TRAJECTORY ANALYSIS FOR THE HY-V SCRAMJET FLIGHT EXPERIMENT AND THE EFFECTS OF A RECOVERY SYSTEM

Amanda I. Smith
University of Virginia, Charlottesville, Virginia 22904
Dr. Christopher P. Goyne, Advisor

With the retirement of the space shuttle near and rising fuel prices driving a demand for more efficient travel, alternative engine technology is being heavily researched. The scramjet, or supersonic combustion ramjet, has proven to be a promising development in reusable hypersonic transportation. Flight testing these engines, however, is very expensive and no scramjet flight has yet been recovered in reusable condition. To decrease costs, ground testing and simulations are being conducted to better model scramjet flight characteristics. In this project, NASA Wallops’ GEM software was used to simulate the trajectory of a scramjet flight experiment and analyze the effects of varying flight parameters on the trajectory to increase accuracy of ground simulations. Sensitivity of the trajectory to each input parameter was noted so corrections could be applied in flight tests to achieve desired flight conditions. Integration of a recovery system was included in the simulation and potential landing sites were found.

I. INTRODUCTION

A scramjet, or supersonic combustion ramjet, is a type of air-breathing jet engine that, unlike conventional jet engines, has no moving parts and relies solely on the forward velocity of the vehicle to compress the incoming air. Operating in the hypersonic regime of Mach 5 (3,800 mph at sea level) and above, scramjets are unique because the airflow through the combustion chamber remains at supersonic Mach numbers. However, these engines produce no static thrust and therefore require a separate propulsion system to accelerate the vehicle to the appropriate operating speed. Scramjets could be used in high-speed civil transport, reducing travel time and cost; in military reconnaissance and strike aircraft, increasing the mobility of the armed forces; and as a new and safer means to access space (NASA Dryden Fact Sheet). Because flight testing these engines is expensive, few tests have been performed and no test scramjets have been recovered. On the ground, wind tunnel testing is used to match flight conditions, and computer simulations have been developed to provide trajectory data; however, more accurate simulation tools for the evaluation of scramjet design are needed.

At the Aerospace Research Laboratory (ARL) of the University of Virginia, researchers in the Hy-V (pronounced “high-five”) Program are conducting ground tests for a scramjet that will be launched on a Terrier Improved-Orion sounding rocket from NASA Wallops Flight Facility in 2009. Hy-V is a research project involving member universities of the Virginia Space Grant Consortium. “Hy” is short for hypersonic, and “V,” as the Roman numeral, represents the Mach number of five and the five universities collaborating on the project, and as a letter refers to the Commonwealth of Virginia (Goyne). In this thesis project, I analyzed the effects of flight variables including weight, flight path angle, and interstage delay, or the time before the second rocket motor stage (Orion) fires. I attempted to determine the optimal trajectory to reach the desired conditions for the Hy-V experiment; steady Mach number of 5, low dynamic pressure, and a steady altitude over the test range. An optimal test time was calculated using the aforementioned conditions. A mission profile of the experiment is provided in Figure 1. The results need to be compared to wind tunnel data and ultimately verified by flight data to provide an accurate comparison between ground and flight tests.

![Hy-V Mission Profile](image)

Figure 1. Hy-V Mission Profile, showing individual stages in the experiment (Goyne).

No scramjet has yet been recovered after flight testing. In a reusable vehicle, scramjets must be
recovered. The weight was adjusted to accommodate for the various recovery systems currently being researched by other members of the Hy-V team. The recovery options are assessed on their ability to slow the scramjet to subsonic speeds before crashing into the ocean. The resulting trajectory indicated landing sites. These sites were evaluated in their feasibility and compliance with NASA Wallops safety standards. In this research, the Hy-V team would like to become the first to recover a scramjet intact and inspect its condition after the test.

II. TRAJECTORY ANALYSIS

SELECTION OF SOFTWARE

To best analyze the Hy-V trajectory, software must be able to match the intended flight conditions. Accurate prediction of a moving body’s trajectory is based on specified flight conditions, including wind speed, geographical location of launch, launch angle, and payload weight. By iteratively solving the equations of motion for a dynamic body, trajectory software can predict where the body will land. Common rocket trajectory software includes RockSim, RockSim Pro, Trajectory Analysis and Optimization System (TaOS), the Program to Optimize Simulated Trajectories (POST), and GEM from NASA Wallops.

RockSim is distributed by Apogee Components and primarily used for their model rockets. It is a 3-degree-of-freedom solver. This assumes that the rocket has some built-in control system and therefore no angular acceleration, or, alternatively, is always in a trimmed condition. The maximum altitude and velocity that can be achieved are 86 kilometers and Mach 2, respectively. RockSim Pro is also by Apogee Components, but is a 6-degree-of-freedom solver. This considers the rocket’s angular orientation and rate. RockSim Pro shows all potential impact points with a level of confidence. There is a maximum altitude and velocity of 632 kilometers and Mach 10, respectively (RS-PRO).

TaOS was written by Sandia National Laboratories and is a 3-degree-of-freedom solver. It is a point-mass simulation that can be calculated much faster and requires less information about the vehicle than a 6-degree-of-freedom simulation, therefore making it ideal for conceptual design, mission planning, and vehicle performance analysis. In solving, the trajectory is broken into segments, and guidance rules control how it is computed. This software is used for high-speed vehicles at hypersonic velocities and high altitudes. However, it is poor for trajectories with large angular accelerations (Salguero).

POST was written for the space shuttle program by NASA and Lockheed Martin. This program mixes 3 and 6 degrees of freedom to simulate multiple bodies simultaneously. It includes gravity, propulsion, guidance, control, sensor, and navigation systems models; the user can define the atmosphere, planet, and vehicle that is being analyzed. There are also various flight regimes, such as entry, launch, and rendezvous (United States).

GEM, originally GE MASS, is used for NASA Wallops’ sounding rocket missions. It has 6- and 3-degree-of-freedom subprograms and was designed to solve trajectories for missiles and satellites (Simko). For this thesis project, I have chosen to use this software because it is most applicable to the Hy-V program. GEM has been used with NASA Wallops’ sounding rocket missions since the 1980s (Simko). It employs a 6-degree-of-freedom solver, providing the position and velocity of the center of mass as well as the angular orientation and rate of the rocket, and it is easier to obtain than the other software options.

METHOD

Familiarity with Software

NASA Wallops’ GEM software was used to model the trajectory of the scramjet flight experiment. GEM is used for all of the sounding rocket missions that launch from Wallops Island. I received instruction for several weeks via telephone by Mark Simko of NASA Wallops, a sounding rocket researcher and the primary user of this software. Mr. Simko talked me through a PowerPoint presentation (Simko) to illustrate how to change select input variables including weight, flight path angle, and azimuth angle. When the code runs, it solves the equations of motion for a moving body, producing the trajectory results. There are 700 indices that are input to GEM and the results are output as a column matrix of data, with each column holding data for the flight variables (Appendix A). I was only allowed to change up to seven of these indices. The software uses table control cards to easily locate the input data for a particular phase of the trajectory. Certain indices cannot be changed or the program will not run. Simko also explained the output data file extensions so that I could save the data. The software had several output formats, including data lists and graphs of individual variables.

Input Variables and Compilation of Data

I chose three parameters as initial variables: weight, flight path angle, and interstage delay time or the time between Terrier burnout and the Orion ignition. Each had a predetermined optimized value, provided by Simko, during initial trajectory simulation. I refer to this as the standard. When I used GEM, this standard file was loaded first, which included details about the stages of the trajectory and aerodynamic coefficients for the given rocket body. Each variable was tested separately. Weight was varied in increments.
of 25 from 450 to 700 pounds, including the standard input of 500 pounds. I ran the code for each weight variable and then returned this value to the standard. Next, I changed the flight path angle in increments of 5 degrees, 10 degrees above and below the standard of 51.5 degrees. After I ran the code for each flight path angle and returned it to the standard value, the interstage delay time was varied from 39 to 41.5 seconds in increments of 0.5, with 40 seconds as the standard value. The column matrix data set for each variable change were saved.

I then created a Matlab program that generated plots of altitude vs. time and Mach number vs. time. This program read in the column data matrix from GEM for each run (when the variable was changed), chose the correct column of data to display, and combined the results into one plot to easily compare all variable changes for each flight variable to the standard data set. I used Matlab, developed by MathWorks, because it can read multiple file types and compile large data sets quickly. For all variables analyzed, a spreadsheet of the maximum altitude and most constant Mach number at that altitude was developed. An estimation of the duration of constant Mach number was also recorded (Appendix A).

Further Analysis
The FASTT experiment in 2005 demonstrated the importance of correct trajectory analysis to match ground testing predictions with in-flight results. The test vehicle did not reach desired flight conditions due to a launch angle error. In post-flight performance analysis, researchers concluded that the launch angle was overcorrected to compensate for the winds; therefore, the desired altitude for testing was not reached (Foelsche). The researchers reported the corrections to achieve the desired flight conditions were to raise the launch angle by 4.5 degrees and lengthen the interstage delay time by 6 seconds. These corrections were implemented in my trajectory analysis and their effects evaluated. Plots of altitude versus time and Mach number versus time were generated in my Matlab program and compared with the plot of the standard trajectory.

Landing Sites
Landing sites were evaluated with the range data output by GEM for all variable changes. Weight, flight path angle, and coast time changes were each marked on a map of the Maryland, Virginia, and North Carolina coast using the standard launch azimuth of 107 degrees (Appendix B).

III. RESULTS
The optimal trajectory for the Hy-V project has a steady Mach number of 5 and constant altitude so there is minimal pressure change throughout the experiment. Several parameters were varied to evaluate their effects on the trajectory for the Hy-V project, including payload weight, flight path angle, and the time between the Terrier burnout and the Orion motor ignition, or the coast phase.

Payload Weight
Payload weight was varied according to the weight of the potential recovery systems. This weight was added to the initial weight of the rocket as payload. The trajectory analysis showed that the maximum altitude decreased by 5 percent for every 25 pound increase in weight (Figure 2). The time over which the Mach number was constant decreased 2-3 seconds with each 50 pound weight increase (Figure 3). The bold line in all figures represents the standard trajectory model provided by Mark Simko.

![Figure 2. Altitude versus time with varying payload weight.](image2)

![Figure 3. Mach number versus time with varying payload weight.](image3)
**Flight Path Angle**

The flight path angle can vary a lot, especially during the launch phase. This angle can be changed by the launcher when the rocket slides off the launch rail, known as rail tip-off angle, and a correction for this must be included in trajectory analysis. Slight fluctuations can cause the rocket to fail to reach testing conditions, which occurred in the FASTT experiment (Foelsche). In this project’s simulations, very slight changes to the flight path angle caused the maximum altitude to change significantly. When the flight path angle was increased by 5 degrees, the maximum altitude rose 15 kilometers (Figure 4). The Mach number had significant variations as well. When the angle was decreased, the Mach number was held constant for no longer than 10 seconds (Figure 5).

![Figure 4. Altitude versus time with varying flight path angle.](image1)

![Figure 5. Mach number versus time with varying flight path angle.](image2)

**FASTT Corrections**

The correction for induced rail tip-off angle to increase the launch rail by +4.5 degrees and to lengthen the interstage delay time by +6 seconds given in the FASTT experiment was implemented and compared with the standard trajectory model (Figures 6 and 7). This small change adjusted the maximum altitude reached in flight by 3 kilometers and the Mach number reached a higher peak but did not stay constant as long as the standard trajectory.

![Effects of FASTT Adjustments: +4.5 deg launch angle, +6sec on interstage coast.](image3)

**Time to Orion Ignition**

This variable changed the interstage delay in the trajectory, occurring between the Terrier motor burnout and the Orion stage ignition (stage 2 and 3 in the Hy-V mission profile, Figure 1). During this time, the Mach number drops from 3 to 1.6. After coast, the Orion motor is ignited, sending the rocket to maximum altitude and maximum Mach number. The experiment is conducted when the Mach number levels to a constant at the maximum altitude. The trajectory analysis showed that increasing the interstage delay time decreased the maximum altitude by 3 kilometers (Figure 8). The increased delay time decreased the length of time that the Mach number was held constant by 2 seconds (Figure 9).

![Effects of FASTT Adjustments: +4.5 deg launch angle, +6sec on interstage coast.](image4)

![Figure 6. Altitude versus time with FASTT corrections.](image5)

![Figure 7. Mach number versus time with FASTT corrections.](image6)

![Figure 8. Time to Orion Ignition.](image7)
IV. RECOVERY LOCATION

To assess the feasibility of a recovery system, landing sites were evaluated (Appendix B). A standard launch azimuth for NASA Wallops of 107 degrees was used. With 450 pounds of payload weight, the rocket had a maximum range of 143 miles off of the coast. The standard weight of 500 pounds reached 134 miles off of the coast. The varying flight path angle produced a distance off of the coast of 210 miles at 61.5 degrees and 57 miles at 41.5 degrees. The interstage delay variation produced a maximum range of 137 miles and a minimum of 130 miles off of the coast at 39 and 41.5 seconds respectively.

V. CONCLUSIONS AND RECOMMENDATIONS

The sensitivity of the trajectory to the input parameters was shown, allowing more accurate corrections to be applied to a flight test so desired flight conditions can be achieved. A specific recovery system was intended to be included into the trajectory simulation. Additional software, however, was needed, and it could not be obtained for this project.

The next step in this project is to find how long the experiment can be conducted given the trajectory requirements of constant altitude and a steady mach number of five. Further sensitivity analysis can be performed by varying other parameters to evaluate how the trajectory is affected. The appropriate software to integrate a recovery system needs to be obtained so that when a specific recovery system is chosen, the trajectory can be re-evaluated and integrated with the GEM program. This extended analysis will make ground simulations more accurate for scramjet flight tests.
Acknowledgements

This research is funded by the Virginia Space Grant Consortium through its undergraduate research grant program. The author would like to thank Dr. Christopher P. Goyne of the University of Virginia for serving as an advisor to this research. Gratitude is also extended to Mark Simko of the NASA Wallops Flight Facility for providing instruction for the GEM software and continually answering the author’s unending questions.

References

Appendix A

### Altitude and Mach number for Hy-V Experiment with Variable Flight Parameters

<table>
<thead>
<tr>
<th>Varied Flight Parameters</th>
<th>Altitude (km)</th>
<th>Altitude (ft)</th>
<th>Mach Number</th>
<th>sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>29.5</td>
<td>96500</td>
<td>5.3</td>
<td>100-122</td>
</tr>
<tr>
<td>475</td>
<td>28.7</td>
<td>93900</td>
<td>5.25</td>
<td>95-122</td>
</tr>
<tr>
<td>500</td>
<td>28</td>
<td>92000</td>
<td>5.16</td>
<td>96-122</td>
</tr>
<tr>
<td>525</td>
<td>27.3</td>
<td>89900</td>
<td>5.08</td>
<td>97-125</td>
</tr>
<tr>
<td>550</td>
<td>26.8</td>
<td>87700</td>
<td>5.01</td>
<td>97-130</td>
</tr>
<tr>
<td>575</td>
<td>26</td>
<td>85800</td>
<td>4.94</td>
<td>97-129</td>
</tr>
<tr>
<td>600</td>
<td>25.6</td>
<td>84000</td>
<td>4.84</td>
<td>100-128</td>
</tr>
<tr>
<td>625</td>
<td>25</td>
<td>82000</td>
<td>4.77</td>
<td>95-125</td>
</tr>
<tr>
<td>650</td>
<td>24.6</td>
<td>80700</td>
<td>4.7</td>
<td>90-122</td>
</tr>
<tr>
<td>675</td>
<td>24</td>
<td>78800</td>
<td>4.62</td>
<td>90-122</td>
</tr>
<tr>
<td>700</td>
<td>23.5</td>
<td>77000</td>
<td>4.57</td>
<td>90-122</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flight Path Angle (degrees)</th>
<th>Altitude (km)</th>
<th>Altitude (ft)</th>
<th>Mach Number</th>
<th>sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.5</td>
<td>11.38</td>
<td>37000</td>
<td>not constant</td>
<td></td>
</tr>
<tr>
<td>46.5</td>
<td>16.79</td>
<td>55000</td>
<td>not constant</td>
<td></td>
</tr>
<tr>
<td>51.5</td>
<td>28</td>
<td>92000</td>
<td>5.14</td>
<td>95-122</td>
</tr>
<tr>
<td>56.5</td>
<td>45.87</td>
<td>150000</td>
<td>4.7</td>
<td>120-145</td>
</tr>
<tr>
<td>61.5</td>
<td>69</td>
<td>227000</td>
<td>4.94</td>
<td>125-175</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coast time (time before Orion ignition) (sec)</th>
<th>Altitude (km)</th>
<th>Altitude (ft)</th>
<th>Mach Number</th>
<th>sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>28.35</td>
<td>92800</td>
<td>5.19</td>
<td>100-120</td>
</tr>
<tr>
<td>39.5</td>
<td>28</td>
<td>92400</td>
<td>5.17</td>
<td>100-115</td>
</tr>
<tr>
<td>40</td>
<td>28</td>
<td>92000</td>
<td>5.19</td>
<td>90-125</td>
</tr>
<tr>
<td>40.5</td>
<td>27.8</td>
<td>91000</td>
<td>5.16</td>
<td>90-125</td>
</tr>
<tr>
<td>41</td>
<td>27.6</td>
<td>90600</td>
<td>5.1</td>
<td>95-123</td>
</tr>
<tr>
<td>41.5</td>
<td>27.5</td>
<td>90000</td>
<td>5.1</td>
<td>93-125</td>
</tr>
</tbody>
</table>

Figure A. Spreadsheet of manipulated variables with maximum altitude reached, Mach number at that altitude, and how long this Mach number was held constant.
Appendix B

Landing Sites

Figure B1. Landing sites with weight variation. Weights of 450 and 700 pounds are displayed, where the boxed marker is the standard trajectory.

Figure B2. Landing sites with flight path angle variation. The boxed marker is the standard trajectory.
Figure B3. Landing sites with coast time variation.
Times of 39 and 41.5 seconds are displayed, where the boxed marker is the standard trajectory.