StarBooster Demonstrator Cluster Configuration Analysis/Verification Program

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by

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HIGH POWER ROCKET CLUSTER SEPARATION TESTING

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In order to study the flight dynamics of the cluster configuration of two first stage boosters and upper-stage, flight-testing of subsonic sub-scale models has been undertaken using two glideback boosters launched on a center upper-stage. Three high power rockets clustered together were built and flown to demonstrate vertical launch, separation and horizontal recovery of the boosters. Although the boosters fly to conventional aircraft landing, the centerstage comes down separately under its own parachute. The goal of the project has been to collect data during separation and flight for comparison with a six degree of freedom simulation.

The configuration for the delta wing canard boosters comes from a design by Starcraft Boosters, Inc. The subscale rockets were constructed of foam covered in carbon or fiberglass and were launched with commercially available solid rocket motors. The first set of boosters built were 3-ft tall with a 4-ft tall centerstage, and two additional sets of boosters were made that were each over 5-ft tall with a 7.5 ft centerstage. Figure 1 shows the flight profile of the cluster system. The rocket cluster is launched vertically, then after motor burn out the boosters are separated and flown to a horizontal landing under radio-control. An on-board data acquisition system recorded data during both the launch and glide phases of flight.

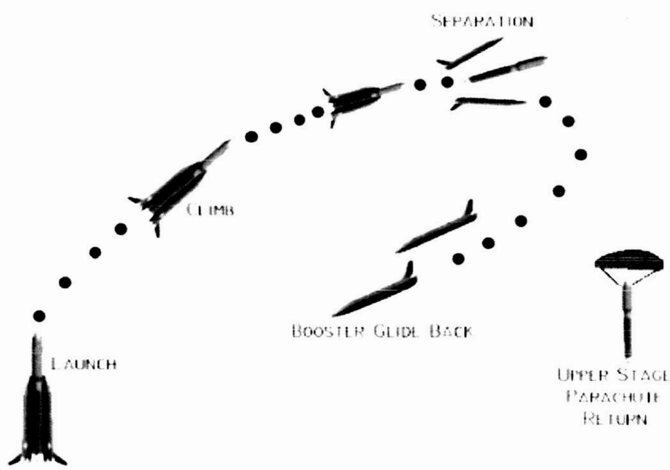

Figure 1 – Cluster Flight Profile

DATA ACQUISITION

In order to complete an aerodynamic analysis, booster flight data had to be measured and stored to an on-board data acquisition system for comparison with simulation results after flight. Figure 2 shows a schematic diagram of the complete onboard data acquisition system. The most critical flight data comes from inertial sensors, which includes accelerometers and rate gyros that measure three-axis acceleration and angular rate. A GPS receiver measured the position of the vehicle. A magnetometer was used to detect the pitch and roll attitude and differential pressure transducers measured both static and total pressure. Angle of attack, side-slip angle and control surface deflections were measured with potentiometers. These measured data were stored either in an onboard flash memory, or transmitted to the ground by telemetry system. To date, all of these devices have been implemented and tested in at least one of three actual flights using two separate data systems. The complete data collection package in both boosters has not yet been tested.

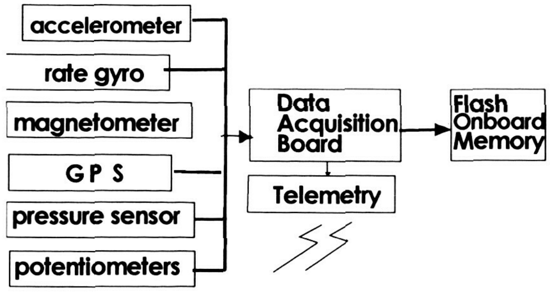

Figure 2 – Data Acquisition System

BOOSTER SIMULATION MODELING

To analyze the flight characteristics of the StarBooster™ demonstrator, a six degree of freedom simulation model was developed. The models used in the simulation include the equations of motion, aerodynamics, thrust and inertial characteristics, as well as a constraint force model.

NOMENCLATURE

U, V, W : Body-axes components of vehicle's velocity relative to the ground

P, Q, R : Body-axes components of vehicle's angular velocity relative to the ground

q_1, q_2, q_3, q_4: Quaternion between Body-axes and Ground-fixed-axes

X, Y, Z : vehicle position on Ground-fixed-axes

F_x, F_y, F_z : Body-axes components of external force acting on the vehicle, including gravitational force

T_x, T_y, T_z : Body-axes components of external moment acting on the vehicle

m : mass of the vehicle

J_* : inertial moments and products

MOTION EQUATIONS

The equations of motion were based on the flat-earth approximation. To avoid the singularity around pitch angle of 90 degree, quaternion is used to represent the attitude. The first vector equations are the translational motion equations for the center of mass. The second set of vector equations describes the rotational motion of a rigid body around the center of mass. The third and fourth equations express the relationship between velocity and position change, angular velocity and attitude change, respectively. The matrix in the right hand side of the third equation corresponds to the transformation matrix between the two coordinate systems.

$$\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} = \frac{1}{m}\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} - \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \times \begin{bmatrix} U \\ V \\ W \end{bmatrix} \quad \begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} = \begin{bmatrix} J_{xx} & -J_{xy} & -J_{xz} \\ -J_{xy} & J_{yy} & -J_{yz} \\ -J_{xz} & -J_{yz} & J_{zz} \end{bmatrix}^{-1} \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}$$

$$
-\begin{bmatrix} J_{xx} & -J_{xy} & -J_{xz} \\ -J_{xy} & J_{yy} & -J_{yz} \\ -J_{xz} & -J_{yz} & J_{zz} \end{bmatrix}^{-1} \left(\begin{bmatrix} P \\ Q \\ R \end{bmatrix} \times \begin{bmatrix} J_{xx} & -J_{xy} & -J_{xz} \\ -J_{xy} & J_{yy} & -J_{yz} \\ -J_{xz} & -J_{yz} & J_{zz} \end{bmatrix} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \right)
$$

$$
\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} 1-2(q_2^2+q_3^2) & 2(q_1q_2+q_3q_4) & 2(q_1q_3-q_2q_4) \\ 2(q_1q_2-q_3q_4) & 1-2(q_1^2+q_3^2) & 2(q_2q_3+q_1q_4) \\ 2(q_1q_3+q_2q_4) & 2(q_2q_3-q_1q_4) & 1-2(q_1^2+q_2^2) \end{bmatrix} \begin{bmatrix} U \\ V \\ W \end{bmatrix}
$$

$$
\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix} \begin{bmatrix} P \\ Q \\ R \end{bmatrix}
$$

BOOSTER AND CENTERSTAGE MODELS

Aerodynamic coefficients of the boosters were estimated with Digital DATCOM by inputting geometric dimensions of the 5-ft booster. Figure 3 shows the geometric aspects of the vehicle. Estimations were executed parametrically with respect to Mach number and angle of attack, then the tabulated data were used to generate the aerodynamic interpolation subroutines. Figure 4 shows example plots of the resulting estimated aerodynamic data. Estimates were made for three Mach numbers (0.2,0.4,0.6), however the differences between them were not significant.

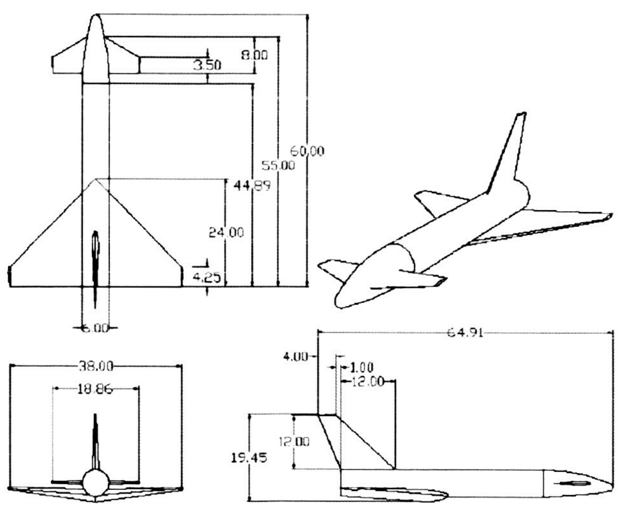

Figure 3– Geometry of Booster (in inches)

In addition, an inertial characteristics model for the boosters was constructed based on actual measurement. The resulting inertial moments and products are summarized in Table 1. Results are reasonable for the highly swept delta wing canard configuration. The low I_{xx} explains why the boosters are sensitive to roll. Inertial characteristics for the centerstage were estimated from 3-D CAD data and are also included in Table 1. For simplicity, uniform density was assumed. The results are necessarily similar to a simple cylinder and the CAD estimation is more than adequate for the centerstage which is only used for vertical flight.

Table 1 – Booster and Centerstage Inertial Characteristics Model

	Booster	Centerstage
mass	4.55 [kg]	11.25 [kg]
I_{xx}	0.07 [kg m^2]	0.03 [kg m^2]
I_{xz}	-0.01 [kg m^2]	0.00 [kg m^2]
I_{zz}	0.99 [kg m^2]	3.90 [kgm^2]
I_{yy}	0.94 [kg m^2]	3.90 [kgm^2]

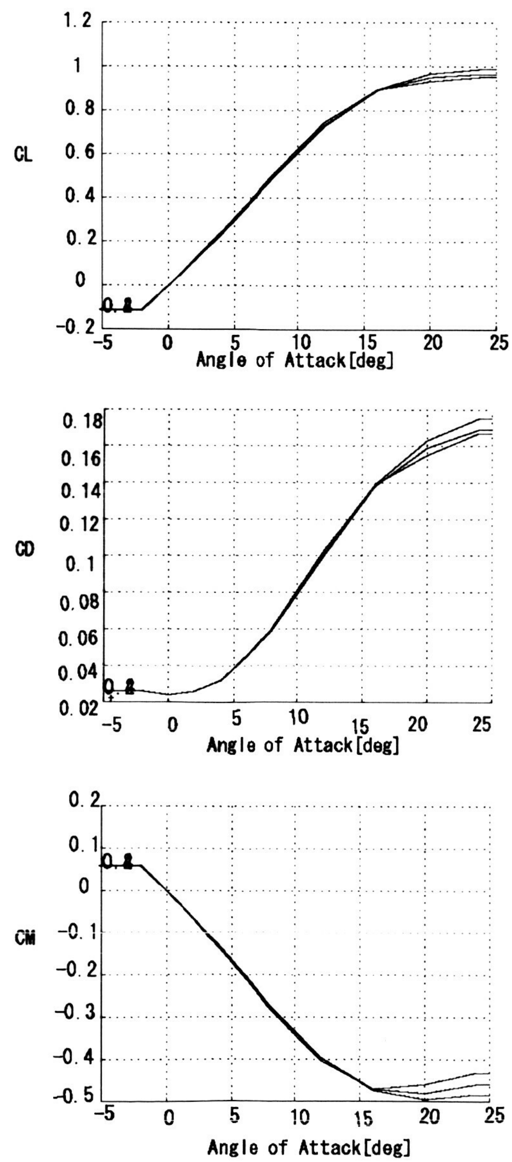

Figure 4 – Aerodynamic Model

The thruster model was built from Figure 5, which shows the time-thrust curve of the L850W solid rocket motor used to power the 5-ft cluster vehicles.

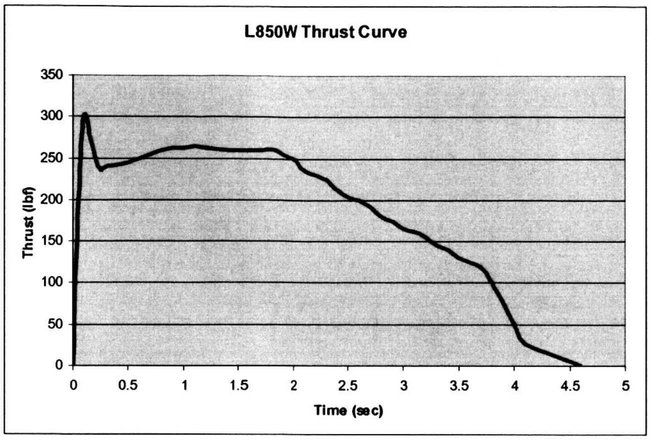

Figure 5 – Thrust Profile for Aerotech L850W

CONSTRAINT FORCE AND MOMENT

The boosters are launched attached in two locations to the sides of the centerstage so that they ascend together as a combined single object. This configuration can be maintained during ascent by combining constraint forces and moments calculated and applied to each object. The individual forces and moments are calculated back from translational and rotational acceleration of the combined object.

SIMULATION EXAMPLE

Figure 6 shows an example of simulation result. In this case the cluster is launched with the initial inclination of 80 degrees. The boosters were separated smoothly and transitioned to gliding without any active control. This example shows that the boosters have good longitudinal stability and can fly stably just after the separation without active control, if the trim settings are suitable. The model also indicates that a low angle of attack is best for smooth separation. It is likely that the CO_2 ejection system used in actual flight is needed only to push off the boosters against friction and to give them a small initial angle of attack.

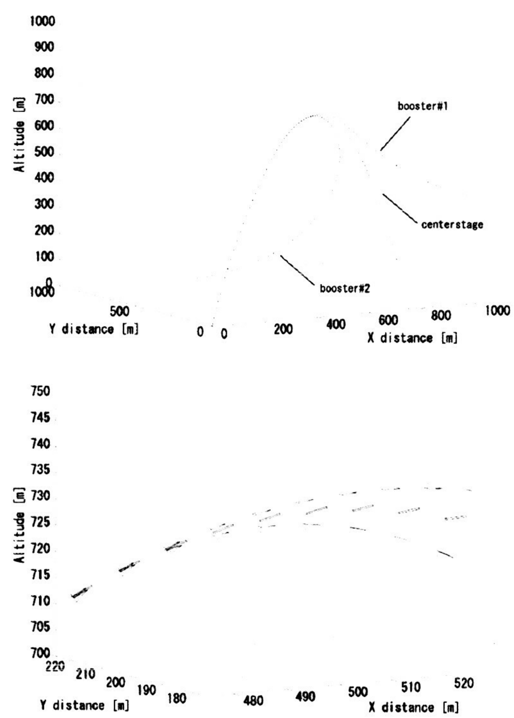

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Figure 6 – Simulation Example

FLIGHT TESTS RESULTS

A total of five flights have been made so far with the three rocket cluster models. Two flights were made using a set of small boosters (3-ft tall), and three flights were made using the larger boosters (5-ft tall). Most of the flights took place in Fresno, CA, at a Tripoli Rocketry Association sponsored launch facility that had an FAA waiver for at least 10,000 ft. However, Cal Poly has recently obtained permission to launch at Camp Roberts in Bradley, CA, which is much closer than Fresno. Launches at Camp Roberts greatly increases the number of launch opportunities because their facility can be reserved for any weekday that other training is not already scheduled.

The first rockets built were 3-ft tall and made from hot wire cut blue foam covered in fiberglass tape for rigidity. The main objective of the launches was to test the separation device. At first, the separation mechanism was a small pyrotechnic charge set off by a timer delayed from launch. The ascent of the first 3-ft model cluster launch was perfect, but a loose wire prevented the charge from igniting and separating the boosters from the centerstage. The centerstage parachute opened as intended and the entire vehicle came down gently in one piece. The second flight of the 3-ft models was powered by a J350W. The motor created too much thrust and acceleration for the structure of the vehicles. The foam models were not strong enough to withstand the high dynamic pressure such that the fuselage structure failed and the boosters were torn off the centerstage.

The decision was made to build 5-ft tall boosters that would be foam covered in carbon composite to increase the strength of the body tube and aerodynamic surfaces. The larger vehicle was also necessary to hold the data system. The body tube was made from blue foam covered in fiberglass. The wings and canards were made from foam covered in carbon cloth. The separation mechanism consisted of a CO_2 tank and a set of pistons that doubled as the forward support holding the boosters to the centerstage. At the moment of separation a Kevlar retaining strap is released and the CO_2 tank is opened pressurizing the pistons and repelling the boosters away from the centerstage. The CO_2 tank was first connected with one tube, then improved to be two separate tubes because the first launch showed that the gas would release one side and then lose enough pressure that the second side would not release.

The control surfaces on the wing were approximately 10% area and variable such that they could control pitch or roll, with one metal gear servo for each wing. The canards had 40% chord control surface each connected to one servo which acted as the main pitch control. The cluster is shown in Figure 7 just before its first launch. Note that the two boosters were not powered for these flights in order to keep the overall weight to a minimum to maximize flight time and controllability for the pilots on the ground. The booster center of gravity could therefore be set before flight to 54% behind the nose, which is the optimum location for glide.

The first set of 5-ft boosters and 7-ft centerstage made two flights, and a second, slightly larger set made a third flight. The first two flew on an Aerotech L850W motor in the centerstage. On the first flight, one of the boosters separated correctly, but the other booster hung onto the centerstage and its trajectory was such that it could not fly after it released. Luckily, the booster carrying the data system flew correctly. Both the second booster and the centerstage were successfully recovered using parachutes.

For the first two flights, a commercially available data acquisition unit developed for model rockets was used for flight data collection. The system consisted of a main module, a telemetry transmitter/receiver module, and additional sensors, including an accelerometer module, GPS module and magnetic attitude sensor module. The main module included an 11MHz processor, 32kB memory, static pressure sensor, temperature sensor, and 1-axis accelerometer. Several data ports were also available to accept additional sensor signal inputs. In addition to the manufacturer prepared modules, three rate gyros were added to measure three-axis angular velocity. One of the two boosters that flew was chosen to carry the on-board data acquisition system which collected and telemetered data during flight.

Figure 7 – 5-ft Cluster Before Launch

Figure 8 shows the pressure altitude time history of one of the boosters for the first launch, in which apogee occurs at about 600 m (2000ft). This altitude is slightly higher than the 550 m value the simulation model predicts. The actual launch occurred with initial inclination of about 90deg, however, its trajectory inclines away from the vertical soon after liftoff because of misbalance between two boosters, offset of thrust axis, and lack of symmetry of the rocket. So, in the simulation, an initial angle of 65 degrees from vertical was given to emulate these effects. The information gained so far only answered questions about launch and not the control glide. To improve the model, more detailed flight data was needed, such as attitude of the vehicle, acceleration, position, ground/air velocity, and control surface deflection.

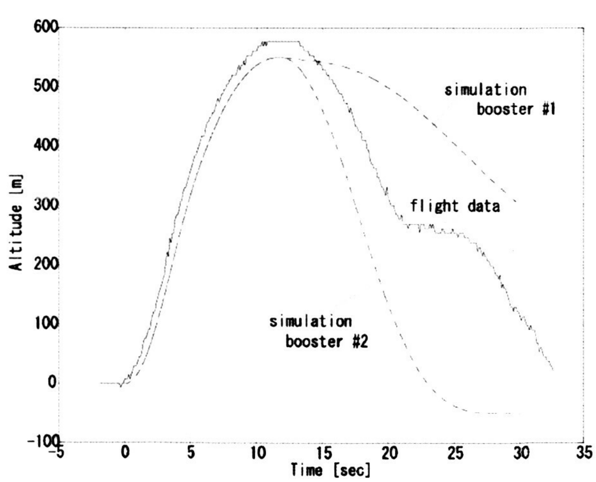


Figure 8 – Simulation and Flight Altitude History

The second flight took place with a much improved separation mechanism that worked perfectly. Both boosters climbed after separation and pulled out to fly for 45 and 75 seconds respectively. Both landed horizontally, but without landing gear, one rolled over after the flared landing and broke off the vertical fin. Unfortunately, the data acquisition system did not collect reliable data on this flight. The flight was recorded on video, however, and Appendix A contains the time sequence of the launch, showing the rocket before separation, at separation and right after. The boosters separate right between motor burnout and apogee, and both boosters pull away quickly from the centerstage.

The third flight of the clusters, which took place in January 2003, was powered by an L1120W motor and reached an altitude of 620 m. Figure 9 shows the rockets just after takeoff. For this flight, the commercial RDAS on-board data system was used in one of the boosters, and a new scratch built data acquisition unit (DMAS) was added on the other. The 16-channel DMAS was configured to collect GPS, three axis gyro and acceleration, static and dynamic pressure, control surface deflection for the wing, rudder and canard, angle of attack and sideslip angle.

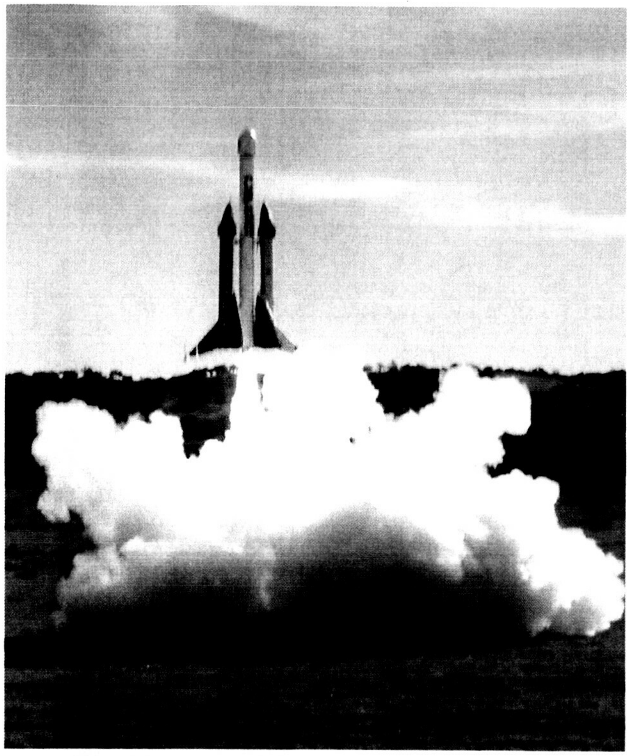


Figure 9 – 6-ft Cluster Just After Launch

The telemetry system accurately recorded 7 channels at 38Hz during flight. The latitude and longitude recorded by the GPS is included as Figure 10. The first ten points are considered suspect, and show up as a random, disconnected line on the left side of the graph. The rest of the trajectory follows very closely the flight path seen on the video. A printout of the actual recorded GPS points along with the number of satellites picked up at each location is included in Appendix B. The time histories of these data are also included here for comparison. Figure 11 shows the maximum altitude of the booster occurring at approximately 9 seconds after launch. Note that separation occurs just before apogee because the booster climbed slightly before turning over. The booster glides toward the ground with a glide slope between 1 and 2, confirming that this configuration is not ideal for low subsonic flight. Figure 12 shows the velocity of the vehicle during the flight. The initial acceleration occurs during the first four seconds of flight while the motor is firing. After leveling out, the booster spends at least 25 seconds flying at an almost constant rate of 90 ft/sec. Figure 13 shows the angle of attack and sideslip results over the entire flight time. The angle of attack of nearly 20% seems too high indicating that although the trend may be correct, the calibration was not precise enough. The sideslip does not show any appreciable magnitude in either direction because a gyro was attached to the aileron that was then mixed with the rudder inputs. The rudder being linked to the aileron significantly reduced the adverse yaw and roll seen in previous flights. Figure 14 documents the aileron, canard and rudder deflections that were measured off of the servo that controlled each movement. Note that the canard deflection indicates an angle of 15 degrees before launch. This was intentionally done by the pilots and is accurate. Overall however, these results are quite noisy and plans have been made to more accurately obtain these values for future flights. Finally, Figure 15 shows the correlation with the uncontrolled boosters from the simulation model which agree very well up until separation.

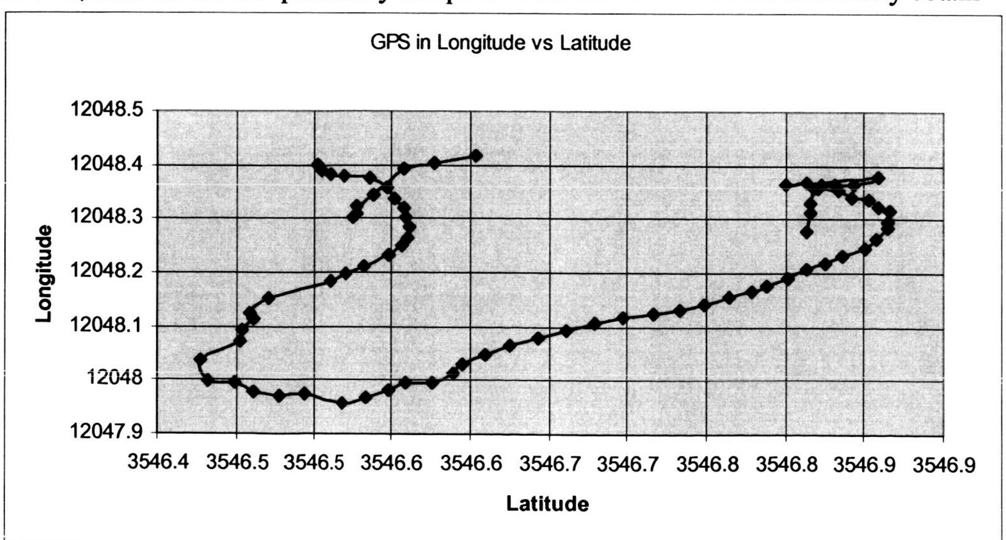


Figure 10 – GPS Data (one point per second)

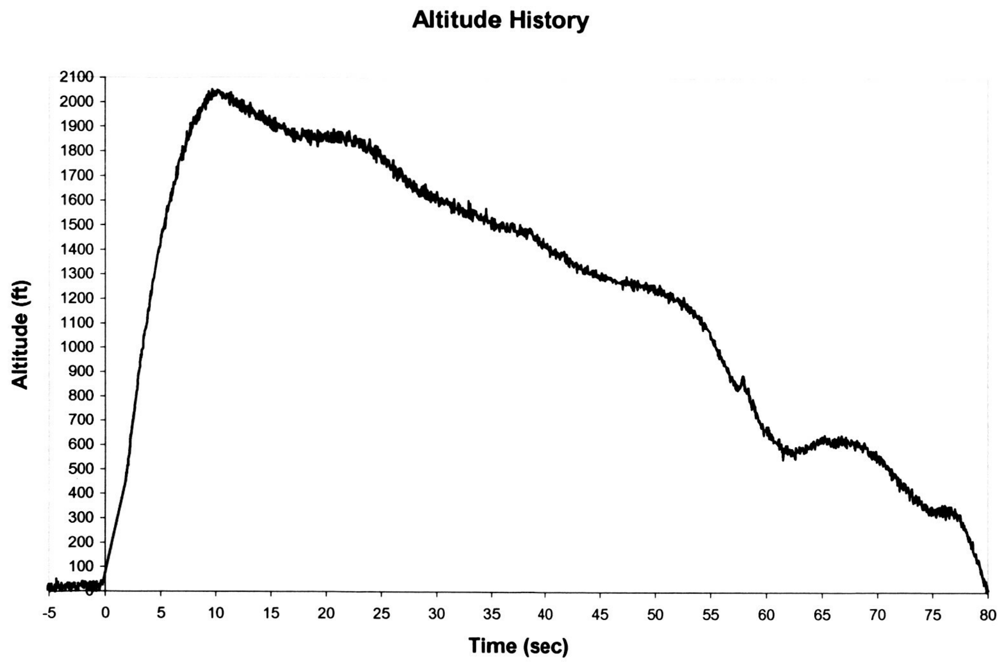


Figure 11 – Altitude vs. Time as recorded by DMAS

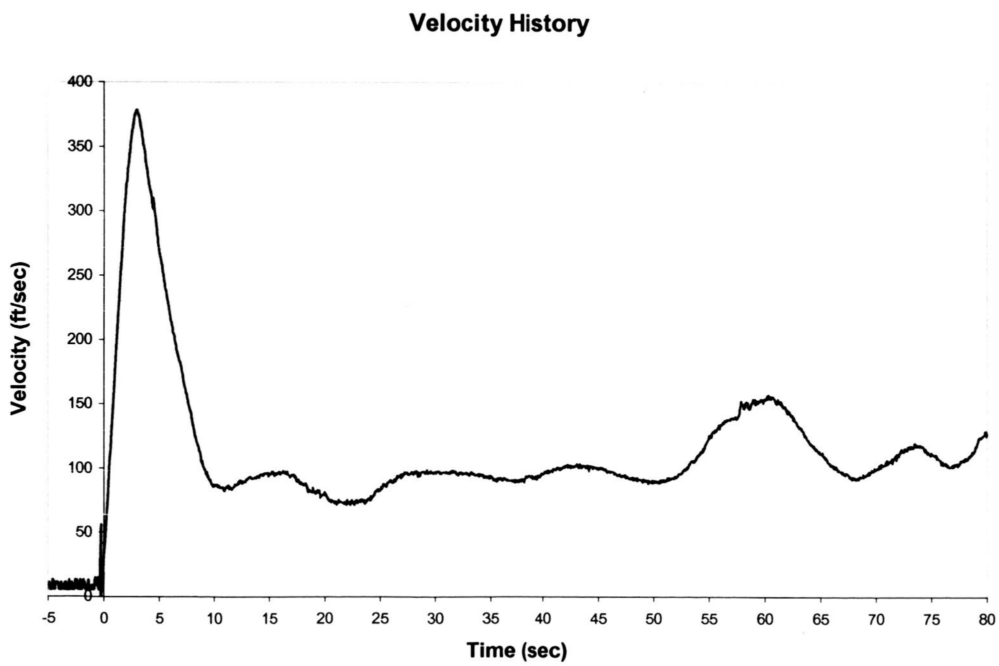


Figure 12 – Velocity vs Time as Recorded by DMAS

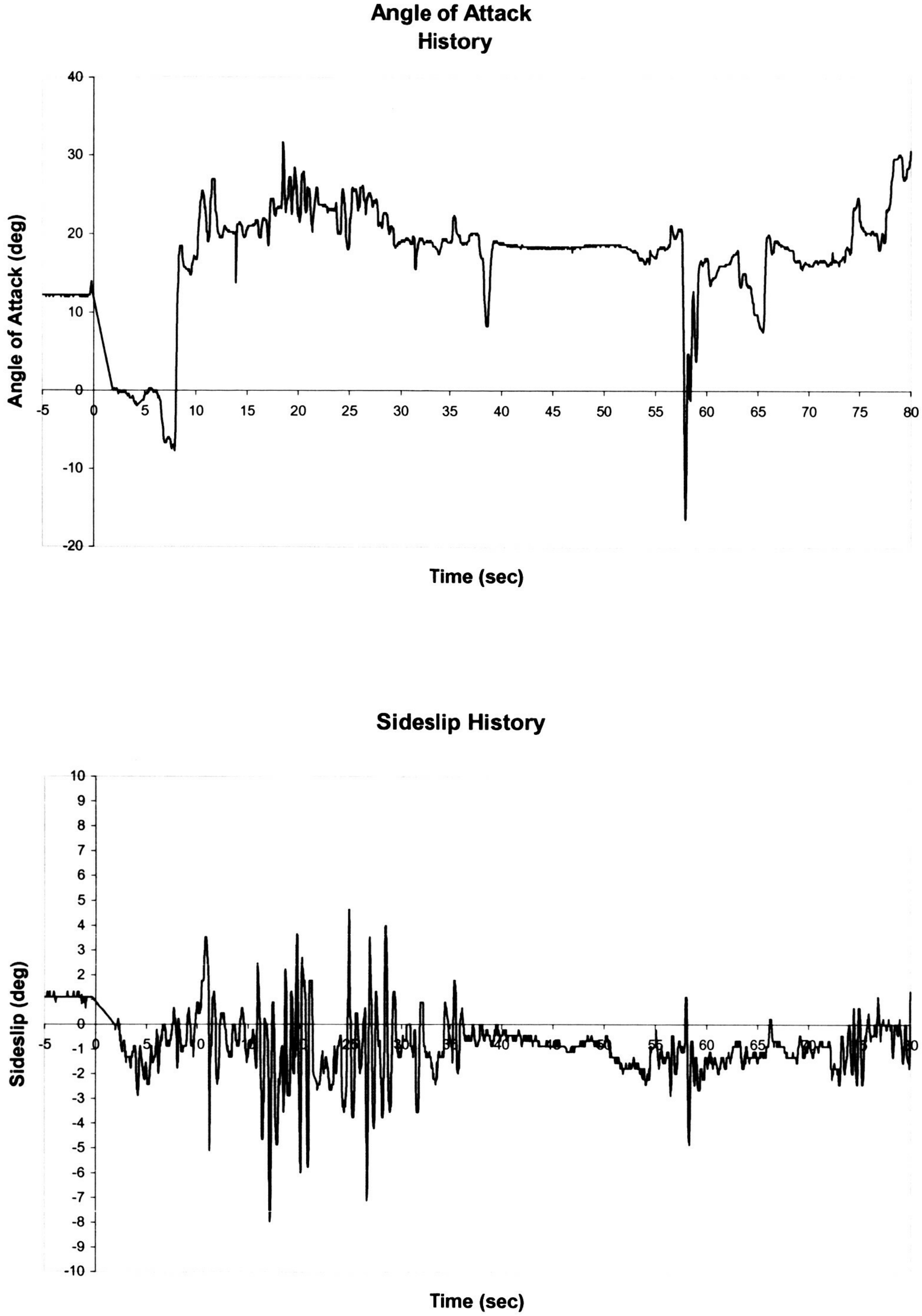


Figure 13 – Angle of Attack and Sideslip vs Time

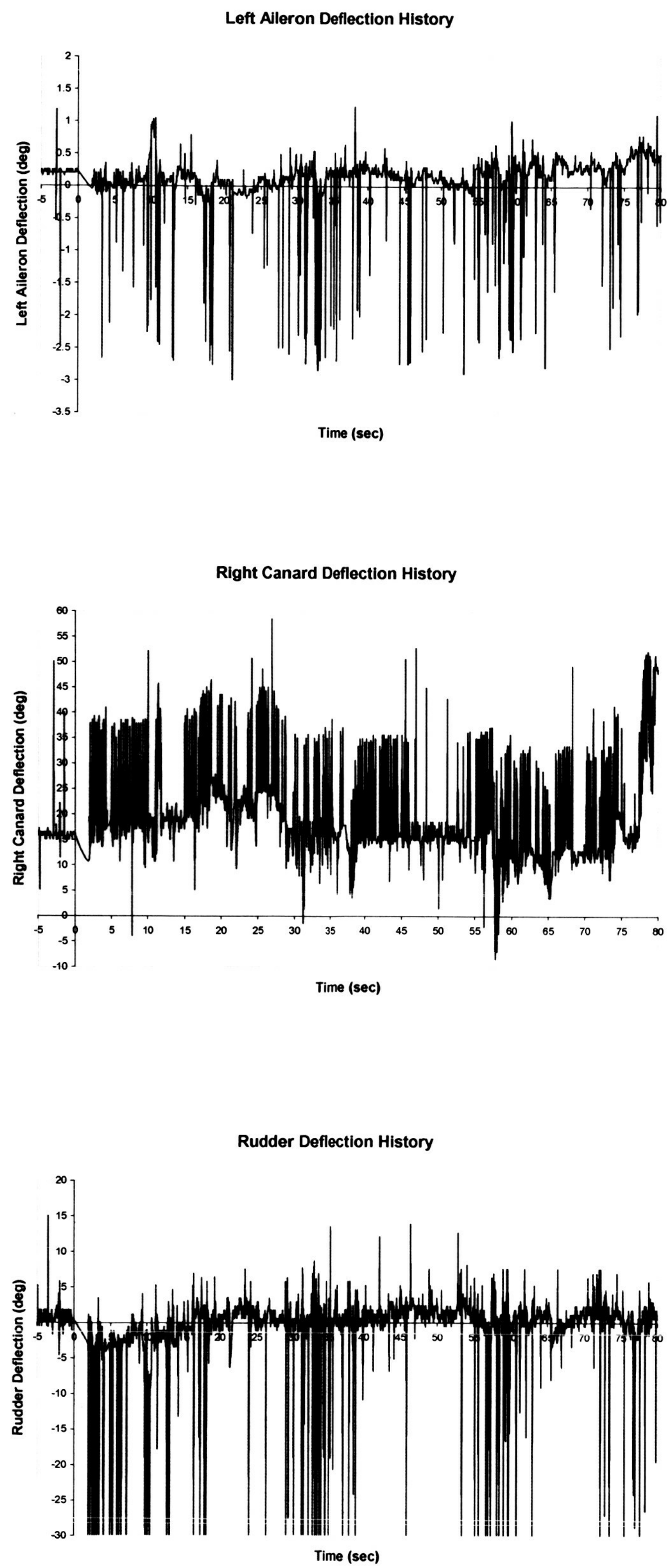


Figure 14 – Aileron, Canard and Rudder Deflections vs Time

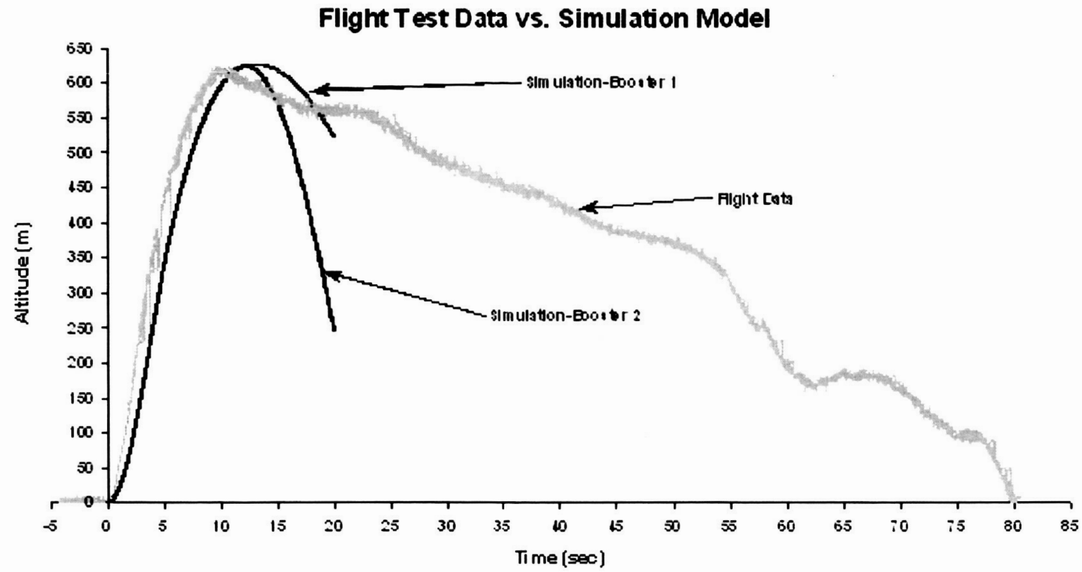


Figure 15 – Flight Test vs Simulation Model (uncontrolled boosters)

SUMMARY AND RECOMMENDATIONS

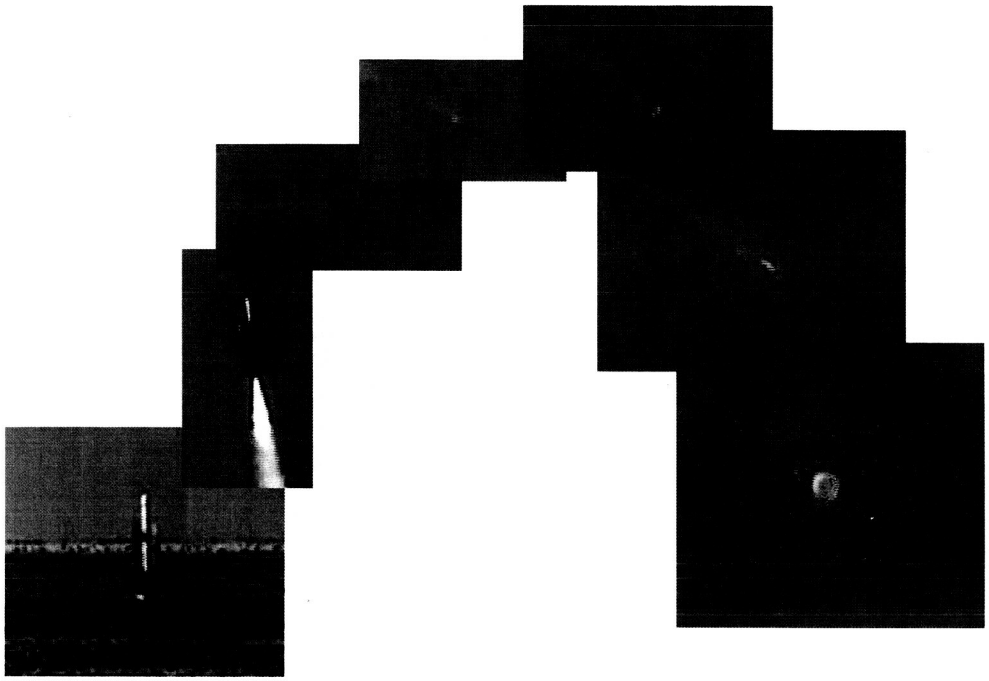
The capability to fly high power rockets as a fixed wing glideback booster has been clearly demonstrated. The three, five and six ft tall rocket models demonstrate the vertical launch and horizontal return flight of a cluster configuration of two first stage boosters and center upper stage. The rockets were flown five times with data acquisition on board for the last three flights. Control surface deflections, pressures, angle of attack, yaw and GPS were recorded during the last flight. A six degree of freedom rigid body analysis model was made of the three vehicle configuration that incorporated models for aerodynamics, constraint, thrust and inertial characteristics. The simulation showed good correlation with flight data for altitude until separation for two launches. The correlation of the glide portion of the flight remains to be examined.

The current flight test series will continue with data acquisition in both boosters for two more flights that will occur in Spring, 2003. Hopefully the simulation model will then be fully correlated. In the meantime, the group has the capability to acquire more detailed measurements during flight, and more instrumentation can be added to the current flight vehicles. The two areas that need to be more closely examined are separation and landing. The boosters have yet to land with landing gear, and the separation has not yet been studied with data from all three rockets simultaneously.

In order to learn more about landing, a 4-ft long powered radio control airplane with the delta wing canard configuration is being built that will take off and land horizontally. One goal for this vehicle is to give the rocket pilots practice with how the vehicle responds near the ground. When instrumented, this vehicle will provide data about specific landing characteristics.

To understand the separation dynamics, the position and orientation of both boosters and the centerstage need to be determined with great precision. First, a data board will be added to the second booster and then to the centerstage. The GPS data received so far is not accurate enough to record position of the vehicles, therefore an IMU is being added to data system for the boosters. If this works, data can be collected from the centerstage in a similar manner.

Appendix A. Photograph of Separation Sequence for Launch in October, 2002



Appendix B. Number of Satellites for Each GPS Data Point

Time (sec)	Latitude	Longitude	# of Sats	Altitude (m)
-1	3546.5256	12048.3011	5	159.1
0	3546.5257	12048.3001	5	162.4
1	3546.5281	12048.3075	5	195.4
2	3546.5283	12048.3214	5	258.3
3	3546.5385	12048.3421	5	327.9
4	3546.5582	12048.3932	3	250
5	3546.5776	12048.404	3	244.7
6	3546.6039	12048.4156	2	243.8
10	3546.8142	12048.2776	3	246.4
11	3546.816	12048.3117	3	243.5
12	3546.8164	12048.3308	3	242.3
13	3546.8181	12048.3567	3	243.2
14	3546.8231	12048.3628	3	240.7
15	3546.8316	12048.3632	3	241
16	3546.8441	12048.363	3	241.6
17	3546.8597	12048.3762	2	242.6
18	3546.7999	12048.3642	5	337.7
19	3546.8133	12048.3688	2	293.1
20	3546.8205	12048.3556	5	305.4
21	3546.834	12048.3534	2	296.5
22	3546.8422	12048.3406	5	306.2
23	3546.853	12048.337	2	300.8
24	3546.8588	12048.3224	5	308.1
25	3546.8667	12048.3147	2	301.6
26	3546.8657	12048.2954	5	307.5
27	3546.8658	12048.283	2	305.5
28	3546.8576	12048.2625	5	307.7
29	3546.8514	12048.2468	2	305
30	3546.8369	12048.2305	5	307.8
31	3546.8251	12048.2168	2	305.6
32	3546.8139	12048.206	5	317.4
33	3546.8014	12048.1903	3	313.5
34	3546.789	12048.1757	2	311
35	3546.7789	12048.166	5	311.2
36	3546.7645	12048.1545	3	310.7
37	3546.749	12048.1421	3	309.4
38	3546.7332	12048.1309	3	308.9
39	3546.7167	12048.1232	3	308.5
40	3546.6974	12048.115	3	308.3
41	3546.6788	12048.1048	3	308.1
42	3546.6609	12048.0926	3	307.9
43	3546.643	12048.0788	3	307.6
44	3546.6256	12048.0636	3	307.8
45	3546.6097	12048.0476	3	307.6
46	3546.5953	12048.0293	3	306.9
47	3546.5892	12048.0111	3	307.3
48	3546.5766	12047.995	2	307.1
49	3546.5595	12047.9931	5	316.7
50	3546.5484	12047.98	5	316.1
51	3546.5341	12047.967	5	318.5
52	3546.5192	12047.957	2	317.6

53	3546.4939	12047.9738	5	339.8
54	3546.4779	12047.9709	5	339.7
55	3546.461	12047.9764	5	350.6
56	3546.4494	12047.9926	5	361.6
57	3546.4329	12047.999	5	351
58	3546.4276	12048.0354	5	362.8
59	3546.4531	12048.0725	5	377.6
60	3546.4544	12048.0932	5	360.6
61	3546.4609	12048.1125	5	347.5
62	3546.4584	12048.1245	5	333.2
63	3546.4709	12048.1522	5	328.7
64	3546.5104	12048.1819	5	329.8
65	3546.5212	12048.1959	5	329.5
66	3546.5325	12048.2122	5	329.6
67	3546.5485	12048.2306	5	329.7
68	3546.5569	12048.2476	5	326.7
69	3546.561	12048.2645	5	325
70	3546.5613	12048.2825	5	322.4
71	3546.56	12048.3014	5	317.2
72	3546.5582	12048.3174	5	308.1
73	3546.5522	12048.3347	5	306.4
74	3546.5477	12048.3583	5	299.2
75	3546.5363	12048.3761	5	283.8
76	3546.5205	12048.378	5	283.4
77	3546.5098	12048.3829	5	273.2
78	3546.5046	12048.3882	5	259.2
79	3546.5022	12048.3979	3	273.9