
mdl = 1,
endphs = 1,
$
c cccccccc Begin Phase 450.000 cccccccccccccccccccc
l$gendat
event = 450,0, critr= 'azb',value = -80.4,
mdl = 1,
ndepvs = 1,
dt = 1,
pinc = 4,
maxits = 10,
iguid(1)= 0,0,1,
c bnkpc(1)= 0,
depvrs = 'azb',
depvls = -80.4,
depts = 0.1,
indvrs = 'alppc1',
igsai(1)= 0,0
perts = 1e-4,
us = 20,
endphs = 1,
$
c cccccccc Begin Phase 500.000 cccccccccccccccccccc
c Bring vehicle out of controlled accel steering when overall accel goes back to acceleration steering
l$gendat
event = 451,0, critr= 'altdot',value =2.5,
mdl = 3, /Derivative must negative/
ndepvs = 0,
dt = 1,
pinc = 20,
iengmf = 0,
dtimr(2) = 1,
c xmin(5) = 0, /Reset min azb to zero/
c xmax(2) = 0, /Reset Max alpha monitoring to zero/
iguid(1) = 0,1,0,
iguid(6) = 2,0,2, / Table lookup of alphas and bank/
$
l$tblmlt $

l$tab
table= 'alphat',1,'timrf2',5,1,1,1,
5, 0,
20, 0,
50, 0,
100, 0,
400, 0,
$
l$tab
table= 'bankt',1,'timrf2',5,1,1,1,
5, 0,
20, 0,
50, 0,
100, 0,
400, 0,
endphs = 1, /End of Phase 500/
$

```

```
c cccccccc Begin Phase 500.100 ccccccccccccccccccc
!$gendat
event = 452,0, critr='tdurp',value = 1,
mdl = 1,
dt = 5,
xmin(5) = 0, /Reset min azb to zero/
xmax(2) = 0, /Reset Max alpha monitoring to zero/
c xmax(1) = 0, /Reset max dynp to zero/
endphs = 1,
$
c cccccccc Begin Phase 900.000 ccccccccccccccccccc
!$gendat
event = 900,0,citr='gdalt',value= 15000,
mdl = 9, /End Simulation if altitude is less than or equal to critr value/
endjob = 1,
endprb = 1,
endphs = 1, /End of Phase 900/
$
```