Maraia Capsule Flight Testing and Results for Entry, Descent, and Landing

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The Maraia concept is a modest size (150 lb., 30" diameter) capsule that has been proposed as an ISS based, mostly autonomous earth return capability to function either as an Entry, Descent, and Landing (EDL) technology test platform or as a small on-demand sample return vehicle. A flight test program has been completed including high altitude balloon testing of the proposed capsule shape, with the purpose of investigating aerodynamics and stability during the latter portion of the entry flight regime, along with demonstrating a potential recovery system. This paper includes description, objectives, and results from the test program.

Nomenclature

α	=	Aerodynamic angle of attack
β	=	Sideslip angle
C_A	=	Axial aerodynamic force coefficient
C_m	=	Aerodynamic moment coefficient
$C_{m,q}$	=	Change in moment coefficient due to pitch rate
C_N	=	Normal aerodynamic force coefficient

I. Introduction

THE Maraia Capsule is envisioned as an entry technology testbed that could be adapted to return small payloads (10-100's of kg) from the International Space Station (ISS) or from beyond Low-Earth Orbit (LEO) destinations. Figure 1 shows the concept of operations. The Maraia Capsule is delivered to the International Space Station (ISS) via a visiting vehicle, such as the SpaceX Dragon or the Orbital Cygnus. It resides in the internal volume (IVA) of the spacecraft and is designed to ISS internal requirements. At the desired time, the Maraia Capsule is attached to the Space Station Integrated Kinetic Launcher for Orbital Payload Systems (SSIKLOPS)[1] device. The SSIKLOPS, along with the mounted Maraia Capsule, is deployed via the ISS Japanese Experiment Module (JEM) airlock. With the aid of a robotic arm (either SSRMS or JEM RMS), the mounted Maraia Capsule is placed in the desired orientation. The robotic arm actuates a designed interface on the SSIKLOPS, which removes a pin holding a spring-loaded pusher plate which provides an impulse to the passive Maraia Capsule.

The capsule remains passive until at least a 2 km separation distance from ISS. It then performs a de-orbit burn to a desired entry interface (EI) condition. It remains in a ballistic mode during the entry, and deploys a parachute prior to land landing.

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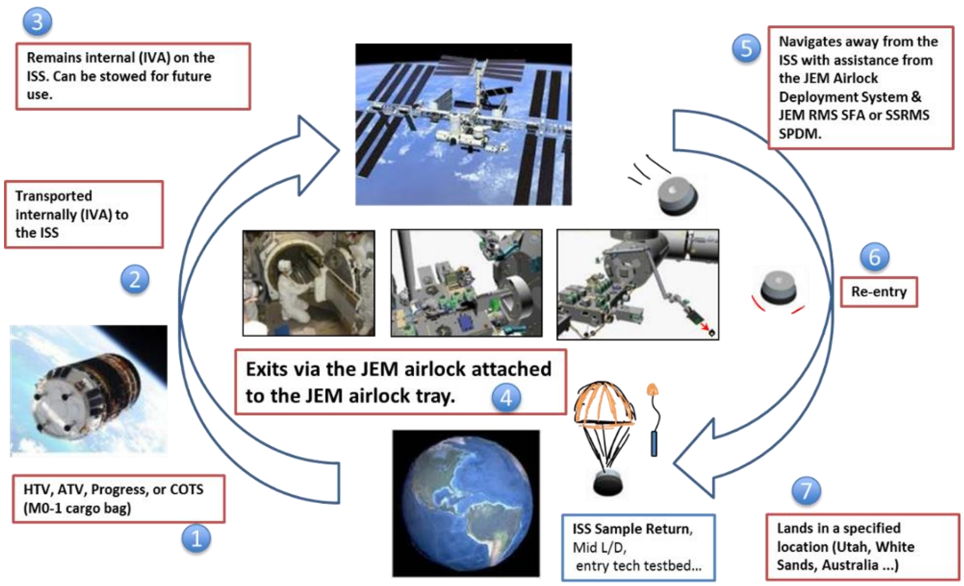

Figure 1. Concept of operations.

II. Entry, Descent, and Landing Testing

Figure 2 shows an overview of EDL testing. A progressive test approach was used, beginning with wind tunnel parachute testing at Texas A&M University's low speed wind tunnel in order to characterize the parachute opening. This was followed by parachute drop testing, more focused on steady-state parachute performance of two competing designs. The drop testing was completed at China Lake using a drop tower.

High altitude balloons were used to drop test the capsule at subsonic velocities. Three tests were completed, two at sub-scale (1/3rd scale, 10" diameter) and one at full scale (30" diameter). These tests were designed to provide insight into dynamic behavior of the capsule in the subsonic regime, verify parachute system design, and push EDL technology development forward with goal of building a capsule fully capable of returning from Low Earth Orbit, and eventually, beyond LEO. The two subscale tests successfully served as development tests for the full scale, but were unable to achieve a clean freefall configuration and did not provide usable capsule aerodynamic data. The full scale test did successfully meet all primary objectives including a clean freefall. Inertial Measurement Unit (IMU) data was used to extract aerodynamic performance during the free flight and to update capsule aerodynamic models.

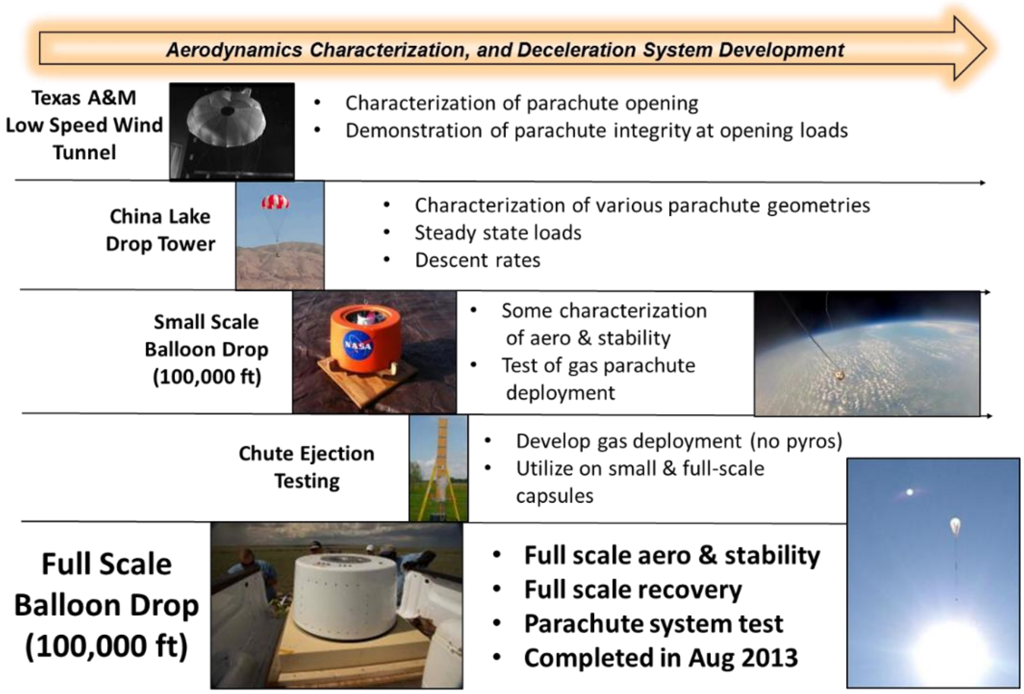

Figure 2. Overview of EDL testing.

III. Small Balloon Testing

High-altitude balloon flights are an inexpensive method used to lift payloads to high altitudes. Federal Aviation Administration (FAA) regulations permit payloads of up to 6 lbs. without requiring any waivers or special permissions. Using such a balloon flight capability, the Maraia Capsule team worked with the Rocket University program at Kennedy Space Center (KSC) to conduct a set of test flights of a sub-scale version of the Maraia Entry Capsule.

The main test objective was to gain insight into the aerodynamic and dynamic properties of the capsule in the subsonic regime. The capsule was scaled accordingly, resulting in a test article 10” in diameter by approximately 6.5” tall at the 6 lb. weight limit. Secondary test objectives included testing subsystems (e.g. avionics, parachutes, and guidance, navigation, and control (GN&C) subsystems) to be used in the full scale flights, as well as training and gaining overall experience in all aspects of designing, developing, and testing spaceflight systems.

Figure 3 shows the small balloon drop test concept of operations. *A priori* winds and trajectory predictions were used to determine a launch location such that the trajectory and predicted landing location is desirable for safety and recovery purposes. The balloon was filled on the ground and payload lines were laid along the predominant ground wind direction. The system was launched from a large open area in order to minimize the risk of entanglement and jerking of the lines and payloads.

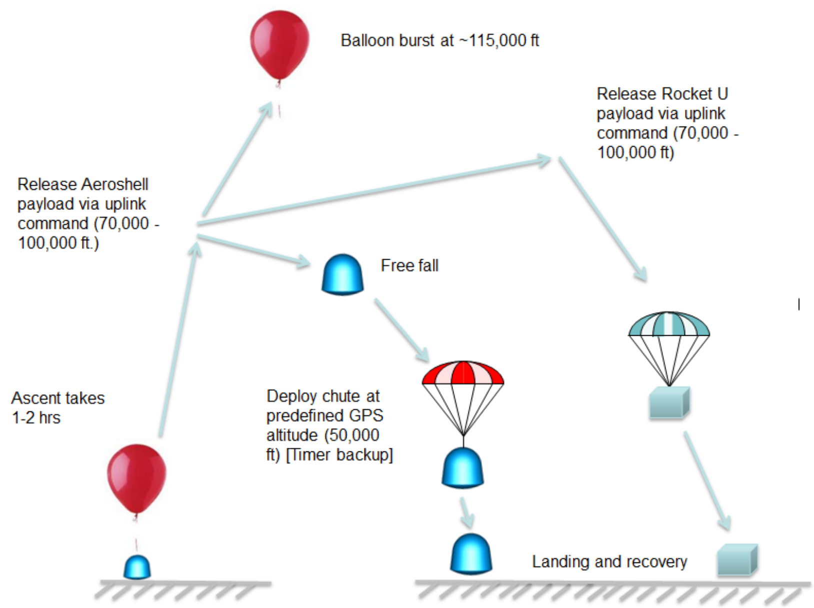

Figure 3. Small Balloon Testing Concept of Operations.

The balloon ascends for one to two hours, depending on payload mass and fill volume. Once above an altitude of 70,000 ft, a release command is issued when trajectory predictions show that the capsule (aeroshell) will land within the landing zone (or when they are closest to the zone, based on real-time trends). The capsule descends in freefall to 50,000 ft, at which point an autonomous command is sent to deploy the parachute. The ground operator may also manually issue a parachute deploy command at any time. The capsule then descends and lands, with an approximate terminal velocity of 38 ft/s.

A separate release command is issued for the separate Rocket U payload, which contains its own avionics, when landing predictions are such that it is desirable for the payload to separate from the balloon and land. (Note: on Flight #1, this command was issued simultaneously for both payloads. Future flights will permit separate commands for better control of payload landing locations). The parachute system for the Rocket U payload is an inline, pre-deployed system that inflates as the payload descends. The balloon then ascends (now more quickly, with less payload attached) and bursts at approximately 115,000 ft, and is not recovered.

The subscale Maraia Capsule includes avionics, a parachute deployment system, communications, power, a global positioning system (GPS) / inertial navigation system (INS) sensor, a GoPro camera, a flight processor, and a data recorder. A barometric altimeter was added for Flight #2. Figure 4 shows the internal components of the capsule as it underwent final integrated software checkout prior to Flight #1.

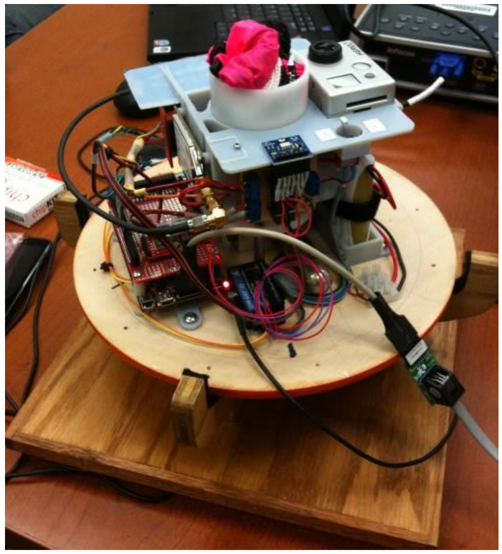

Figure 4. Subscale Maraia Capsule Internal Components (Sides and Top of Capsule Removed).

A. Test Summary of Flight #1

Flight #1 was launched on the morning of July 26, 2012, from Gemini Elementary in Melbourne, Florida, at 9:15 a.m. local time. An eyebolt failure on the capsule occurred immediately after launch, causing the two-point attach to the upper payload to become a single point attach. The balloon ascended at an average ascent rate of 1285 ft/min, near the expected ascent rate. At 72,500 ft, the command to release the capsule was sent. No release was observed. It was determined during post-test analysis that the twisting of the capsule during ascent caused the electrical connection of the burn circuit to pull loose from the power source. The command was received by the avionics, but the lack of power to the release box system prevented it from functioning properly. (The electrical setup of this system was modified for future flights). The entire system continued to ascend to 103,984 ft, at which point a nominal balloon burst occurred. Figure 5 shows the capsule at high altitude.

Figure 5. Capsule at High Altitude (~100,000 ft).

The Rocket U parachute inflated as expected. The system began to experience significant dynamics and the 50-lb line required by FAA regulations snapped between the Rocket U payload and the capsule release box. The Rocket U payload then descended nominally under parachute and landed southeast of St Cloud, Florida. The capsule and release box descended until a nominal parachute deploy was recorded at just under 50,000 ft. The release box later broke away and the capsule descended under the parachute, landing a few miles from the Rocket U payload. Both payloads were recovered.

The primary test objective, obtaining performance data on the aerodynamic and dynamic properties of the sub-scale capsule, was not met since the release box was still attached during the freefall, creating additional drag (and stability). However, all secondary test objectives were met, including successful autonomous parachute deployment, demonstration of avionics and GN&C in flight, execution of ground commands in flight and observation of system response, and recovery of both payloads.

B. Test Summary of Flight #2

Flight #2 was launched from WW James Park in Titusville, FL, on April 24th, 2013, at approximately 10 am local time. The capsule was spotted during final descent on the parachute by the recovery team on the boat. It landed about 2 mi southeast of Jetty Park near Port Canaveral. The ground track and altitude profile are shown in Fig. 6. An uncommanded release of the capsule occurred at 64,500 ft due to severe dynamics of the balloon-tether-payload system. The release system remained attached, so a clean freefall configuration was not obtained. The parachute successfully deployed at 50,000 ft as expected, and the capsule landed softly in the water.

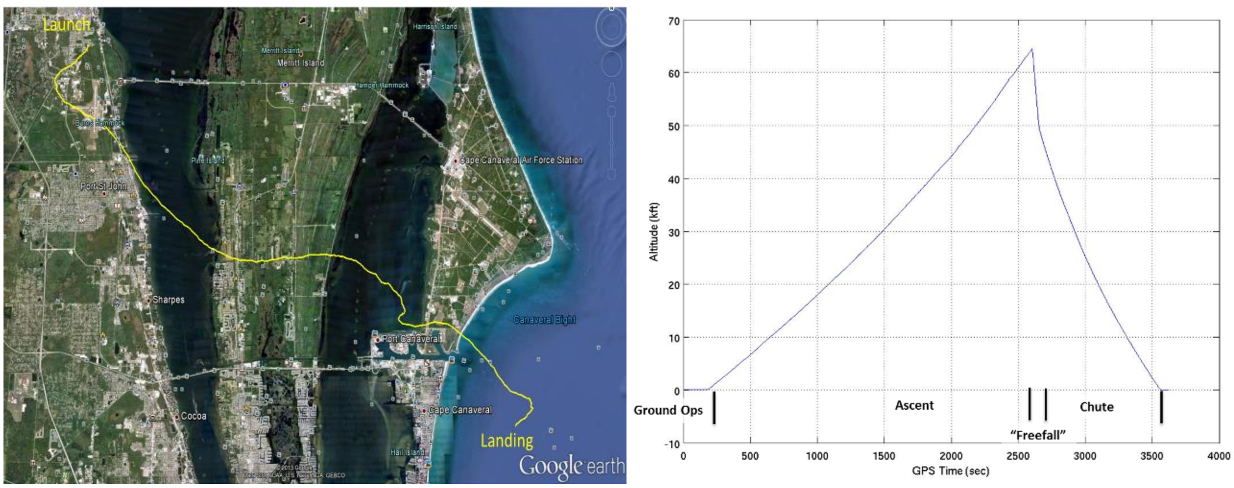

Figure 6. Flight #2 Ground Track and Altitude Profile.

On flight #2, the balloon-payload system experienced dynamics that were much more severe than experienced during flight #1. The dynamics were observed in both the GoPro camera and the accelerometer data. Just prior to the line break, a series of greater than 6 G's spikes were observed in the accelerometer data. Around the same time, the video showed oscillations of the balloon-capsule system of increasing magnitude. Eventually the tether line broke, above the release box. The release box remained attached to the capsule until after the chute deploy occurred. As a result, the freefall objective was not met for this flight.

IV. Large Balloon Testing

The Maraia Capsule project was offered the opportunity to fly a full scale (150 lb., 30" diameter) capsule as a secondary payload on the High Altitude Student Platform (HASP), administered by NASA-Wallops Balloon Program Office and executed by the Columbia Scientific Balloon Facility (CSBF), a world class large balloon capability maintained by NASA. The HASP flight is part of a yearly test campaign flown out of Fort Sumner, NM, which allows student-developed instruments to fly at near space altitudes. Figure 7 shows the Maraia Capsule test article attached to the HASP.

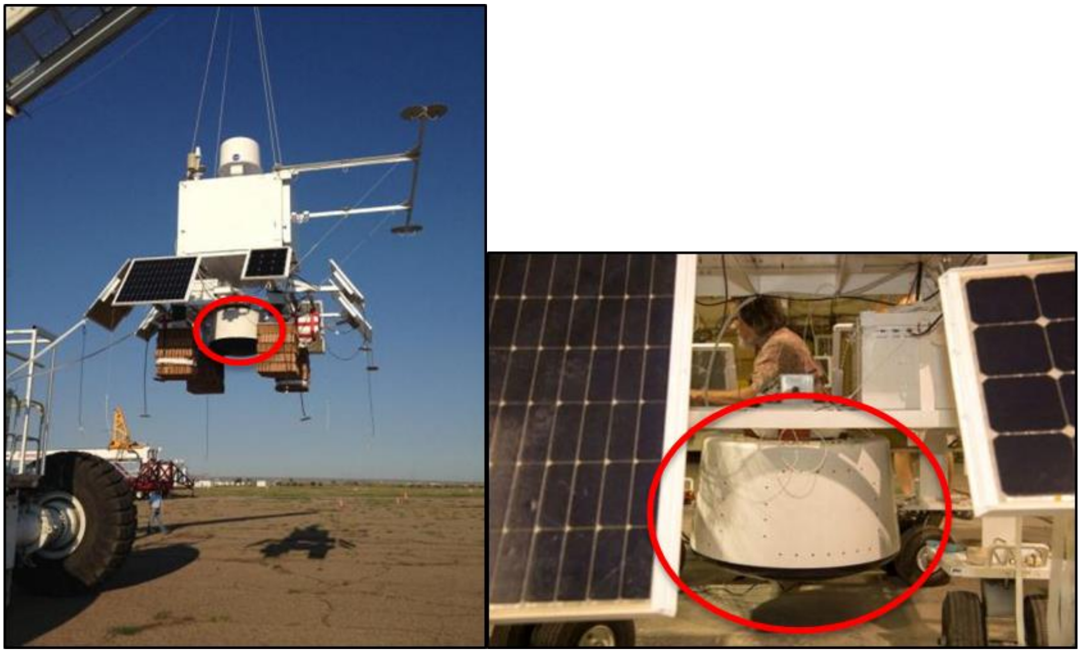

Figure 7. Maraia Capsule Test Article Attached to High Altitude Student Platform Gondola.

The primary test objectives for the Maraia Capsule test were as follows:

- Characterize capsule transonic & subsonic free-fall dynamic behavior and aerodynamics
- Execute full scale autonomous pneumatic parachute deployment and recovery system
- Execute drogue to main parachute transition

Additional secondary objectives included recovery of the capsule and recording good quality, usable video. All objectives were met with the exception of the video objective.

The concept of operations is shown in Figure 8. The balloon climbs to an altitude of about 100,000 ft in a period of 100 min. It drifts at high altitude until the predicted landing location is at a desirable location. At that point, a release is commanded remotely. The vehicle goes into freefall until a drogue parachute is deployed at 60,000 ft. The drogue is released at 14,000 ft and is used to deploy the main parachute, leading to a relatively soft landing.

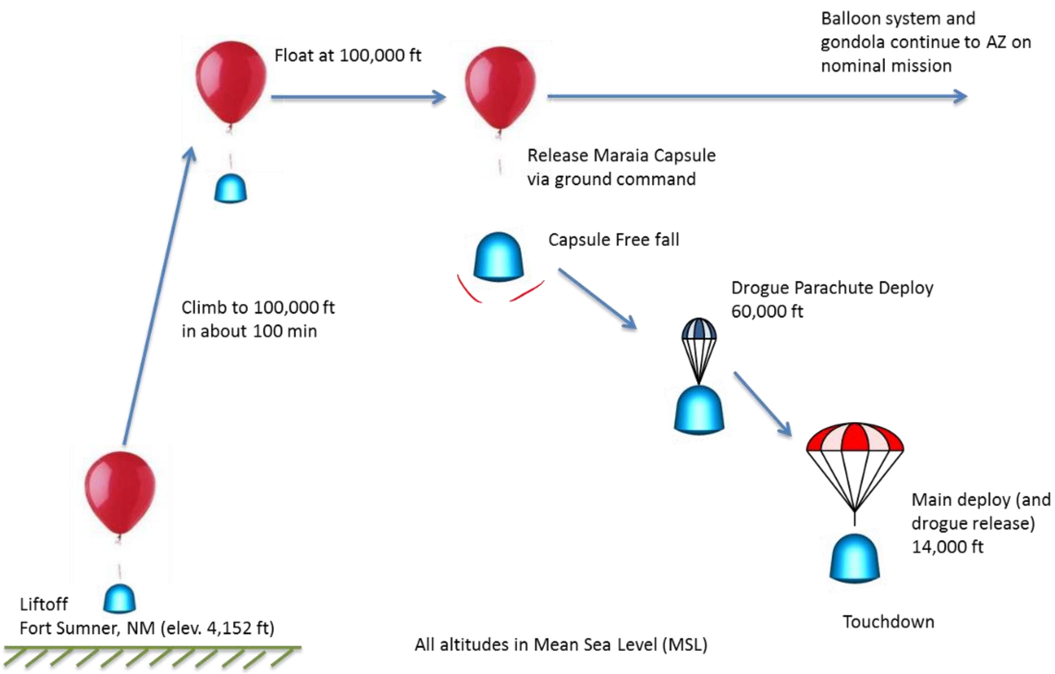

Figure 8. Concept of Operations For Full Scale Balloon Test.

A. Test article description

The Maraia Capsule test article weighed 133 lb when completed. This mass reduction was performed in order to reduce parachute opening loads for this test. The test article included a Microstrain 3DM-GX3-35 GPS / inertial navigation device. The Microstrain device provided position, velocity, acceleration, attitude, and attitude rate. The raw accelerations and rates from the sensor were available in addition to the filtered parameters. Other onboard systems include a barometric altimeter, 900 MHz radio and antenna, and flight computer. The primary structure was built at KSC, made of composite with a metal backbone for mounting. Ballast plates were used to achieve the desired test weight.

The parachute system was built as a separate secondary structure at JSC. It included two parachutes: 4 ft drogue, 14 ft diameter main parachute. A linear actuator with retractable pin was used to hold the drogue chute in place. When the pin is released, the drogue separates from the vehicle. A lazy leg line was used to connect the drogue to the main parachute bag. As the drogue separates, it pulls out the main parachute. Once the lines reach full stretch, the main bag pulls away from the main chute and the main chute inflates. A pneumatic deployment system was developed specifically for this test article, and also to serve as a prototype for the spaceflight vehicle which must comply with ISS internal requirements (so black power or pyrotechnics were not considered to be a viable option). The deployment system consisted of a nitrogen cartridge connected to a length of tubing with a fast acting valve. During operation, the cartridge is punctured in advance and the volume of gas held in place with the valve. Initial development testing with a typical valve showed that chute ejection velocity did not meet requirements. The fast acting valve was able to get the desired chute ejection velocity of 100 m/s. The fast acting valve required AC power, so conversion from a DC battery source was implemented.

B. Flight description

On August 19, 2013, the balloon and payload were launched from the airport in Fort Sumner, NM. A detailed sequence of events is depicted in Fig. 9. Communication with the ground station was working well prior to launch, but a loss of signal occurred at 6,880 ft. It was later determined that a loose antenna connector was the culprit. Onboard data recording was not affected. An uplink command to begin data recording of the camera was sent and received by the capsule at 10,039 ft. Since downlink was not working, the command was not observed on the ground station, so the operator sent it two more times. The onboard data later showed that all three commands were received by the vehicle. From there, all proceeded nominally until a loss of GPS data at 82,655 ft altitude. The GPS was later reacquired during the float period so this event had no impact on objectives. An event that did affect the secondary objectives was that the data card in the GoPro camera filled up after the first 99 min of flight. Unfortunately, the lesson learned that was when using Windows computers, simply deleting the data on a flash memory card (micro HD) is not adequate to clear the memory for future use. As a result, the only video obtained from the capsule video camera was 99 min of the underside of the gondola.

Once the balloon reached the float altitude (100,000 – 102,000 ft), it continued to drift to the west and perform its primary function for the majority of the HASP payloads (time at altitude). The balloon was clearly visible from the ground at 100,000 ft, as shown in Fig. 10. Real-time tracking of the gondola was used along with a real-time landing location prediction to determine the desired time and location of release of the Maraia Capsule. Once the capsule was predicted to land in a very remote area, the release was commanded. It was observed real-time via downlinked video from a downward looking camera on the gondola. The balloon system continued on its nominal mission.

Meanwhile, the Maraia Capsule went into freefall, meeting the primary objective of the flight. At an altitude of 59,622 ft the drogue chute deployed. This was not observed visually, but later determined from the recovered data. The onboard data stopped at 21,357 ft altitude. This was determined to be a combination of a loose wire and the timing of the file writing. When the main parachute deployed, it is believed to have pulled loose the wire providing power to the flight board temporarily, causing the file not to write the data at the coded interval. No data was recovered confirming the main deploy, however, the capsule was recovered with the main chute still attached and was fully intact so it clearly deployed successfully. A recovery photo is shown in Fig. 11. The touchdown point was (34.335303, -105.259085) in a remote location 23 miles from the nearest highway (and 6.4 miles from the nearest road).

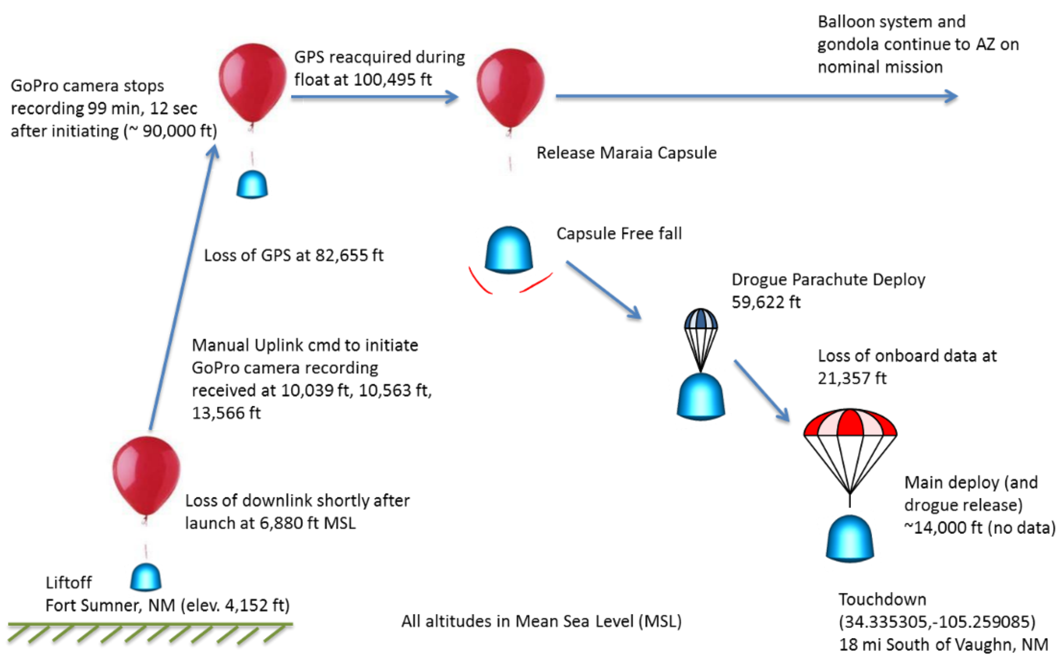

Figure 9. Full Scale Balloon Flight Timeline and Events.


Figure 10. View of Balloon at 100,000 ft.


Figure 11. Maraia Capsule at Post-Touchdown.

C. Flight Data and Reconstruction

The primary test objective of the flight was to obtain data on the aerodynamic performance of the vehicle in flight. In particular, the dynamic aero coefficients are not able to reasonably be determined by CFD. An assumed $C_{m,q}$ model was used prior to flight to predict the expected behavior in flight. The assumed $C_{m,q}$ model was based on Apollo Entry capsule data. The model of the static aerodynamic coefficients – C_A, C_N, and C_m – was developed from CFD. Using the Flight Analysis Simulation Tool (FAST) simulation, results were generated pre-flight. These are compared to flight data in Fig. 12. The altitude vs velocity plot shows that the flight data experienced a slightly lower effective C_A than predicted, however, the basic trend is the same. The angle of attack plot shows that the assumed pre-flight model of $C_{m,q}$ was very different than the actual performance of the vehicle. The pre-flight simulation actually shows a fairly unstable vehicle. The flight showed a limit cycle behavior on the angle of attack and sideslip parameters.

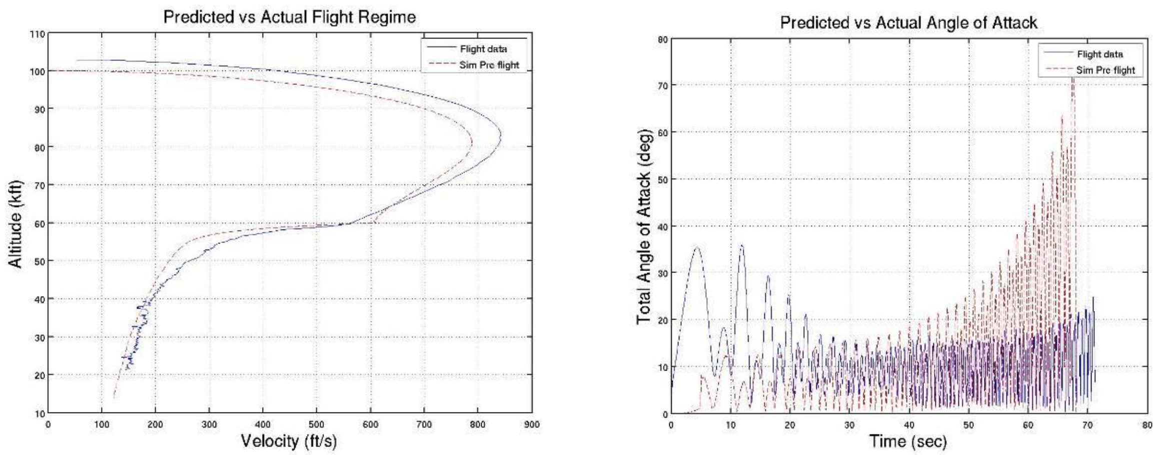

Figure 12. Pre-flight Comparions to Flight Data.

The vehicle sensors supplied position, velocity, attitude, and attitude rate. The aerodynamic model in the FAST simulation was systematically adjusted in order to match the flight data. Figure 13 shows the matched velocity and altitude profile. The match appears to be very good. A constant value of -0.078 was added to CA in order to achieve this matching.

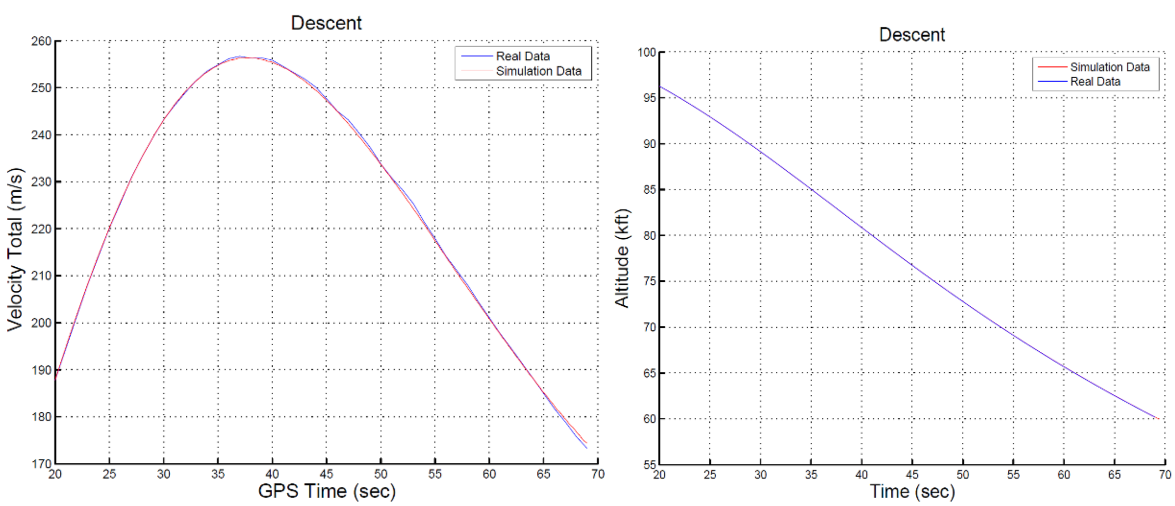

Figure 13. Matching Simulated Altitude and Velocity Profiles to Flight Data.

The velocity vector of the vehicle was provided by the onboard GPS. In order to obtain the velocity vector in the wind axis, an assumed wind profile was required. Estimated day of flight winds were provided by a local weather station, however, this wind profile lead to an unsatisfactory ground track match. An alternative method tested was extraction of the wind profile from the balloon ascent data. This also led to a poor match of the ground track. The vehicle traveled approximately 70 miles from the launch site prior to release, so the local winds may have been very different. The selected method for the wind profile was to modify the wind velocity vector such that the simulation matched the flight data. The resulting wind profile is shown in Fig. 14, in red. The left plot shows the easterly component of the wind vector. The right plot shows the northerly component. The vehicle velocity during this time is included for reference. Figure 15 shows the resulting ground track from using the wind profile, which matches well.

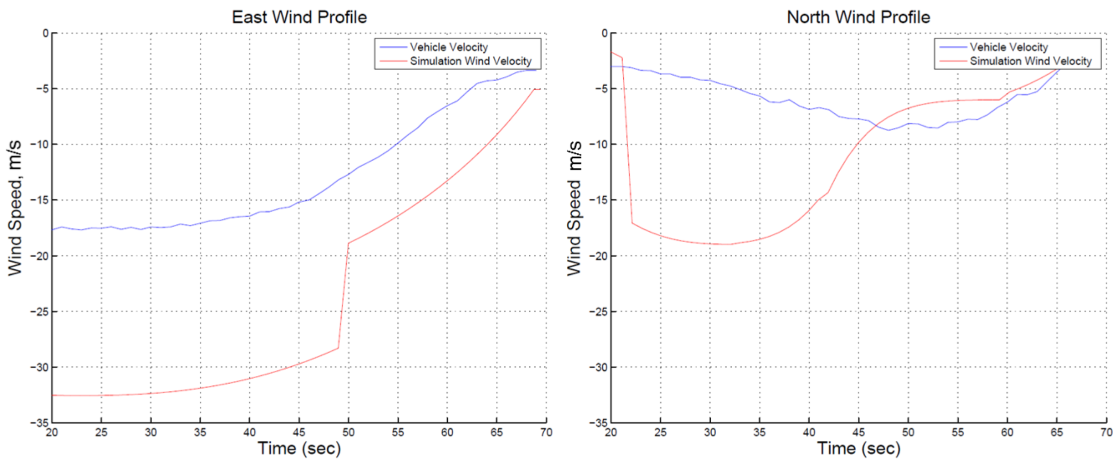

Figure 14. Wind Profiles Used in Simulation.

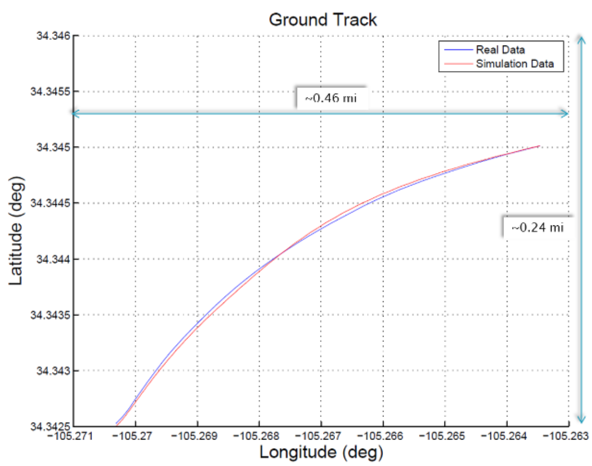

Figure 15. Matching Ground Track.

Once the wind axis was determined, it was possible to find the aerodynmic angles by using the wind velocity vector and the attitude data from the Micrsostrain sensor. A description of that process is not included here.

Figure 16 shows the resulting total alpha from the reconstruction, in blue. The time period shown (20 s to 71 s) is the portion of the flight data that was used for the $C_{m,q}$ model matching and extraction. Note that the maximum amplitude of the total angle of attack is approximately 25 deg. The data shows a very stable capsule with strong limit cycle behavior. The Mach number during the test period is also shown in green. Good quality data was obtained for Cmq model points at Mach = 0.6, 0.7, and 0.8. In red, the final simulation run with the updated $C_{m,q}$ is shown for comparision. The simulation run does a good job of matching the amplitude throughout the 51 sec period. It also matches the frequency well initially. There is an expected frequency variation with dynamic pressure, however, the Cmq model varies only with angle of attack and Mach number, so this effect is not taken into account in the model. This leads to a slight mistiming of the peaks and crossing after about the first 20 s of the simulation run. The alpha total plot exaggerates the error as it is essentially integrated over time. It is possible to initialize the sim at a later time and state and better match the timing of peaks and crossings.

Figure 17 shows the angle of attack and rate comparison. The alpha match is fairly close and the rate matching is even better. Figure 18 shows the sideslip angle and rate matching. This is not quite as matched as the angle of attack channel. It also appears that a change in the sideslip trim angle occurred during the test period. Some possibilities include a change in the center of mass during this time or a wind gust.

Figure 19 shows the extracted $C_{m,q}$ model from the matching. At low angle attack the sign of $C_{m,q}$ is positive, leading to an excitiation at low angle of attack. All of the subsonic curves show a negative slope with angle of attack, leading to a fairly large stabilization effect due to a negative $C_{m,q}$ at high angle of attack. The Mach 1.1 curve is not derived from flight data. Rather it is assumed in the simulation from historical data and included here for completeness.

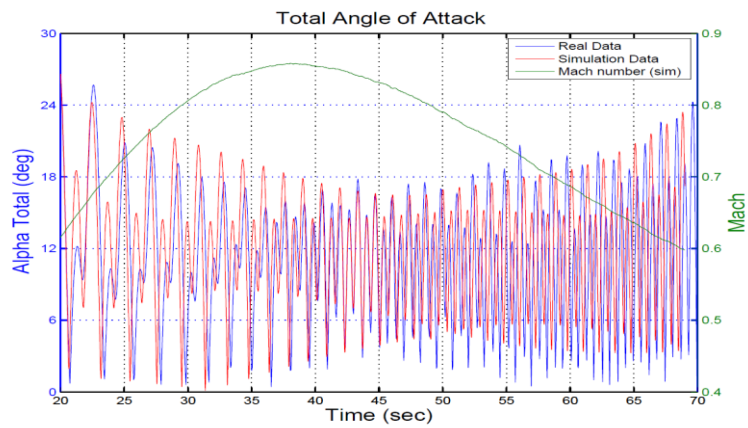

Figure 16. Total Angle of Attack During the Test Period.

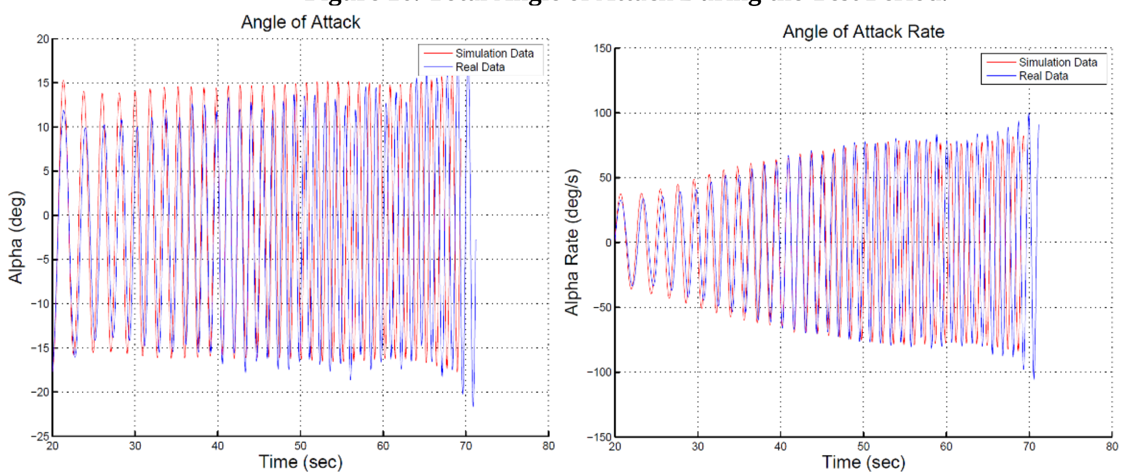

Figure 17. Angle of Attack and Rate During Test Period.

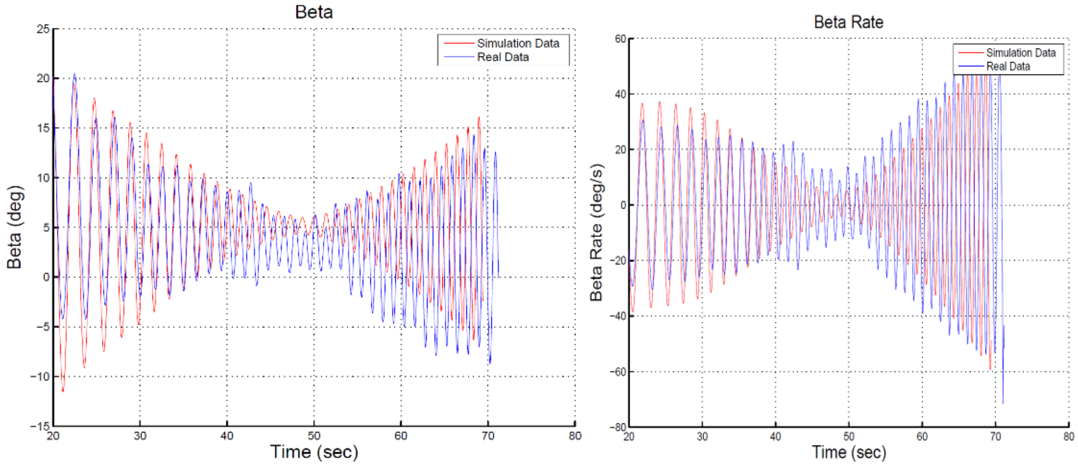

Figure 18. Sideslip Angle and Rate During the Test Period.

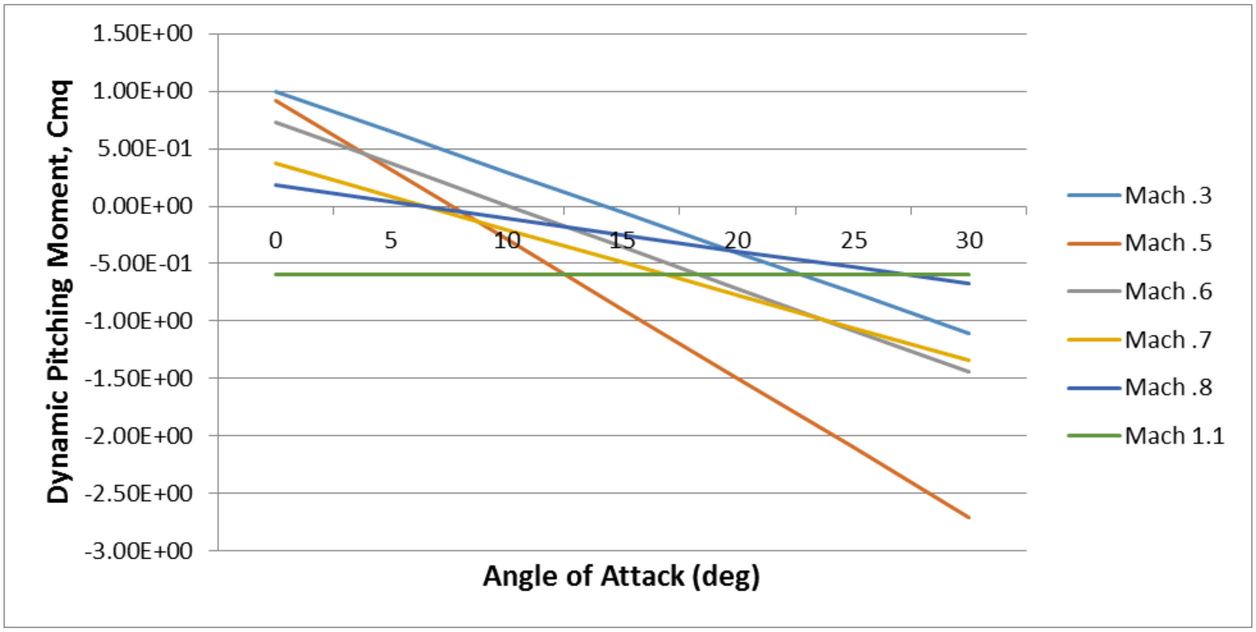

Figure 19. Resutling Dynamic Pitching Moment Coeffcient Model.

V. Sounding Rocket Testing

A 9.7" diameter version of the capsule is to be flown in Nov 2015. The test is funded by NASA's Space Technology Mission Directorate, through the Game Changing Technologies and Flight Opportunities Office. The test will use the Up Aerospace Spaceloft XL rocket and will be tested in New Mexico.

Objectives are follows:
[1] Explore and Investigate aerodynamics and dynamic stability of the proposed Maraia capsule shape at velocities up to Mach 2.5 or greater.
[2] Demonstrate active closed-loop flight control for the proposed Maraia capsule utilizing small thrusters (cold gas).
[3] Capture and record trajectory data (position, velocity, attitude, rates) for the free flight portion of the proposed Maraia capsule shape from just after sRLV platform separation through parachute deployment, to support flight dynamics reconstruction and further simulation development.

The flight profile is shown in Figure 20. The rocket will ascend to 120 km before deploying the subscale Maraia Capsule. The capsule is expected to achieve a peak velocity of Mach 3.5 before deploying a parachute and landing.

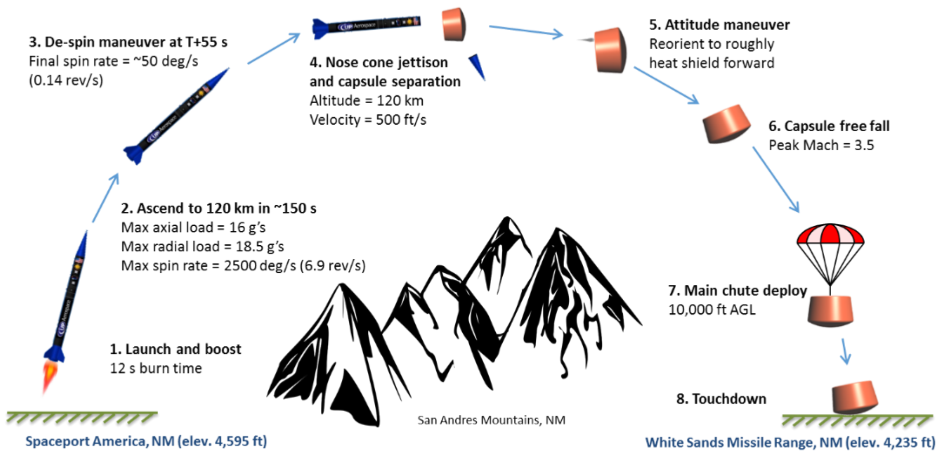

Figure 20. Maraia Sounding Rocket Test Profile.

VI. Conclusion

A robust EDL test program of the Maraia Capsule shape at subsonic velocity has been completed. This has led to significant improvement in understanding of the aerodynamic performance of the shape. Future test plans include attempting to obtain supersonic test data on a subscale sounding rocket test.

Acknowledgments

The authors would like to thank the numerous individuals who contributed to the success of the Maraia Capsule EDL test program and the work shown here. In particular, Adam Hawkins contributed greatly to the FAST simulation matching and $C_{m,q}$ model extraction. The authors are indebted to the contributions of (in no particular order) Chris Cerimele, Danny Newswander, Carlos Ortiz-Longo, Warren Tyree, Chip McCann, Gary Bourland, Phil Stuart, Fred Martin, Leandro James, Kelvin Ruiz, Nicole Dawkins, Steven Sullivan, Chris Iannello, Paul Paulick, Mike Lane, Karl Stolleis, Alejandro Azocar, Breanna Johnson, Matt Honeychuck, Gail Chapline, Debbie Fairbrother, the Columbia Scientific Balloon Facility personnel, and many others. Ron would also like to thank his wife, Jennifer Gruber, for putting up with some rather strange equipment and prototype testing at home and all of the support during the process.

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