AIAA Aerodynamic Decelerator Systems (ADS) Conference
25-28 March 2013, Daytona Beach, Florida

AIAA 2013-1261

Tailoring a Parachute Recovery System for Commercial Space; the Commercial Crew Development II Parachute Recovery System for the CST-100 Space Capsule

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This document observes the transition of government space flight to privately operated space ventures by discussing Airborne Systems (AS) managerial and design approach for The Boeing Company's Commercial Space Transportation 100 (CST-100) parachute recovery system. It follows the CST-100 parachute system development for the Commercial Crew Development II (CCDev II) phase of work. During this development phase Airborne Systems worked with Boeing to adopt only the best of the many program management practices and procedures that are used for government customers. A small dedicated team was formed to provide continuity throughout the project and thus optimize the overall effort. Risk was minimized or avoided altogether by benefitting from the vast knowledge of past and ongoing government programs. This experience helped forecast potential system enhancements such as integration and installation foresight, simplified routing and parachute components, and additional system flexibility. Moreover, by adopting AS heritage systems and parachute planforms to fit the CST-100 recovery requirements, critical time was redirected on design maturation and simplification in order to provide a highly effective, yet lean system. This led to the initial system development, marked by two highly successful development parachute drop tests, thus paving the road ahead for further qualification of the CST-100 parachute system.

Nomenclature

AGL = above ground level
AS = Airborne Systems
BP = boiler plate
CCDev = Commercial Crew Development
CCTS = Commercial Crew Transportation System
CM = crew module
COTS = commercial off the self
CPAS = Capsule Parachute Assembly System
CST-100 = Commercial Space Transportation 100
D_o = parachute reference diameter
DZ = drop zone
EVMS = Earned Value Management System
FHS = forward heat shield
GN&C = guidance, navigation and control
GPS = Global Position System
IMU = Inertial Measurement Unit

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int x = integrated body rate in boiler plate ‘x’ axis (yaw)
int y = integrated body rate in boiler plate ‘y’ axis (pitch)
int z = integrated body rate in boiler plate ‘z’ axis (roll)
IPT = integrated product team
LEO = low earth orbit
MSL = mean sea level
NDI = non-developmental items
PM = program manager
SDRL = Subcontract Data Requirements List
SOW = Statement of Work
WDI = wind drift indicator

I. Introduction

SINCE 2006 the US government has set forth the goal of commercializing space by stimulating competition and jumpstarting several commercial space endeavors. This has been largely instigated through NASA’s space transportation service investments; one of which continued funding for manned transportation with the second phase of the Commercial Crew Development (CCDev) initiative. This spurred the development of the Commercial Space Transportation 100 (CST-100) capsule’s parachute recovery system; designed and manufactured by Airborne Systems (AS) under Boeing leadership. The parachute system plays a crucial role in the partnered Boeing and Bigelow Aerospace’s Commercial Crew Space Transportation System (CCTS) Space Segment. Under CCDev II funding the CST-100 nominal recovery sequence was to be demonstrated by two separate drop tests (Drop Test 3A and 3B). The AS contract was awarded late May 2011; Drop Test 3A occurred early April 2012 and was repacked for Drop Test 3B four weeks later.

II. CST-100 Recovery System Overview

The CST-100 parachute recovery system is designed to provide stabilization and safely decelerate the Crew Module (CM) from six reentry conditions: nominal, pad abort, ascent aborts, drogue boundary, high altitude abort and GN&C power loss[1]. The parachute system derives itself from NASA’s past Apollo program and the ongoing Orion parachute recovery system, the Capsule Parachute Assembly System (CPAS). The Apollo parachute system incorporated a backup system, which included a reserve drogue and main parachute; this for simplification purposes was simultaneously deployed with the primary system[2]. The CST-100 parachute system utilized this parachute system layout to achieve fault tolerance at each deployment stage and to also benefit from the wealth of available knowledge and successful missions. Ancillary to the parachute system, a reorientation system and airbags allow the capsule to touchdown on land, which greatly enhances the chances for system reuse. The system also operates for a water touchdown.

Figure 1. Drop Test 3B view under mains, courtesy: Boeing.

The drop test parachute system was selected and designed in anticipation of the previously described reentry flight scenarios, the requirements recorded in Boeing’s parachute specification[1], and further system qualification as described in the *Requirements for Human Spaceflight for the Trailing Deployable Aerodynamic Decelerator (TDAD) System*[3]. Monte Carlo simulations were completed for both the flight and drop test scenarios to obtain operating loads and dynamic pressures. Design analysis and factors were completed in accordance with standard practice AS parachute design and in reference to the *Parachute Recovery Systems Design Manual* suggested design factors[4]. The system was designed proving positive margins on all components for the flight and drop test scenarios[5]. The drop test parachute system was comprised of two 23 ft D_o Variable Porosity Conical Ribbon Drogue Parachutes and Mortar Assemblies, three 9.85 ft D_o Conical Ribbon Pilot Parachutes and Mortar Assemblies, and three 94 ft D_o Quarter Spherical Ringsail Main Parachute Assemblies. The stated drop test objectives included the following: perform integrated parachute system deployment tests, obtain parachute line deployment dynamics, and obtain drogue, pilot and main parachute performance data[6].

A. *CST-100 Reentry Concept of Operations*

As described in the Boeing parachute specification[1] the nominal reentry case begins with the CM in Low Earth Orbit (LEO) and then descends into Earth's atmosphere. At 20,000 ft (AGL) the Forward Heat Shield (FHS) parachutes are mortar deployed and extract the FHS from the CM. Two independently mortar deployed drogue parachutes are then deployed, disreefed through two reefing stages, and decelerate as well as stabilizes the CM. At 8,000 ft (AGL) the drogue parachutes are released from the CM and three independently operated pilot parachutes are mortar deployed releasing the main retention system and extracting the three main parachutes from their stowed states. The main parachute canopy inflates after line stretch through two disreef stages and establishes a projected steady state descent rate of 27 ft/s. After obtaining steady state conditions the rotation handle attached to the main risers is released, reorienting to the proper landing hang angle, and airbags are deployed prior to a land touchdown providing additional attenuation. The handle and airbags do not operate for a water landing.

B. *Test Demonstration Concept of Operations*

The drop tests demonstrated the CST-100 recovery system sequence for a nominal touchdown on land; excluding the FHS operation. The drop tests began with the test vehicle, Boiler Plate (BP) being lifted to the release altitude and adjusted location accounting for winds. After release and a predetermined free fall to clear lines the drogue mortars were fired and inflated straight to full open (reefing was not required for the demonstration). After maintaining a steady state condition the drogue parachutes were cut away and the three pilot parachutes were mortar deployed. The pilot parachutes released the main retention system and extracted the three main parachutes from their stowed states. The main parachutes inflated through two reefing stages. Rotation handle reorientation and airbag inflation occurred after maintaining main steady state. In order to mitigate inherent risk from unknown test conditions, Drop Test 3A did not deploy the drogue parachute system and went straight to pilot deployments. This aided in characterization of test release conditions and provided an opportunity for adjustments prior to completing a full parachute system operation for Drop Test 3B.

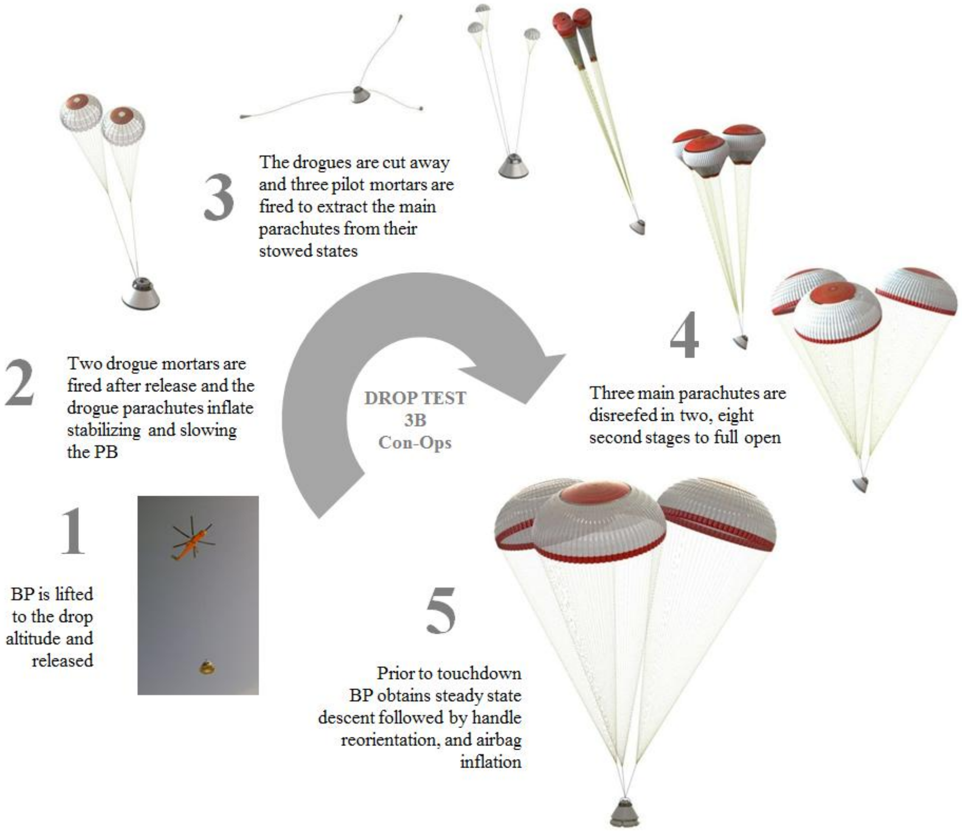

Figure 2. Drop Test 3B Con-Ops, Drop Test 3A skipped part 2.

I. Program Management

Knowing that the CCDev II program had to be efficient, cost effective and dynamic, AS put together a small highly driven team that was dedicated to the program. The Program Manager (PM) had full responsibility and authority for overall compliance with the requirements of the Statement of Work (SOW) and contract, including Management, Engineering, Manufacturing, Test, and Quality Assurance activities. Using a matrix management type of organization structure, the PM drew upon the functional resources needed to meet the program requirements. In this matrix, the PM had full programmatic control and authority for activities on the program and the people assigned to support the program report to the PM regardless of the functional organization to which they belonged. The program was broken down into manageable and meaningful work packages that clearly identified the tasks to be performed and the allocated hours required to complete the tasks. Using this breakdown, along with following the principles of Earned Value Management System (EVMS), enabled the team to control costs and maintain the required schedule.

Communications with Boeing were kept relatively informal except when absolutely necessary. Keeping communication to an *as need* basis, rather than multiple weekly IPT meetings, immensely aided in streamlining the program. Typically, a program of this size and scope would have a long Subcontract Data Requirements List (SDRL) of required deliverables. In an additional effort to streamline the program, Boeing and AS agreed that only the basic amount of documentation was required and when the full program was started all the SDRLs would be re-evaluated.

A big driver in the CCDev II program, compared to traditional government programs, was the approach to risk. Excess conservatism was avoided during Monte Carlo analysis, which avoided over designing the system. Overall risk was managed by foreseeing both positive and negative events that could significantly impact the program. Heritage programs enabled the AS team to identify, assess and provide mitigation planning early on in the design phase of the program.

II. Design Approach

Designing a parachute system to recover a modern day manned spacecraft came with similar space recovery challenges, namely: extreme reentry and deployment conditions, thermal and space environment considerations, mass reduction, volume constraints, system reliability, etc. In addition, the commercial parachute system must satisfy a truly competitive budget, reduced schedule, and provide sufficient reuse of five flights in order to reduce life cycle costs to aid in the profitability of the transportation system. In order to accomplished this task the design approach lowered risk and development costs by relying on existing AS parachute planforms. This has been completed on nearly all space programs as non-developmental items (NDI) or commercial off the shelf (COTS) components[7]. In order to evaluate available components and system compatibility a similar type of *heritage review*[7] was completed prior to contract award. Much of the parachute system would not require a specialized, redesigned product, however, several components would require minor alterations to interface and adapt to Boeing's system along with material evaluations in order to maintain a mass efficient, yet fully capable parachute system. Furthermore, a lean, yet highly effective design team rather than a large, complex team was selected; this helped provide cohesive links between subsystems and in turn maintain budget. This approach, coupled with previous space recovery experience helped ready the way towards system qualification and further flight readiness.

A. Cohesive Design

The smaller team resulted in effective communication between customer requirements and interfaces as well as stimulated a wide system view that helped identify and incorporate redundancy between various subsystems. An example of this was the deployment bags and retention system material selection, which utilized nearly identical materials and constructions. In turn this redundancy helped minimized additional design verification work and helped reduce material orders. Likewise, the parachute seam and joint effort was drastically reduced, as many of the parachute joint constructions could be designed in parallel and evaluated through similarity or were previously completed. The smaller team also helped project organization and efficiency by reducing communication lag and unnecessary process complexity.

The downfall to the relatively smaller team was work distribution, which required filling in the technical workload with successful AS parachute designs to ultimately deliver the drop test parachute system on schedule. Since using current AS parachute planforms were the initial design goal in order to maintain a competitive budget, the smaller team was properly suited for this development project.

B. Utilizing Heritage

As previously discussed a completely specialized system was impractical due to the surmountable associated development costs and research. Therefore, alongside AS's 90+ years of parachute and recovery experience, and insight from Apollo and the ongoing CPAS development many of the components could be pieced together to adequately assess and reduce risk. Furthermore, building off the successful designs allowed work to be focused on alternative system functions such as: simulations and analysis, parachute deployments, integration processes, etc.

In addition to utilizing previous parachute systems and mortars, the retention system selected parachute type COTS components. The system incorporated parachute standard three ring release hardware to restrain and release the main deployment bag prior to operation. This reduced deployment risk and any unnecessary incurred cost or time from a completely redesigned release mechanism. Likewise, military standard attach links and parachute reefing rings were used for the drop test system that will be later modified for accepted space materials and processes prior to qualification and flight.

Alternatively, in order to provide a mass efficient design the main parachute system required resizing and redesign. The main parachute design used previous experience from CPAS, Apollo[1], and alternative ringsail design reports[8]. Along with resizing the main parachute the system weight was reduced with the incorporation of shorter (Apollo-like) risers and implementation of a lighter, sacrificial riser protection in lieu of previous wire rope designs. The shorter risers were estimated to attain sufficient drag efficiencies relative to longer risers without drastic reductions from cluster or wake effects[4,5]. The lighter riser protection also helped mitigate deployment risks and increased complexity associated with higher deployed masses, which therefore helped simplify the drogue and main systems.

C. Simplify, Foresight, and Flexibility

Upfront design simplification and foresight from previous space parachute systems was necessary in accelerating the design towards later system qualification. This included forecasting and avoidance of any unwarranted system complexity. The mains were designed for stowage in identical volumes, which lowered associated packing and shipping costs as well as provided integration flexibility. The pilots and drogue systems were nearly identical; orientation only, designated each configuration.

Foresight into the parachute packing and vehicle integration was aided from previous AS experience with similar systems. This helped avoid integration and deployment complexity, which could drive associated costs and or reduce program progress. Maintaining the main parachutes irregular shape required careful processes and previous experience from Apollo, CPAS, and other large parachute programs to avoid deployment bag growth beyond the required allotted volumes. Vehicle integration was recognized upfront as a critical element in the design process, which helped reduce potential integration and system routing complications, thus in turn reduced deployment risks. An example of this was the riser stowage and attachments in the main parachute bays, which was simplified and minimized as much as possible due to upfront collaboration with Boeing.

Also, as the system required reusability, the design was also focused on establishing flexibility by allowing separation of lines and ease of refurbishment. In addition to effectively protecting the structural elements of the riser, the layered protection also provided the ability of removal and replacement. This allowed the sacrificial layers to be removed if damaged during testing or the protection required alterations throughout the life of the program. The riser and suspension lines for the drogue and mains were attached via textile links, thereby potentially preserving the suspension lines along with the canopy after being cut. The pilot parachutes were separated from the mains until integrated at the vehicle level, which allowed for ease of installation and replacement of parts rather than whole systems.

III. Procurement & Manufacturing

AS maintains a quality system that is AS9100 certified. The system includes procurement methods and procedures that ensure that all materials purchased are in accordance with all contract requirements. Design phase efforts enabled the use of materials that were readily available, already in stock or had short lead times while still meeting the required performance goals. This reduction, or elimination of lead times all together, was critical in meeting the schedule objectives in this commercial program. Minimum purchases were avoided by piggy-backing material purchases with buys for other programs and borrowing small quantity items from in-house stock.

The AS Santa Ana, CA locations maintain a large textile manufacturing facility, which enabled all the textile components to be completed in house and on schedule. It provided the ability to create packing and deployment prototypes prior to the finalized drop test design as well as completion of the system and refurbishment in the most efficient manner and at the same quality standards used with AS space parachute systems.

IV. Test Results

The parachute integration was conducted at Bigelow Aerospace facilities in North Las Vegas, NV. The drop tests occurred at Delamar Dry Lake near Alamo, NV on April 3, 2012 and were repacked and tested on May 2, 2012. The parachute system was integrated onto a test vehicle, BP with simulated upper parachute interfaces and lifted by an Erickson Aircrane, which provided the initial drop conditions. The Drop Test 3A recovery system included the pilot and main parachute deployments and operations in conjunction with the rotation handle reorientation and airbag functioning. Drop Test 3B included the drogue system, and the FHS and associated components were not tested during the demonstrations.

Figure 3. Drop Zone prior to testing at Delamar Dry Lakebed, NV.

A. Drop Test 3A

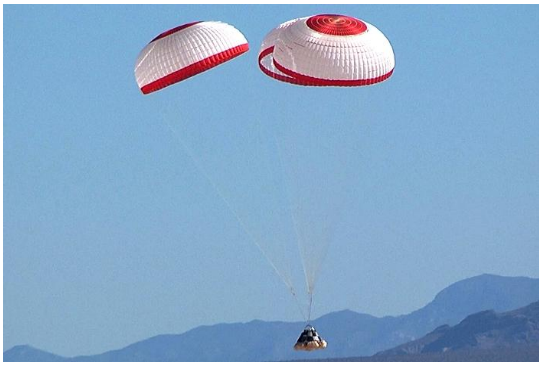

Figure 4. Drop Test 3A prior to landing, courtesy: Boeing.

Drop Test 3A began by lifting the BP to approximately 11,600 ft MSL (6,981 ft AGL) with a forward velocity of 60 kts. Prior to BP release Wind Drift Indicators (WDI) were dropped to help predict the release location; the goal being a BP touchdown at the lakebed center. After a 2.5 s free fall, the pilot mortars fired beginning the parachute deployment sequence. The pilot parachutes were deployed, inflated, and released and extracted the main parachutes from their stowed state. The main parachutes successfully progressed through a reefing stage schedule of 3.5%, 16% and 100% at eight second intervals. Rotation handle deployment occurred 35 s after release with airbags fully inflated approximately 45 s after release. The PB landed approximately 190 s from release northeast of the Drop Zone (DZ) center.

The main riser sacrificial protection was tested during the main parachute deployments when they contacted the outer BP structure. Riser damage was observed on the outer sacrificial overbraid protection, but not apparent on the inner protective layers and structural elements. Little to no damage was observed throughout the remaining parachute system. The outer sacrificial protection was easily replaced and all refurbish able mortar components were used on Drop Test 3B. Onboard IMU data observed less than 2.2 g's of combined riser loading (see figure 5). GPS data was not available for this test.

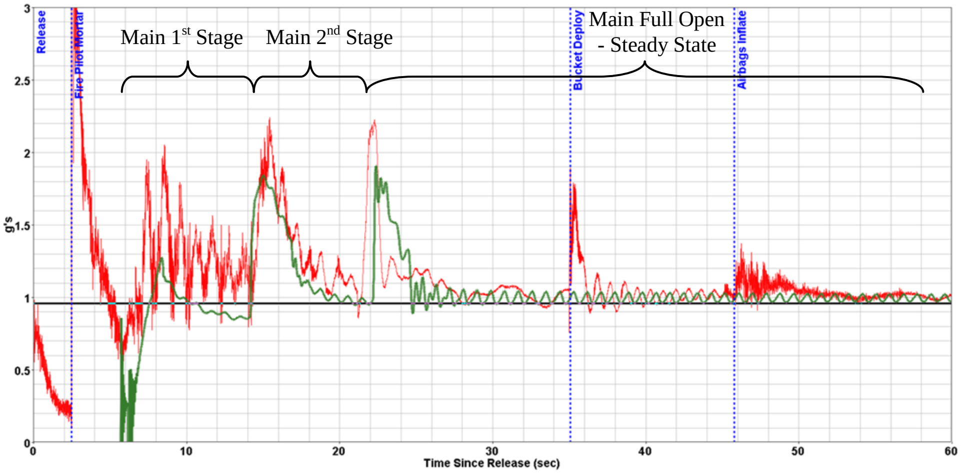

Figure 5. RSS's and filtered accelerometer data vs. preflight riser loads (shown green) for Drop Test 3A.

B. Drop Test 3B

During Drop Test 3B the BP was lifted to approximately 14,000 ft MSL (9,400 ft AGL) and released at an adjusted location accounting for winds, while maintaining a forward velocity of approximately 50 kts. After a 0.5 s free fall (adjusted to reduce initial BP body rates), the drogue mortars were fired and the drogue parachutes inflated straight to full open. The drogue parachutes were cut away 23 s after BP release and three pilot mortars were fired 0.1 s later. The pilot parachutes were deployed, which released the main retention system and extracted the three main parachutes from their stowed states. The main parachutes again successfully progressed through a reefing stage schedule of 3.5%, 16% and 100% at eight second intervals. Rotation handle reorientation occurred 54 s after release with airbag inflation starting approximately 66 s after release. The CM landed approximately 170 s from release and northeast of the DZ.

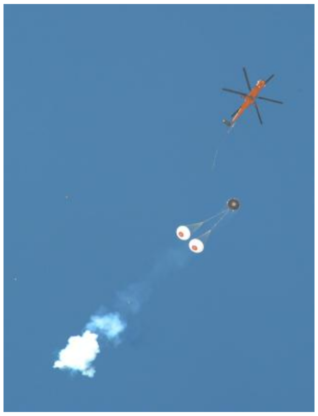

Figure 6. Drogue deploy during Drop Test 3B, courtesy: Boeing

Figure 7. Drop Test 3B prior to landing, courtesy: Boeing.

Due to the high ground winds two mains remained inflated and pulled the BP over, dragging it across the remaining un-inflated main parachute prior to safely cutting the textile links separating the attached riser and inflated canopies. This was an acceptable risk and addressed prior to the drop test. A damage assessment showed only minor to no test induced damages. However, the tipped BP did damage several mortar components and the single main beyond repair; the main has been kept for future degradation analysis.

The steady state rate of descent was estimated from the FlyTec GPS data. The altitude data provided an average rate of descent of 26 ft/s over the interval of rotation handle deployment to touchdown. Rate of descent averaged 27 ft/s during the main parachute steady conditions from 55 s to 114 s after BP drop. Data showed a transient in rate of descent, likely due to a change in wind and atmospheric conditions. Steady conditions were again observed during final descent during which time the rate of descent was estimated at 24 ft/s. Release adjustments did help contribute to reduced body rates prior to drogue deployment (see figure 8). IMU onboard data observed a maximum combined riser load of less than 2.6 g's, which proved similar to predicted values (see figure 9).

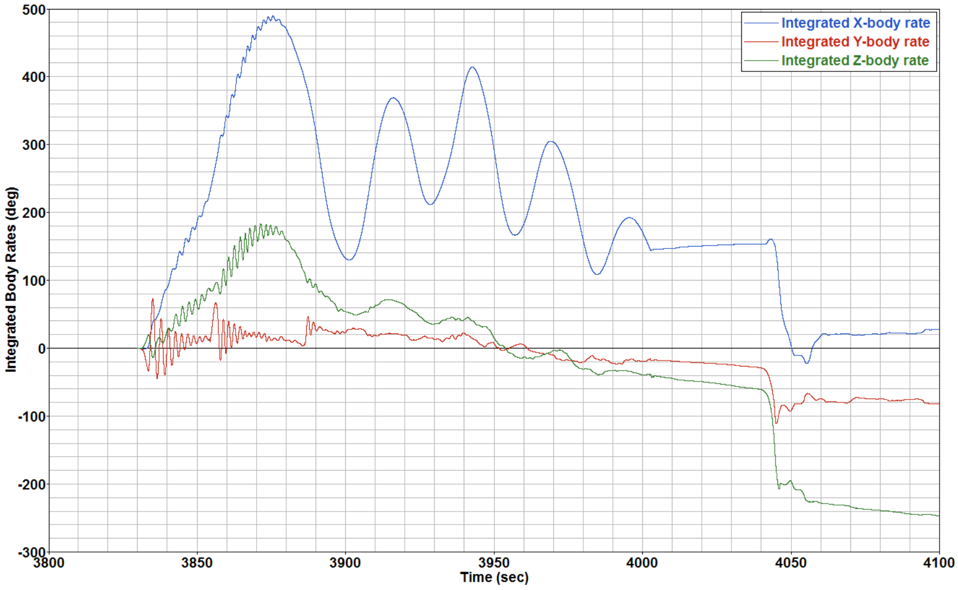

Figure 8. Integrated body rates for Drop Test 3B.

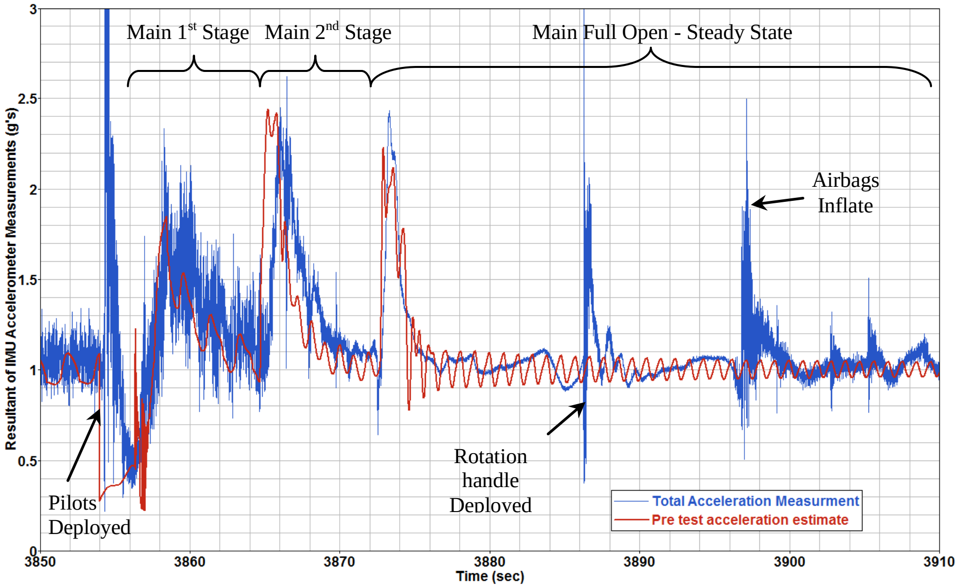

Figure 9. RSS's and filtered accelerometer data vs. preflight riser loads (shown red) for Drop Test 3B.

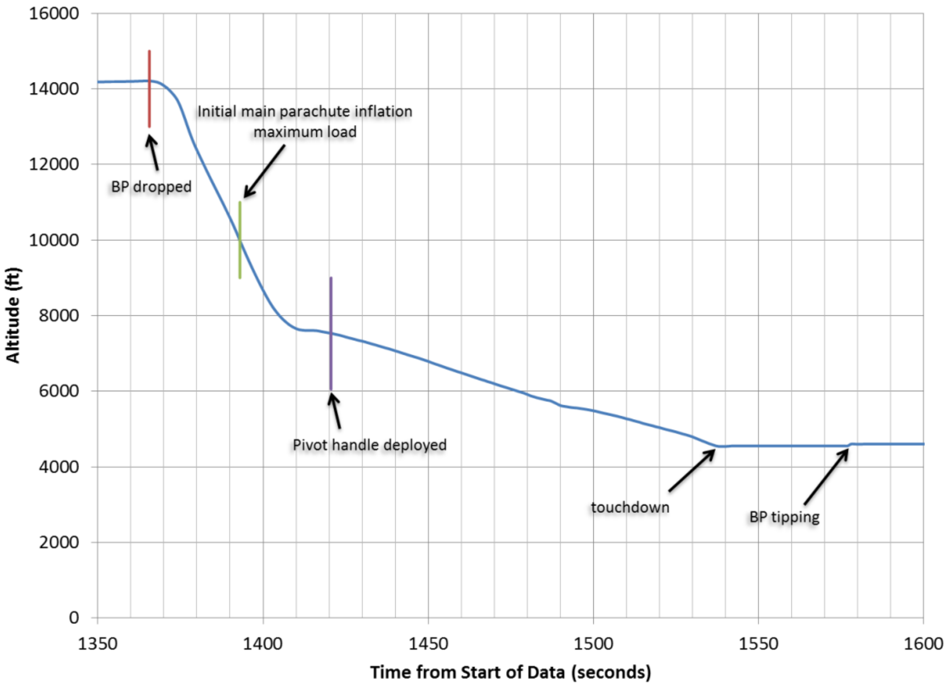

Figure 10. Altitude above mean sea level generated from GPS altitude for Drop Test 3B.

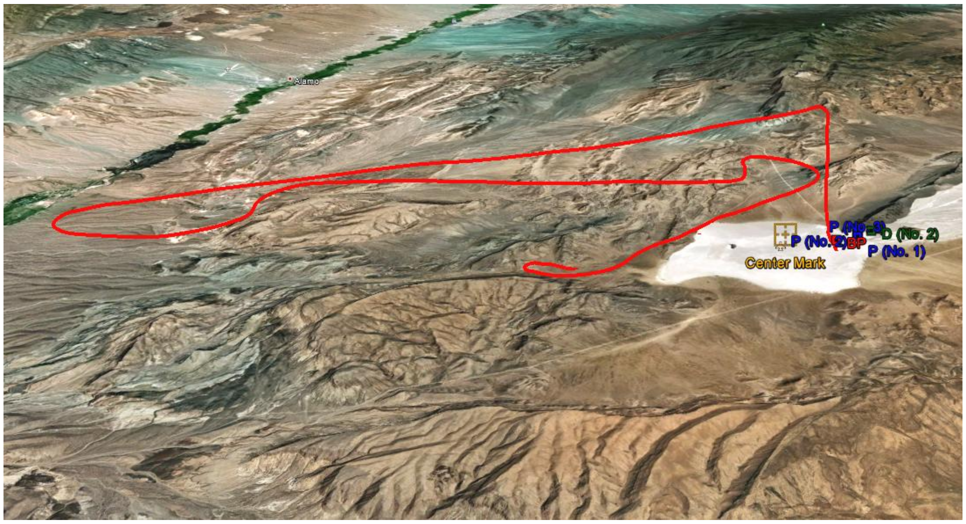

Figure 11. Boiler Plate flight path, courtesy: Google.

V. Conclusion

The development CST-100 parachute system funded under the CCDev II initiative incorporated a lean, efficient team and used existing heritage designs and previous experience to reduce risk, lower costs, and accelerate the program. Using a matrix management type of organization structure along with manageable and meaningful work packages allowed the program to be managed efficiently and smoothly. Review and use of only the best government processes help keep the program on track and within cost expectations. The design team focused on reduction of system complexity, integration foresight, and system flexibility. The parachute recovery system was designed in anticipation of the CST-100 reentry flight scenarios and showed positive margins on all parachute components.

The drop tests successfully demonstrated integration of the drogue, pilot and main parachute systems onto the BP upper bays as well as the deployment and operation of the parachute sequence in conjunction with the reorientation process and airbag operation. Drop test acceleration data recorded deployment events and on board GPS showed main cluster steady state decent rates at or below the predicted 27 ft/s. Negligible test damage was observed for the parachute system components helping to verify system robustness. The tests also demonstrated the successful reusability of the system as well as proving the capability of a relatively low cost and efficient recovery system for commercial space. The initial design and successful testing of the system will enable proceeding with further CST-100 parachute development and qualification.

Acknowledgments

The authors would like to acknowledge the following for program leadership and support: The Boeing Company, *Boeing Corporate Offices*, *100 North Riverside*, *Chicago, Illinois 60606*, Bigelow Aerospace, *1899 W. Brooks Ave. North Las Vegas, Nevada 89032*, and Tony Taylor, *Senior System Engineer*, *The Cimarron Group*, *6855 Santa Monica Blvd.*, *Hollywood, CA 90038*

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