Lightweight Broadcloth Recovery Parachute Testing and Reconstruction

Eric S. Ray
MRI Technologies (JETS), Houston, TX 77058

Sarah E.R. Manning
NASA Johnson Space Center, Houston, TX 77058

Jared Daum
NASA Johnson Space Center, Houston, TX 77058

Early in the Orion CPAS (Capsule Parachute Assembly System) project a main parachute was fabricated with lighter weight broadcloth in the lower part of the parachute skirt in order to look into different options for reducing the mass of the CPAS. At the end of Orion CPAS airdrop testing this parachute was used as a test equipment recovery parachute in order to gather data on the performance of this parachute. The parachute was the single recovery parachute in order to achieve the proper load under the parachute. It was flown on the final CPAS qualification test CQT 4-8 in September 2018.

This paper will include imagery analysis, performance analysis based on all the gathered data, a full description of the configuration of the recovery parachute, as well as a comparison between this parachute and other CPAS recovery parachutes and other CPAS Main parachutes.

Nomenclature

BET	=	Best Estimate Trajectory
CPAS	=	Capsule Parachute Assembly System
CQT	=	Cluster Qualification Test
CPSS	=	Cradle Platform Separation System
DOF	=	Degrees of Freedom
FAST	=	Flight Analysis and Simulation Tool
LWBC	=	Lightweight Broadcloth
PCDTV	=	Parachute Compartment Drop Test Vehicle
PTV	=	Parachute Test Vehicle

Introduction

Throughout the design of the Capsule Parachute Assembly System (CPAS), the team has pursued new ways of reaching goals more efficiently. The CPAS team has never shied away from trying new things to improve the parachutes, give margin or mass back to the Orion vehicle overall, or generally make the system safer. During the early phases of design of the CPAS, it was discovered that the lower sails that only experience full loading after the parachute reaches full open were very robust. At the time there was not a lighter weight fabric with as much testing and history behind it as the nylon the team was using for the sails, however the team wanted to consider options to reduce the weight of the broadcloth in these lower sails since their strength seemed to be more than the parachutes needed. This would have allowed CPAS to reduce mass to the benefit of Orion as a whole.

The team learned about a new lightweight fabric that could possibly be used. Due to a lower level of prior testing with this fabric, CPAS produced a parachute using this fabric for testing. The parachute was used to recover the Cradle Platform Separation System (CPSS) on CQT 4-8. In order to achieve canopy loading similar to that of a main on Orion, only one recovery parachute was used with two additional small stabilization parachutes. Using only one recovery parachute led to much higher loads on the CPSS and all its avionics upon landing, which is why CPAS waited until the last qualification test to use this parachute for recovery.

Trajectory data was collected on the CPSS as well as load date for the parachute in order to allow for reconstruction of the performance of the parachute. After the test, the Analysis Team performed the reconstruction that enabled the writing of this paper.

Lightweight Broadcloth Parachute Description

The Lightweight Broadcloth (LWBC) main is somewhat unique among CPAS parachutes due to the fact that it was manufactured early in the project when aspects of the CPAS were still changing significantly. The LWBC main has a lower porosity than the final CPAS mains have, because it does not include the windows in the canopy that the final mains do. It does however have the same suspension line length as the final CPAS main parachutes.

In comparing the data from the LWBC main to other CPAS test data, there are several important factors to consider. First, CPAS only has signle-main parachute data on relatively few number of tests, all of which were fairly early in the CPAS project. The early CPAS mains had a shorter suspension line length than the LWBC main and current main parachute have, which makes data comparisons more difficult. Second, the one single-main test that CPAS has with the longer suspension line length also has added porosity which the LWBC main does not. So, while comparison to previous one-main tests is helpful, it's not completely conclusive given the other variables that were changing along with the weight of the fabric in the lower sails.

This is illustrated in Figure 1 below.

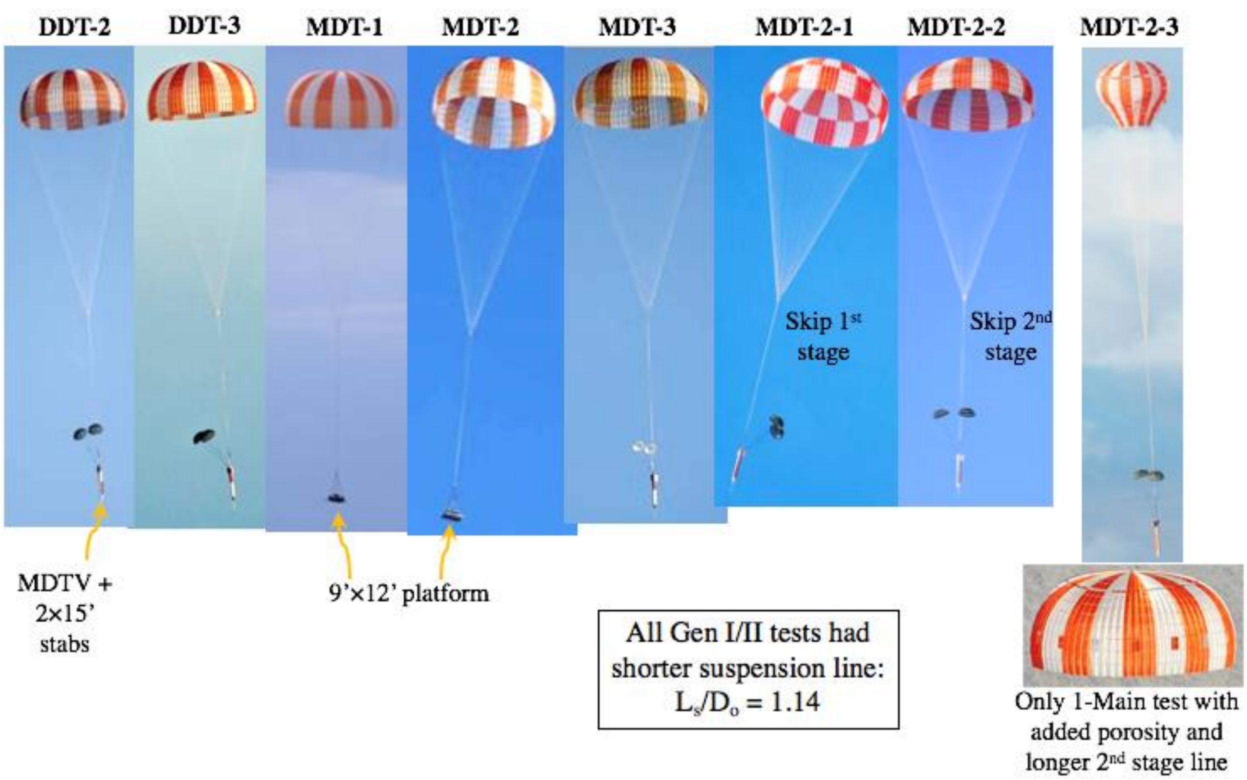

Figure 1 – CPAS Single Main Testing

Concept of Operations and Instrumentation

As mentioned previously, the LWBC main was flown as the recovery parachute on the CPSS in CQT 4-8. Due to the fact that CPAS was not considering a design change to the parachute system, the parachute could not be flown on the Parachute Test Vehicle (PTV) or Parachute Compartment Dropt Test Vehicle (PCDTV) due to the fact that it would have detracted from the CPAS testing of its chosen design.

The CPSS is usually recovered with two CPAS main parachutes in order to reduce the risk of damaging avionics on the cradle as well as the cradle itself. However, with two main parachutes, the canopy loading of each is much lower than it is with two or three mains on the PTV, PCDTV or Orion. In order to have a more useful understanding of the performance of the LWBC main parachute, with a canopy loading similar to two parachutes on the PTV, and to prevent muddying the data by adding a different type of parachute to the cluster, the CPAS team chose to fly only one recovery parachute on the CPSS.

With the increased risk to the test equipment, the CPAS team chose to wait until the final qualification test to use the LWBC main.

As seen in Figure 2 below, the PTV/CPSS were extracted using two reefed extraction parachutes. The separation of the PTV and CPSS took place shortly after extraction, at which point the CPSS descended under the extraction parachutes for ~125s. The LWBC main and the stabilization parachutes were then static-line deployed by the two extraction parachutes.

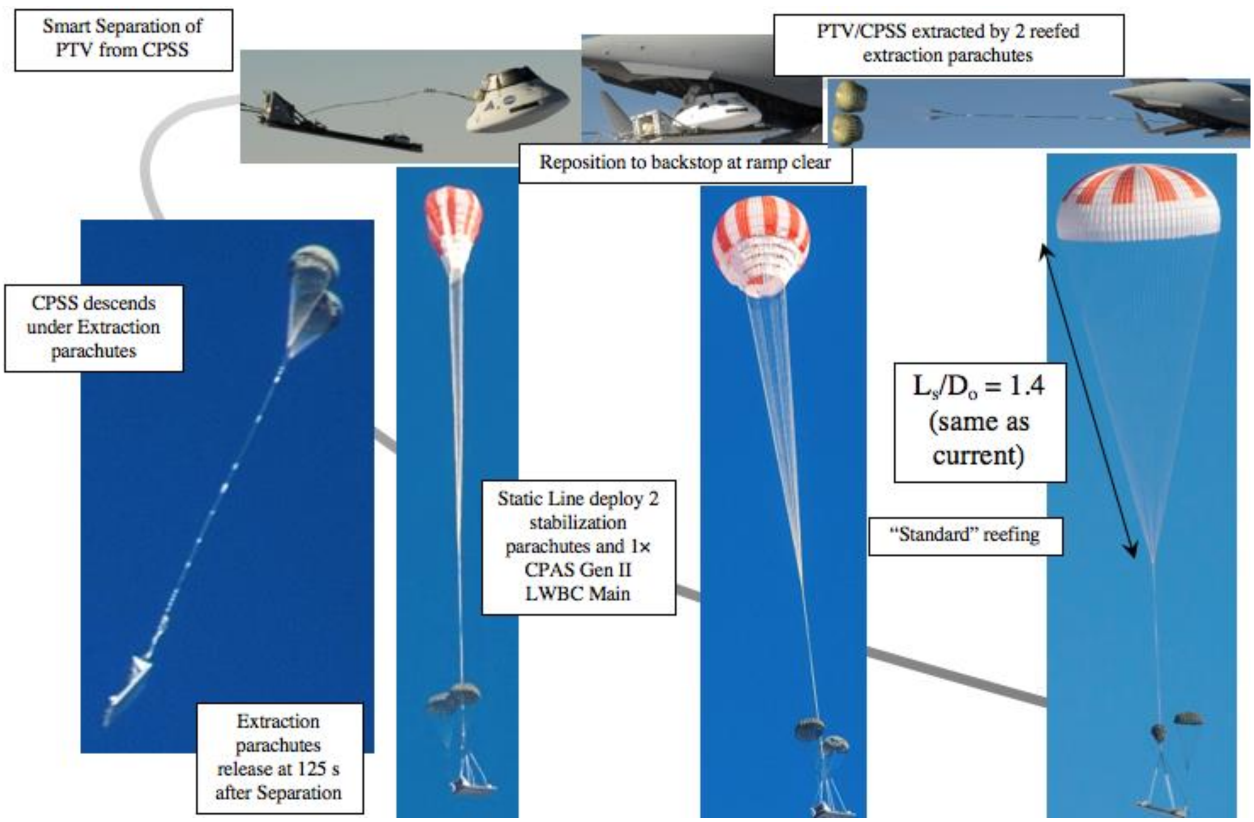

Figure 2 – CPSS Concept of Operations

CPAS instrumented the CPSS with NovAtel SPAN-SE in order to get good trajectory data for reconstruction purposes. An instrumented confluence fitting was used to obtain riser load data on the parachute. Using these sources of data a three degree of freedom reconstruction of the CPSS was accomplished.

Reconstruction Process

In planning this test the analysis team first had to make a prediction about the reefed drag area of the single parachute. As shown in Figure 3, the team used Knacke's predictions along with the data that CPAS has to make predictions.

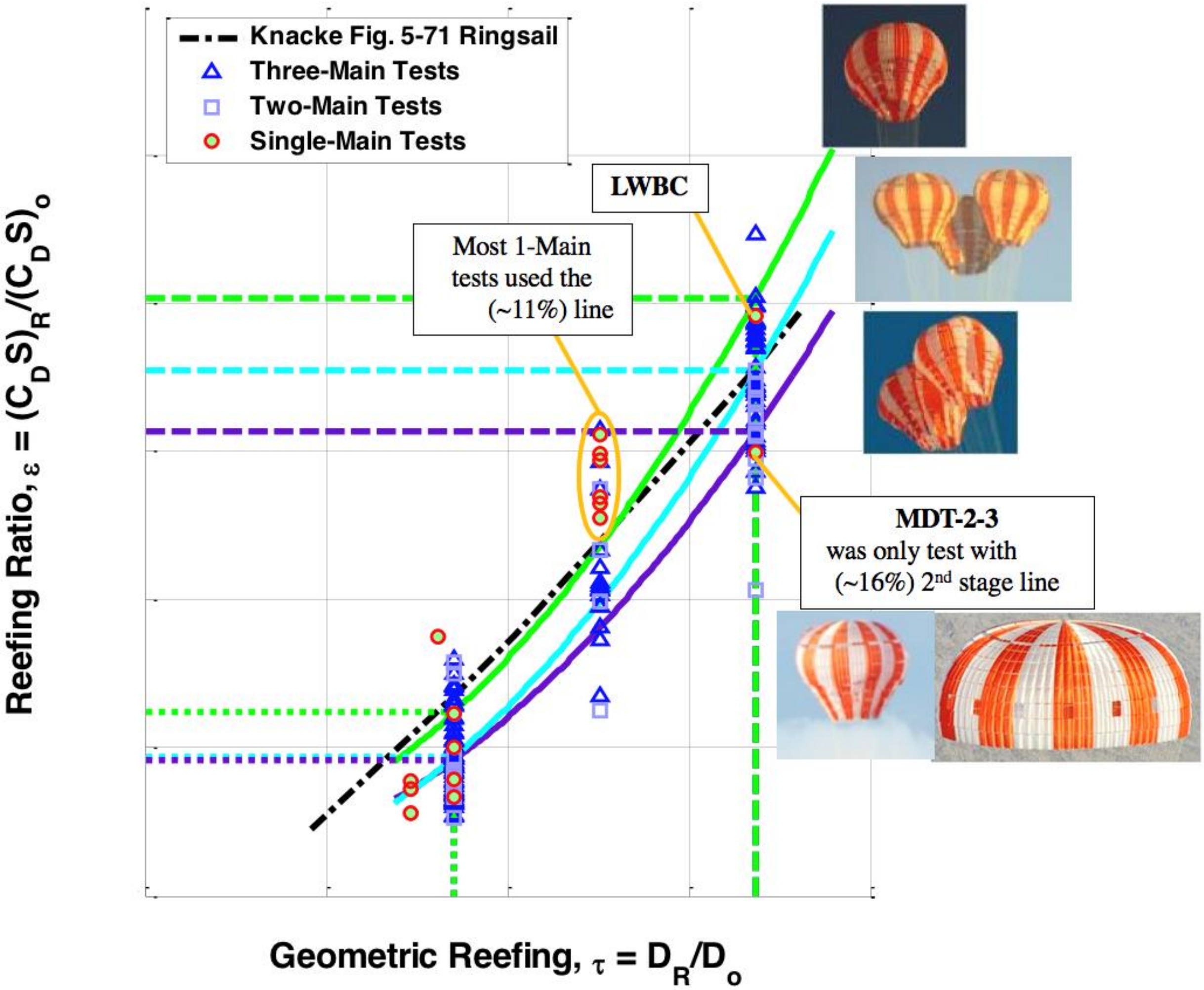

Figure 3 – Predicted Reefed Drag Area Trends

Using these trends the team was able to predict the drag area of both the LWBC main as well as the two reefed extraction parachutes. Before reconstructing the LWBC main, the team had to reconstruct the phase under the extraction parachutes in order to be able to match the trajectory of the CPSS. Using the acceleration data from the IMU, the team was able to start with a fit of the extraction parachute drag area during inflation. As seen in Figure 4 below.

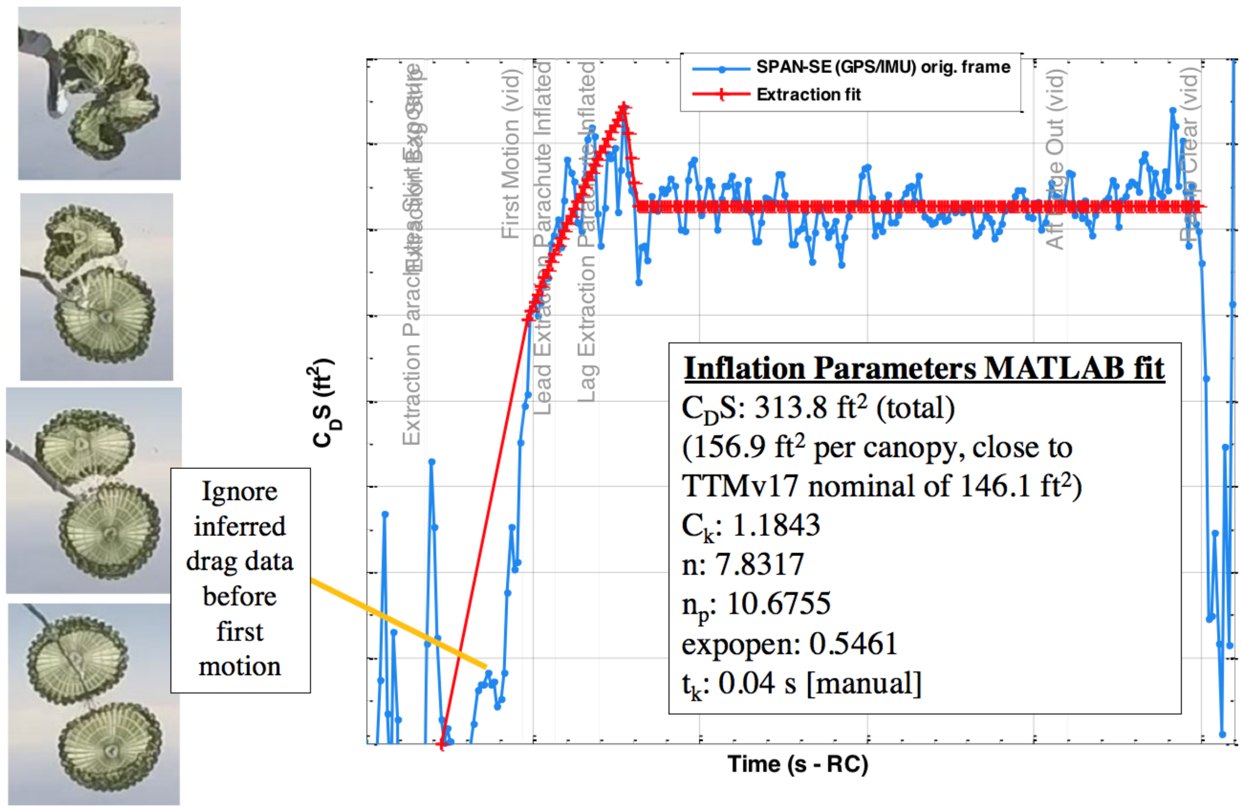

Figure 4 – Extraction Parachute Inflation Fit

Using that fit he was able to show that the reefing ratio of the extraction parachutes was in family with similar reefing line length extraction parachutes as seen in Figure 5.

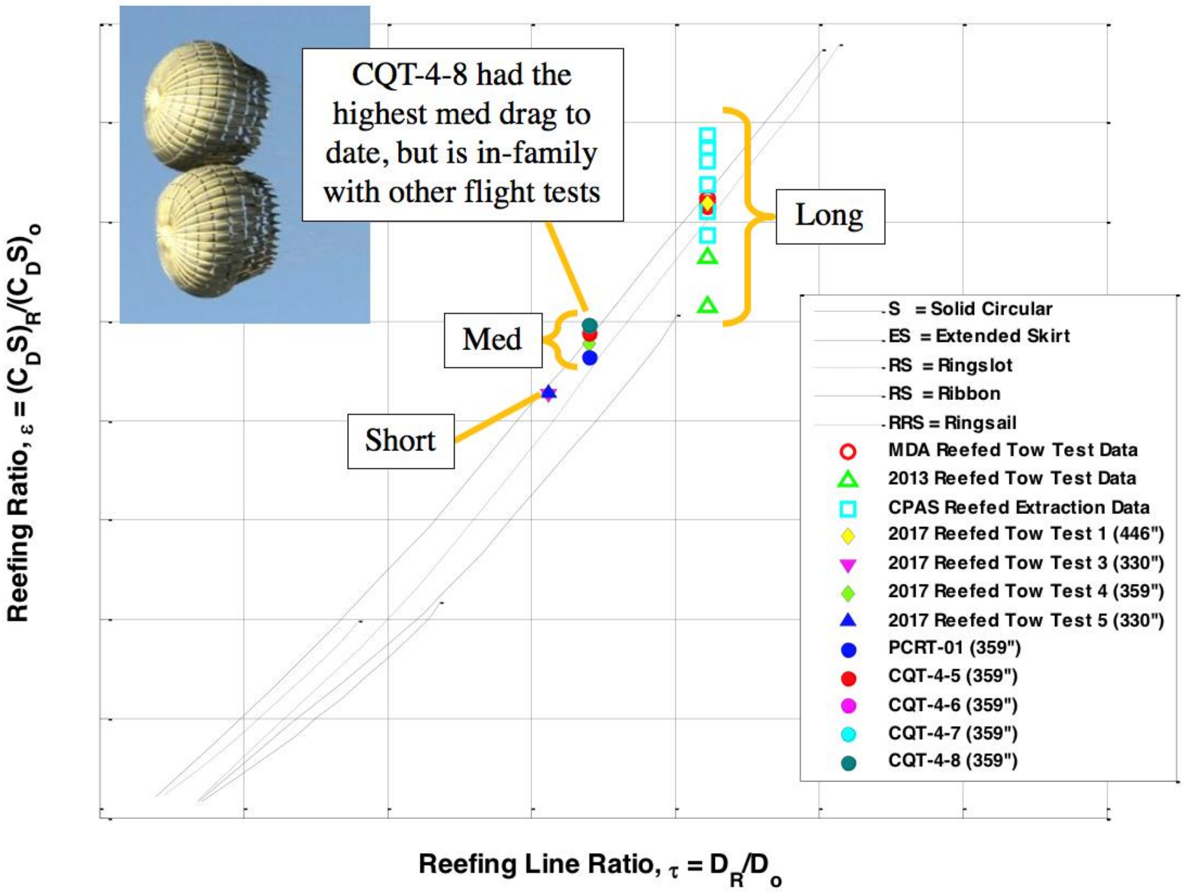

Figure 5 – Reefed Extraction Parachute Performance

Using a combination of the available data, the team produced the Best Estimate Trajectory (BET) for use throughout the rest of the reconstruction in the Flight Analysis and Simulation Tool (FAST). In Figure 6 is the CPSS Pitch Attitude History.

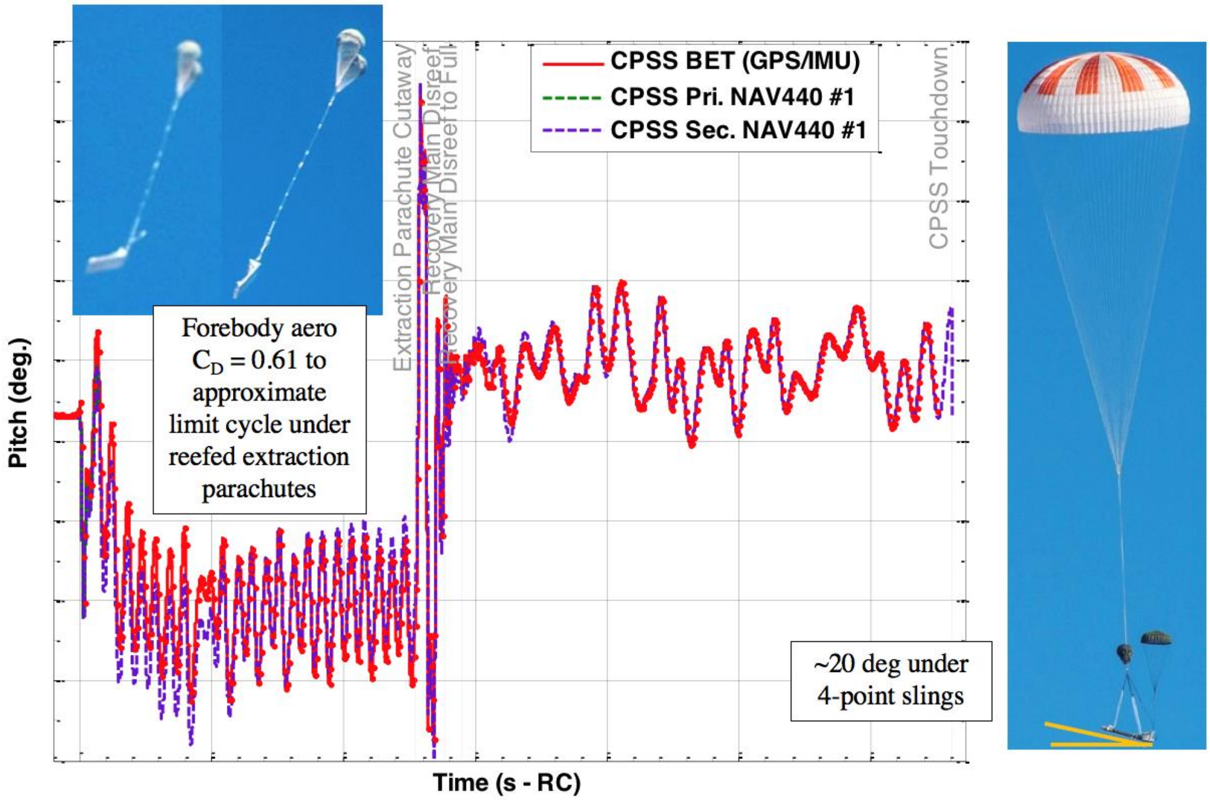

Figure 6 – CPSS Pitch Attitude History

By scaling the drag area first of the extraction parachutes, then of the LWBC main, the team got a very close match of the CPSS altitude and LWBC main dynamic pressure seen in Figures 7 and 8 respectively.

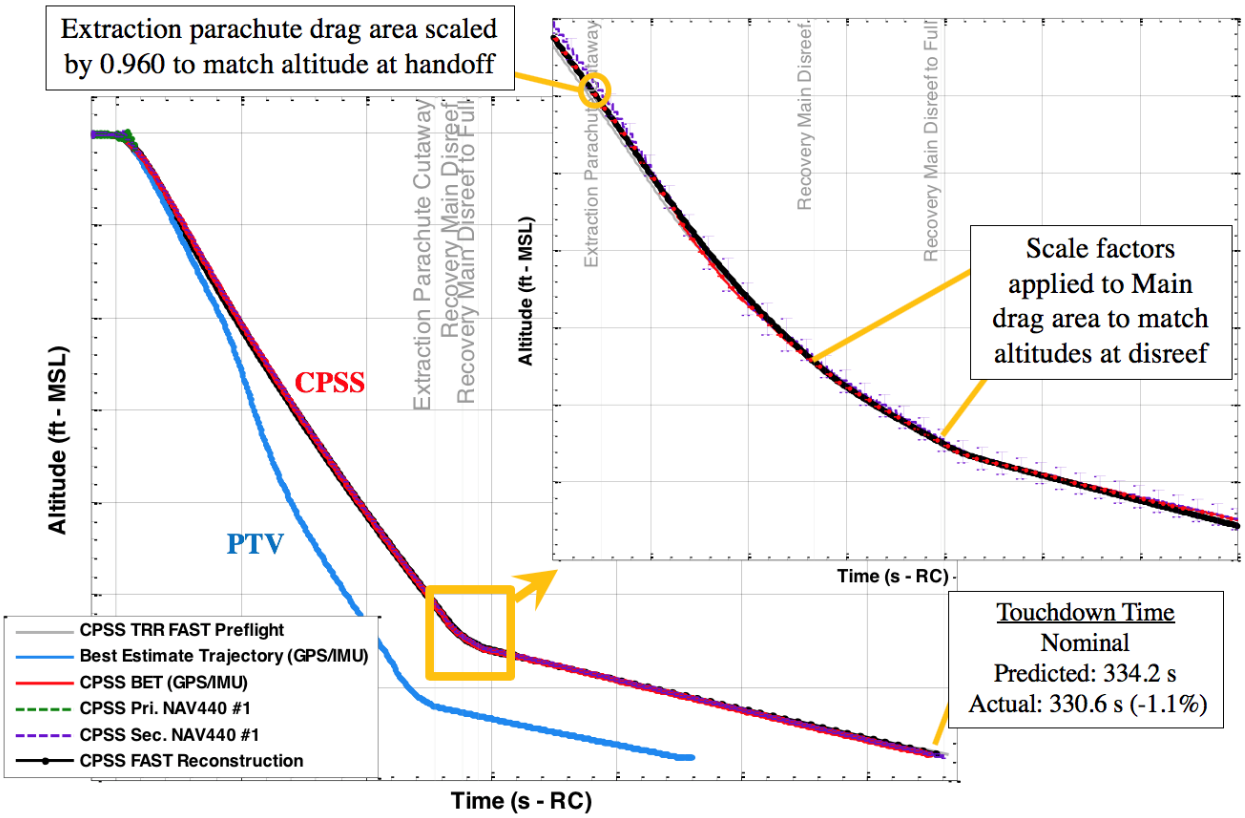

Figure 7 – CPSS Altitude Match

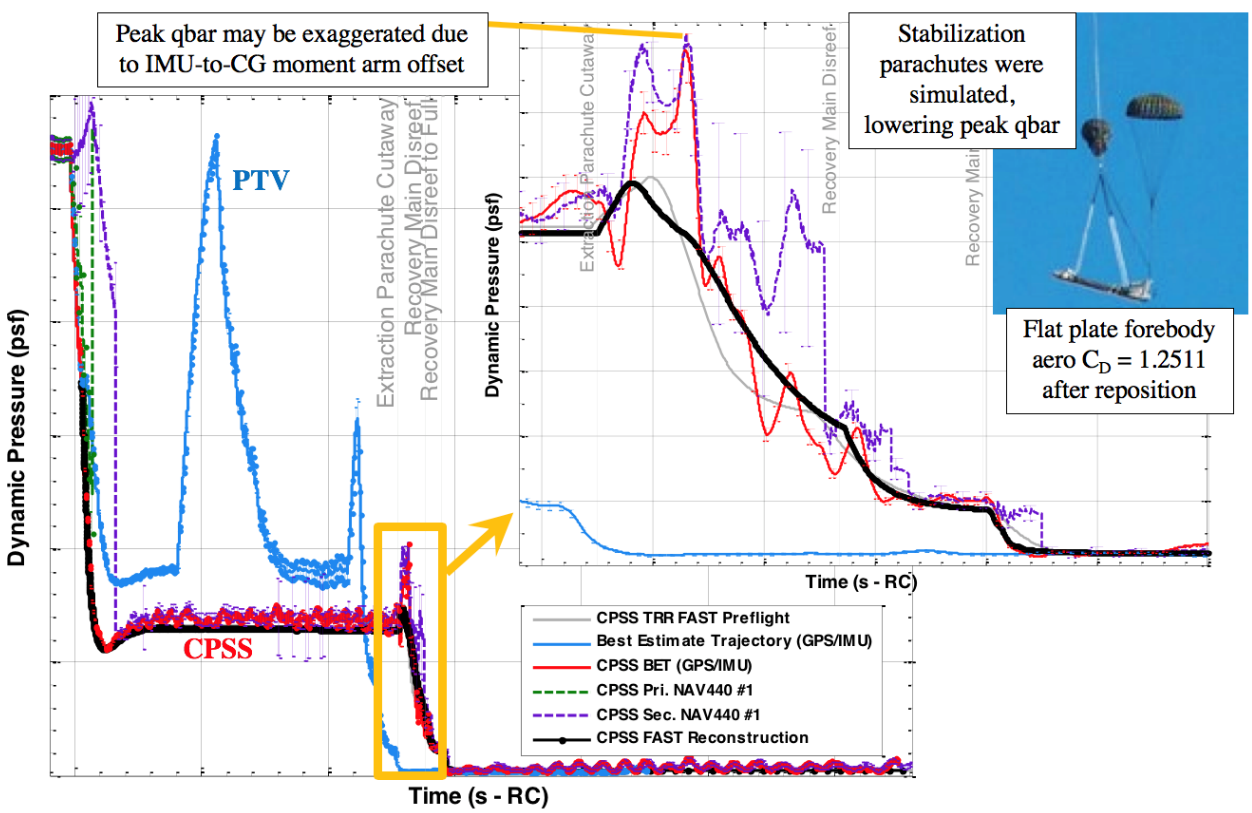

Figure 8 – LWBC Main Dynamic Pressure Match

The scaled LWBC main drag area for the first two stages is seen below in Figure 9, including the inflation parameters for each. The full open drag area and inflation parametes is in Figure 10.

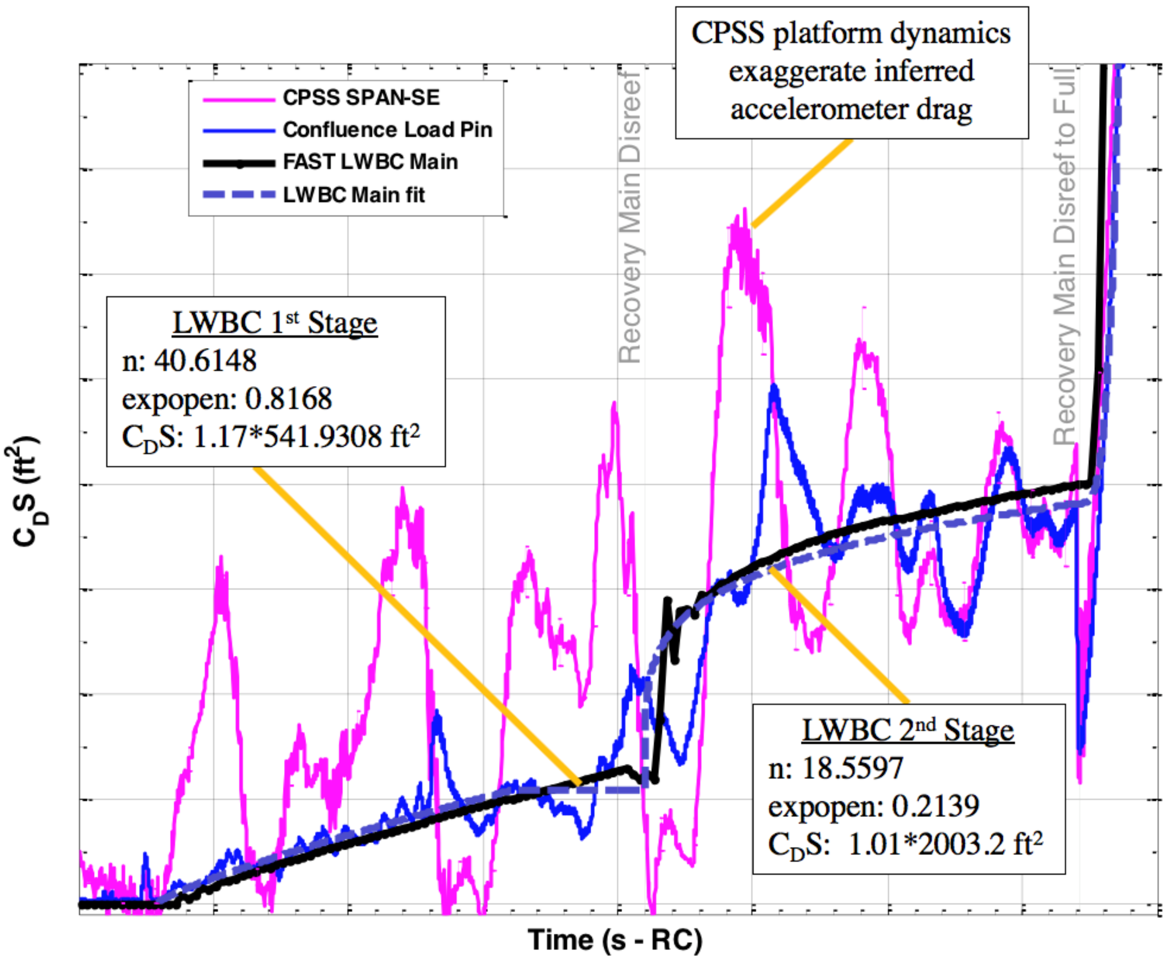

Figure 9 – LWBC Main Reefed Drag Area

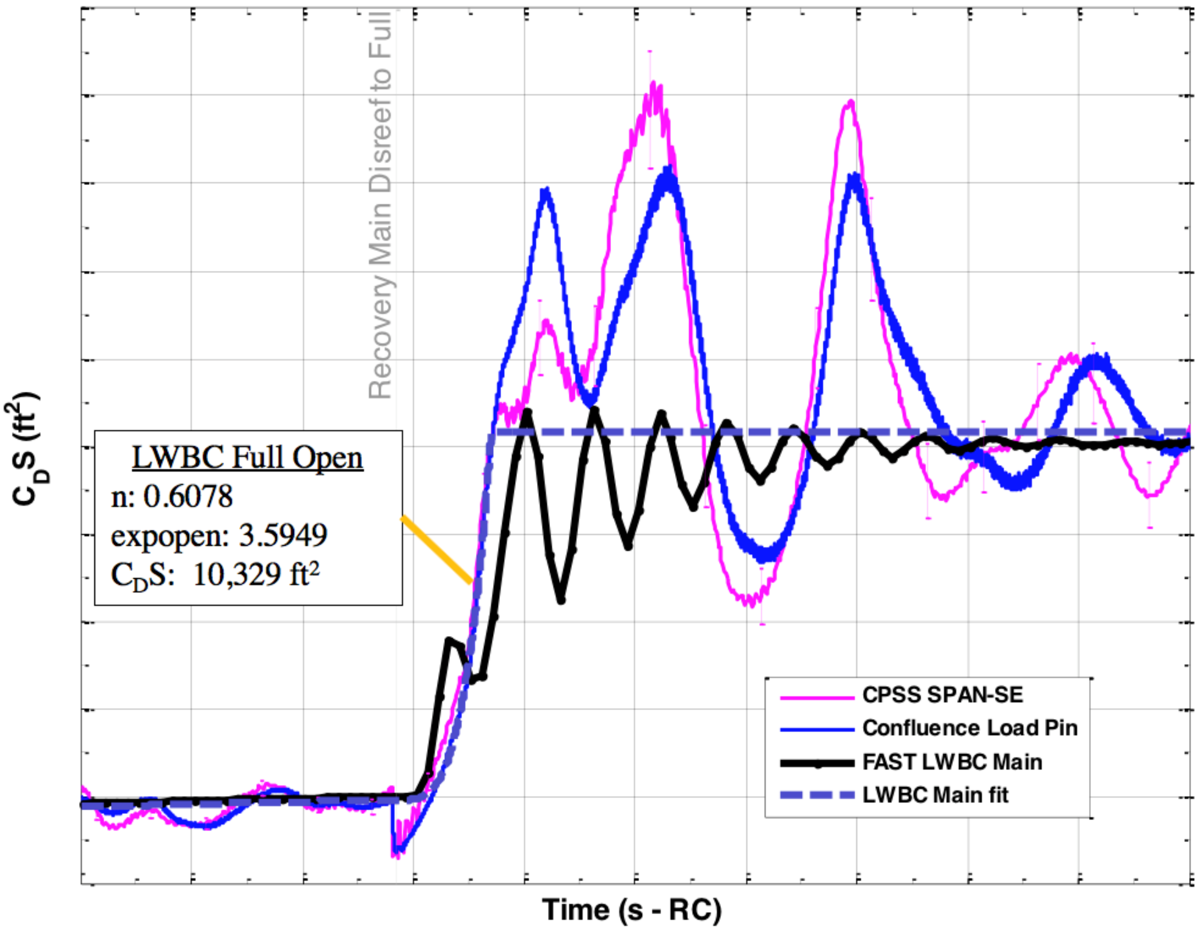

Figure 10 – LWBC Main Full Open Drag Area

Using the drag area that was optimized to match the altitude and dynamic pressure, the LWBC main loads were produced as seen in Figure 11. The simulation produced loads with good similarity to the confluence load pin. There are large oscillations seen in the accelerometer data since the platform was swinging a lot during the first stage of the LWBC main after the reposition of the platform. The swinging damped significantly in the first and second stage.

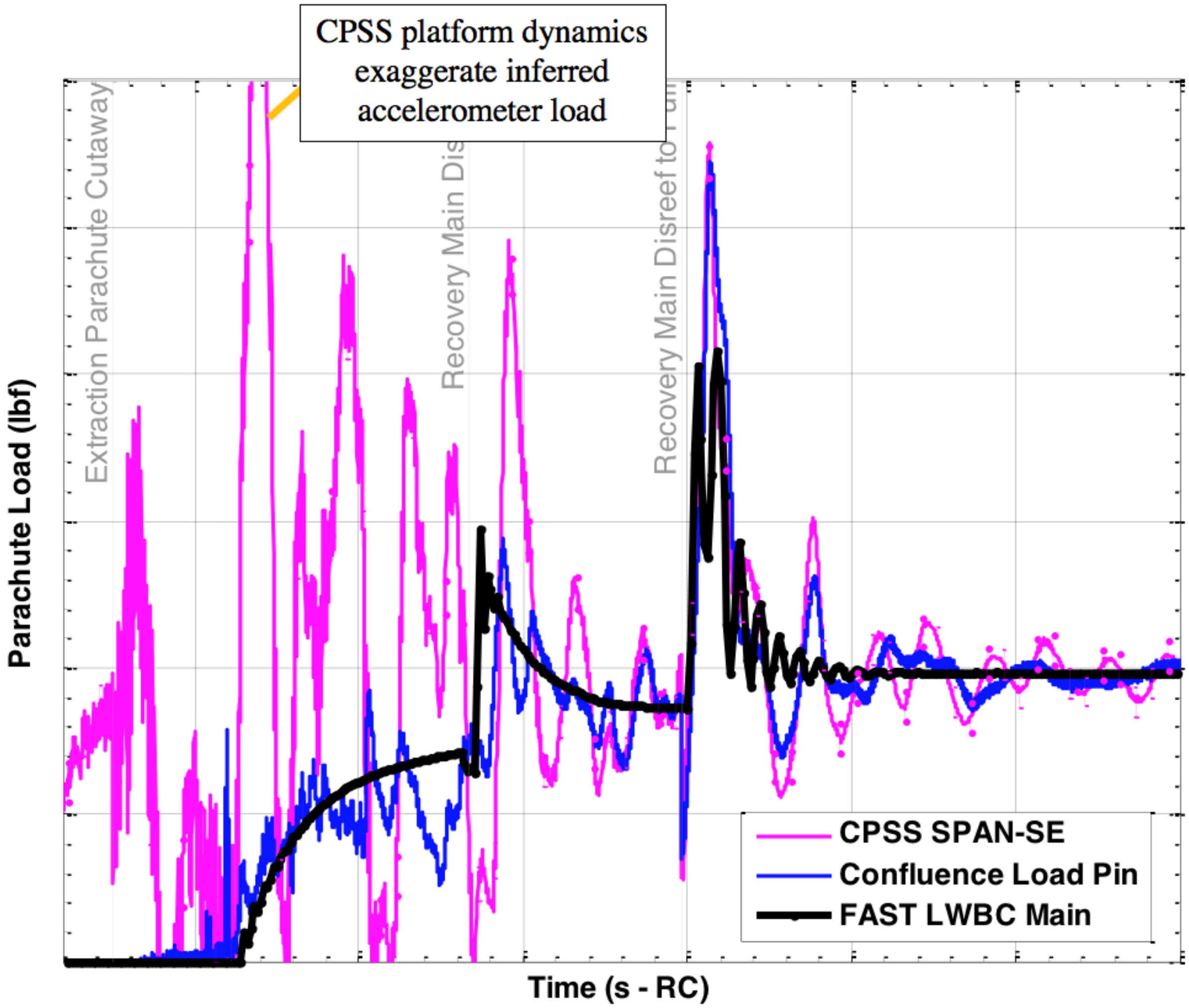

Figure 11 – LWBC Main Load

Findings

Significant canopy breathing and pendulum motion of the CPSS were observed during descent under the LWBC main. This is possibly due to the higher canopy loading achieved for this parachute. It is also possible that the decreased porosity relative to the Engineering Development Unity (EDU) and qualification CPAS mains increased the dynamics.

Figure 12 – CPSS Pendulum

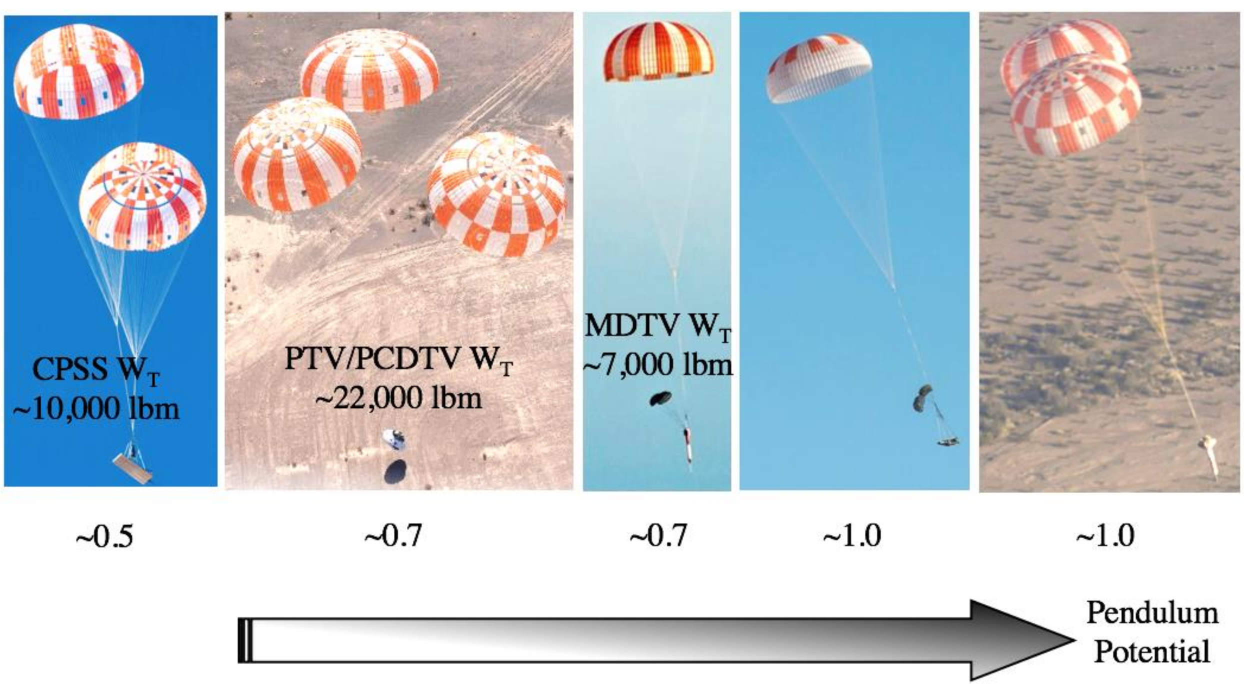

Figure 13 – Canopy Loading

The drag area of the LWBC main fell near the middle of the distribution for one main parachute data, close to the predictions as seen in Figure 14. The inflation parameters for the first stage fell within the pre-existing distribution while the inflation parameters for the second stage and full open fell slightly outside of the convex hull encompassing the current distributions, seen in the following figures.

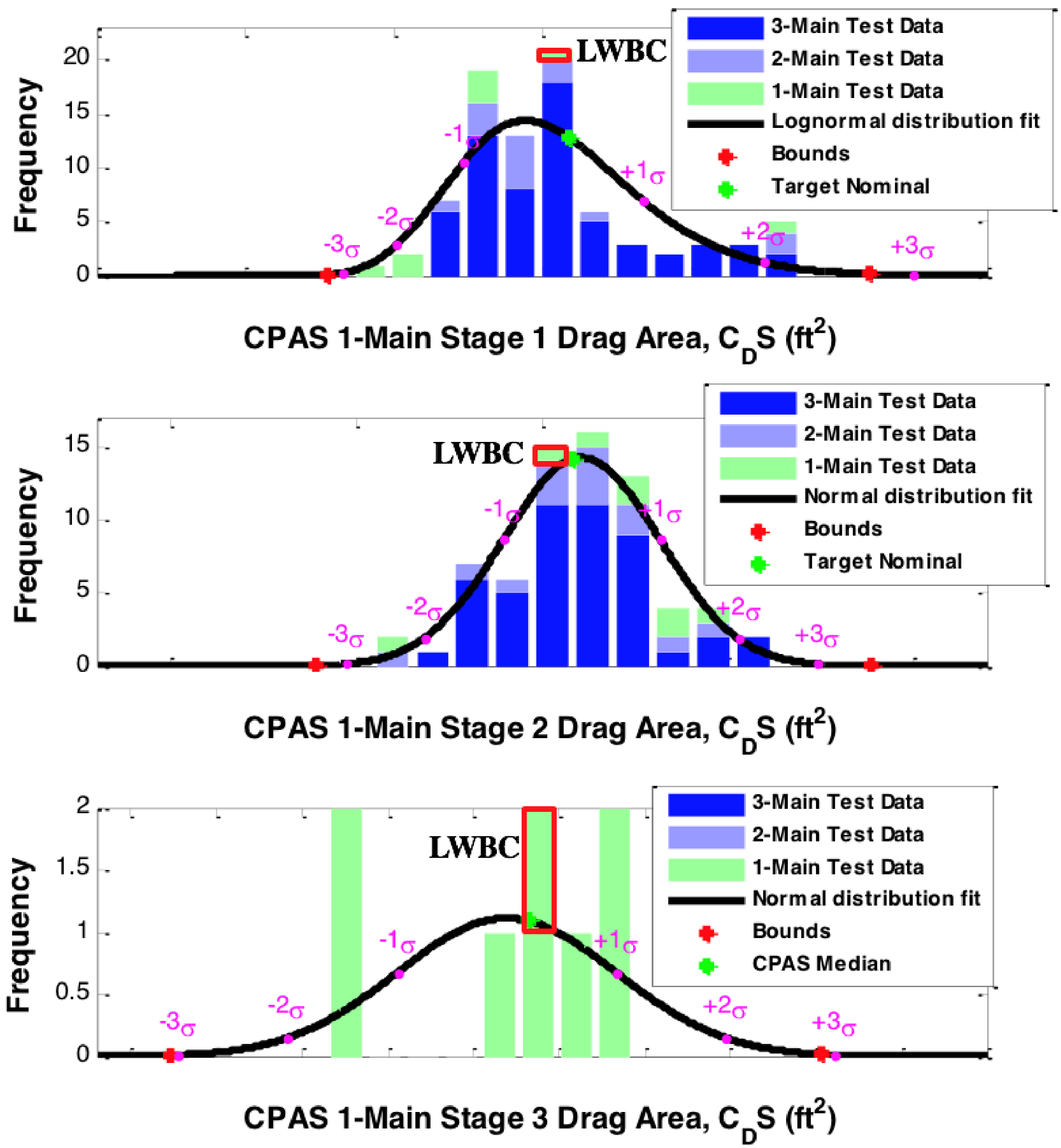

Figure 14 – CPAS 1 Main Drag Area Distributions

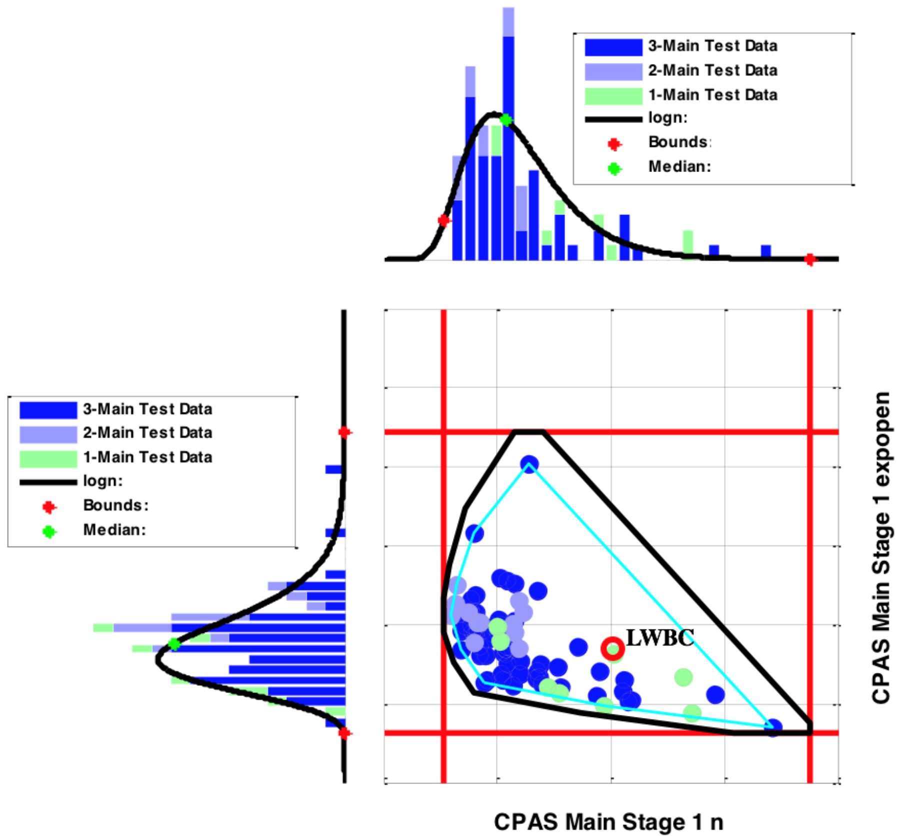

Figure 15 – CPAS 1 Main First Stage Inflation Parameter Convex Hull

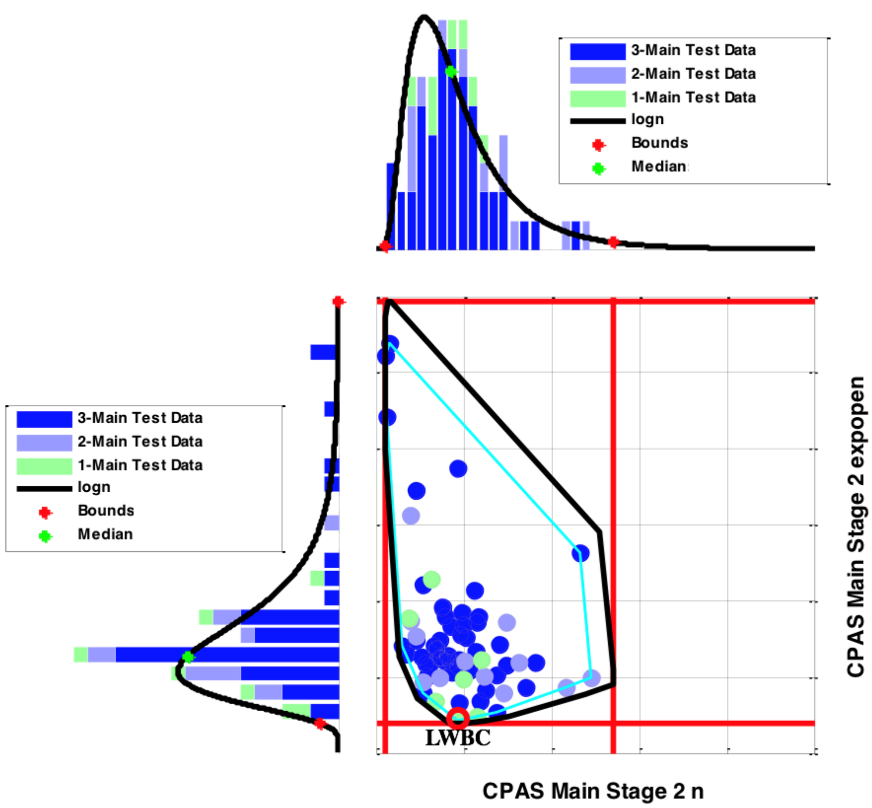

Figure 16 – CPAS 1 Main Second Stage Inflation Parameter Convex Hull

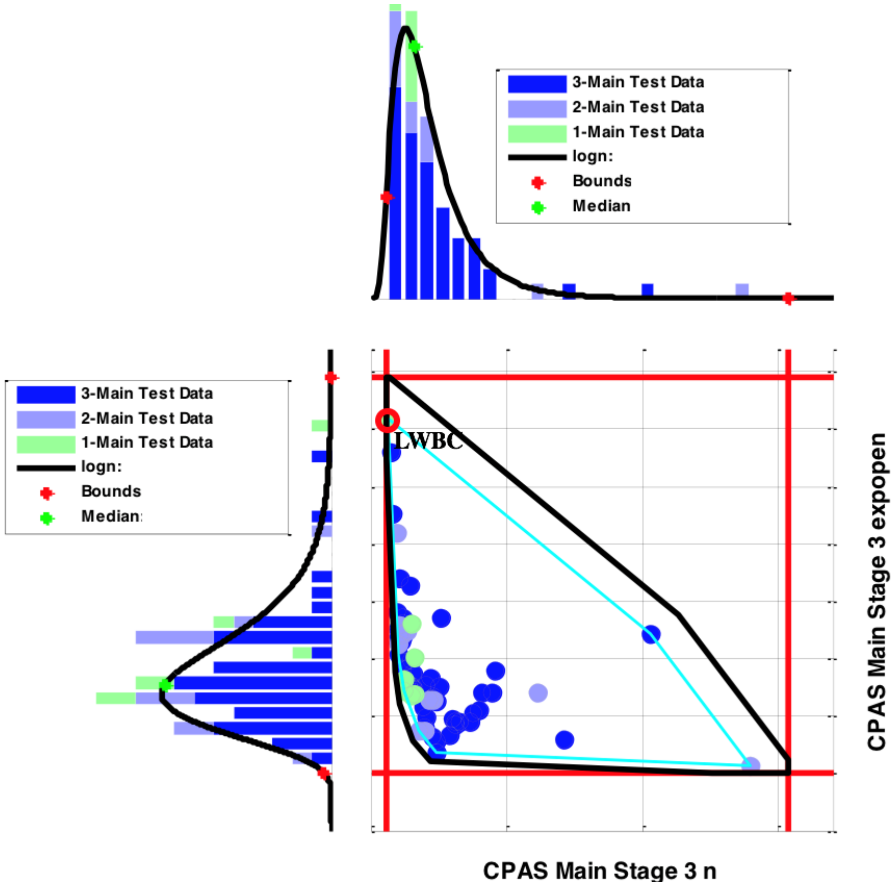

Figure 17 – CPAS 1 Main Full Open Inflation Parameter Convex Hull

Conclusion

Throughout the CPAS project, the team has been doing everything possible within schedule and budget to further NASA and the industry's understanding of parachutes and the materials involved. Thanks to the incredible testing program, the CPAS team was able to successfully demonstrate the LWBC main canopy. They were able to reconstruct the performance in FAST and prove that its performance was close to prediction based on CPAS data and general parachute industry data.