Skipped Stage Modeling and Testing of the CPAS Main Parachutes

Jose G. Varela[1]
GeoControl Systems, Inc., Houston, TX, 77058

Eric S. Ray[2]
Jacobs Engineering, Houston, TX, 77058

The Capsule Parachute Assembly System (CPAS) has undergone the transition from modeling a skipped stage event using a simulation that treats a cluster of parachutes as a single composite canopy to the capability of simulating each parachute individually. This capability along with data obtained from skipped stage flight tests has been crucial in modeling the behavior of a skipping canopy as well as the crowding effect on non-skipping ("lagging") neighbors. For the finite mass inflation of CPAS Main parachutes, the cluster is assumed to inflate nominally through the nominal fill time, at which point the skipping parachute continues inflating. This sub-phase modeling method was used to reconstruct three flight tests involving skipped stages. Best fit inflation parameters were determined for both the skipping and lagging canopies.

Nomenclature

C_D	=	Drag coefficient
$(C_DS)_{p,i}$	=	Dynamic drag area of individual parachute i
$(C_DS)_V$	=	Effective drag area of payload or test vehicle
CDT	=	Cluster Development Test (series)
CM	=	Crew Module
CPAS	=	Capsule Parachute Assembly System
D_o	=	Nominal parachute diameter based on constructed area, $D_o = \sqrt{4 \cdot S_o / \pi}$
DSS	=	Decelerator System Simulation
EDU	=	Engineering Development Unit
ε_i	=	Reefing area ratio for stage i
ε_c	=	Effective cluster composite reefing area ratio
F_i	=	Load for parachute i
Gen	=	Generation
IMU	=	Inertial Measurement Unit
L_r	=	Reefing line length
L_s	=	Suspension line length
MPCV	=	Multi Purpose Crew Vehicle (Orion)
t_f	=	Canopy fill time from either bag strip or disreef to completion of stage
t_{fc}	=	Time when skipped stage canopy completes inflation
Time (s-RC)	=	Time from carrier aircraft ramp clear in seconds
V_i	=	Initial velocity at the beginning of a reefing stage

[1] Analysis Engineer, Aeroscience and Flight Dynamics, 2224 Bay Area Blvd, Houston, TX, AIAA Senior Member.
[2] Analysis Engineer, Aeroscience and Flight Dynamics, 2224 Bay Area Blvd, Houston, TX, AIAA Member.

I. Introduction

THE Capsule Parachute Assembly System (CPAS) analysis team is transitioning from modeling clusters of parachutes as a single composite parachute to modeling individual canopies. Part of the impetus for adding this capability is to better model a skipped stage in a cluster. In an effort to anchor skipped stage simulations, two flight tests have been conducted with skipped stage scenarios, Cluster Development Test (CDT) 3-4 and CDT-3-5.

A skipped stage occurs when the reefing system fails to maintain a constriction of the skirt. Two examples of failures are considered: (1) tension in a reefing line causes it to break and/or the reefing rings are pulled away from the skirt; or (2) a reefing line cutter fires prematurely to sever the reefing line. The reefing system is used to control the timing and severity of peak parachute loads. Therefore, the primary consequence of a skipped stage is a sudden high parachute load in the given canopy.

The Multi Purpose Crew Vehicle/Orion is required to land safely under parachute out and skipped stage scenarios. Effects on the neighboring canopies during this event must also be considered.

II. Modeling a Skipped Parachute Stage

Prior to modeling individual parachutes within a cluster, the CPAS analysis team modeled skipped stages using a composite reefing ratio method. The reefed drag area ratio for a given parachute, ε, is the drag area for that stage divided by the full open canopy drag area[1]. A composite reefing ratio, ε_c, is an average of the effective reefing ratios at the end of the stage. For example, a scenario where one of three Mains skips its second stage reefing is illustrated in Figure 1.

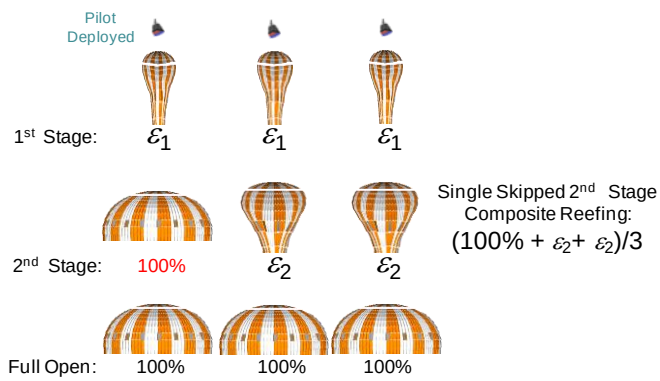


Figure 1. Diagram of a parachute with a skipped stage.

This approach produced a drag area growth curve and subsequent total parachute loads that were conservative and unrealistic. The primary reason being the rapid increase at stage initiation due to the canopy fill constant (n) and the opening profile shape exponent (expopen) terms in the drag area growth as seen in Eq. (1) and Eq. (2).

$$(C_D S)(t) = (C_D S)_{i-1} + \left((C_D S)_i - (C_D S)_{i-1}\right) \cdot \left(\frac{(t - t_i)}{t_f}\right)^{expopen} \tag{1}$$

Where the fill time, t_f, is a function of the reefed drag area ratio, ε_i, nominal parachute diameter, D_o, and initial velocity, V_i.

$$t_f = n \cdot D_o \cdot \frac{\sqrt{\varepsilon_i - \varepsilon_{i-1}}}{V_i} \tag{2}$$

Figure 2 shows in general, for finite mass inflation parachutes, when values of expopen are less than 1 or for small canopy values of n, the resultant drag area growth curve will lead to higher peak inflation loads. Whereas the opposite is the case for value of expopen greater than 1 and large n values.

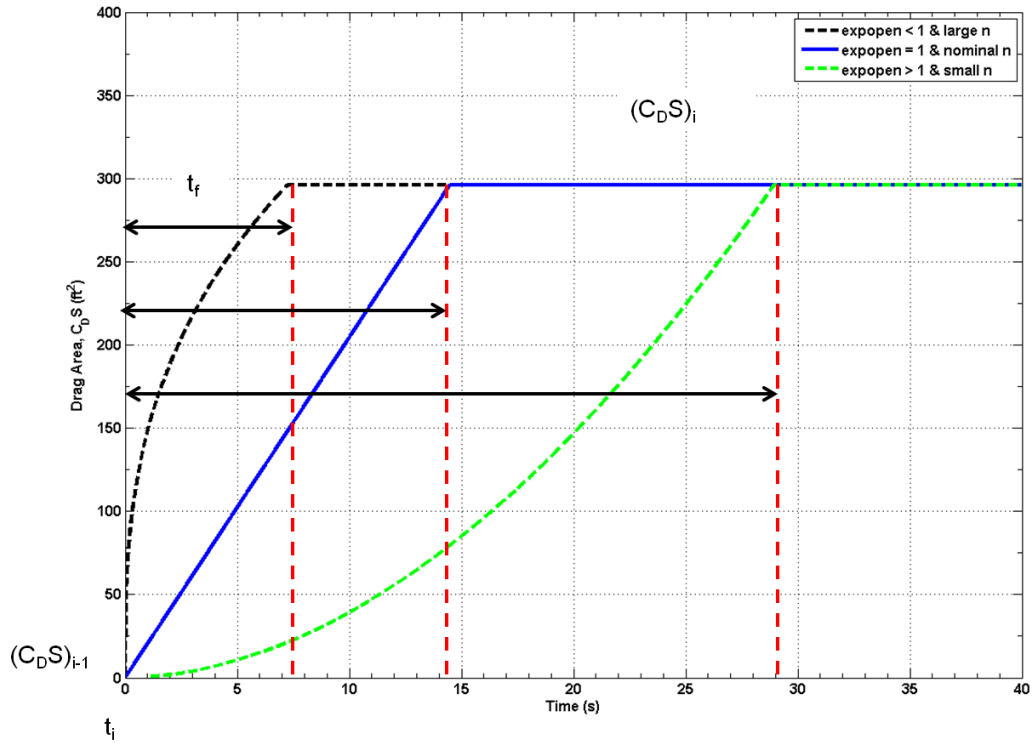


Figure 2. Effect of expopen and n on the theoretical drag area curve for inflation of a finite mass parachute.

A. Inadvertent Skipped Stage Experience: CDT-2-1

The primary objective of CDT-2-1 was to test the performance of a two Main cluster, however, an anomaly led to an unexpected skipped second stage.[23] Both Mains inflated to first stage as expected, however, while in second stage, one of the Mains had a reefing line failure. This allowed the canopy to inflate to full open, which subsequently crowded out the other Main as seen in Figure 3. This resulted in an increase in fill time for non-skipped stage Main.

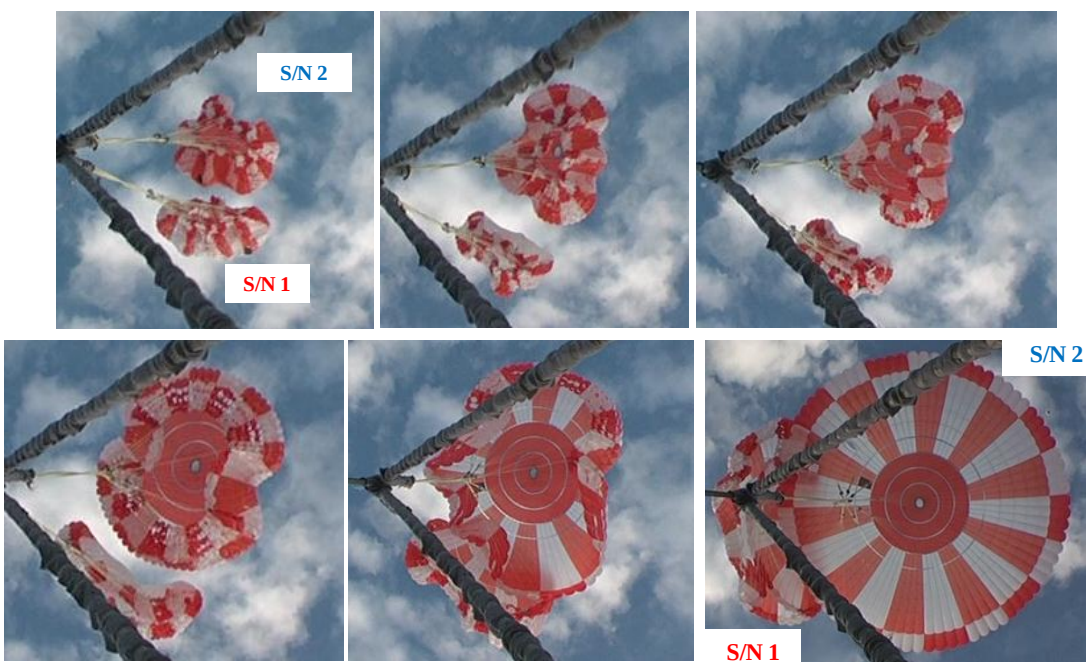


Figure 3. Main inadvertent Skipped 2nd stage during CDT-2-1.

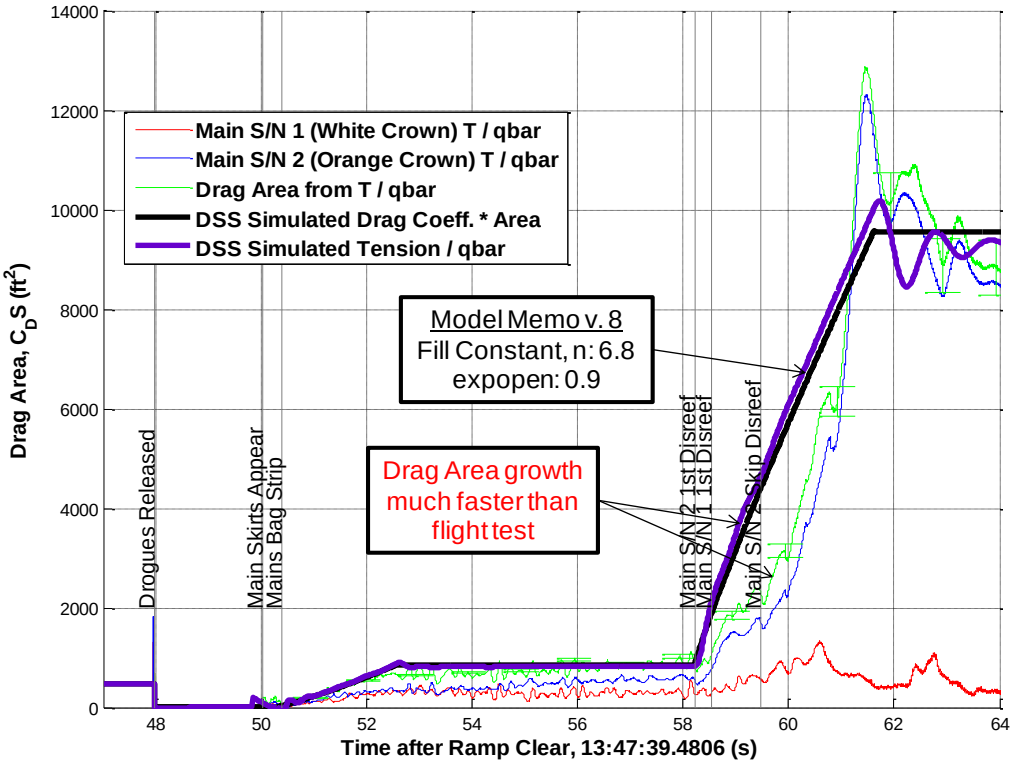


Figure 4. Initial reconstruction of CDT-2-1 Main second stage drag area.

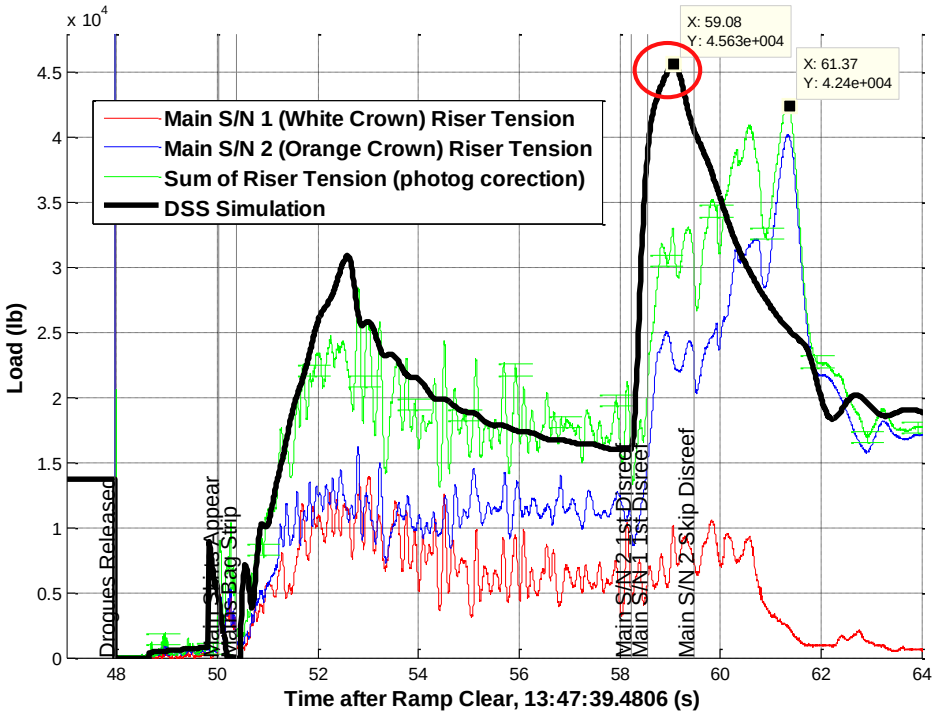


Figure 5. Initial reconstruction of CDT-2-1 Main second stage loads.

Initial reconstructions performed with the Decelerator System Simulation (DSS)[4] using the composite method with inflation parameters that were derived from CPAS Generation (Gen) II testing did not match the resulting loads sufficiently. This was due to the approach of using second stage inflation parameters (expopen, n) in concert with a composite reefing ratio method for time from first stage dis-reef until both reached the full open state. Figure 4 shows that the simulated drag area growth was too abrupt resulting in a simulated peak load that was earlier and larger than the test data.

A different method for modeling skipped stages of a parachute cluster was then implemented. It is based on the assumption that a cluster of parachutes undergoing a skipped stage event can be modeled by breaking the simulation into sub-stages. This concept of sub-stages for CDT-2-1 is illustrated in Figure 6, with a generalized drag area growth plot in Figure 6. The cluster will nominally inflate to the second stage reefing drag area, $(C_DS)_i$, until completion of the canopy fill time, t_f. After this the skipped stage parachute will continue to inflate allowing the drag area growth curve to increase until reaching the composite skipped stage drag area, $(C_DS)_c$. This process requires iteration in order to establish a value for t_f

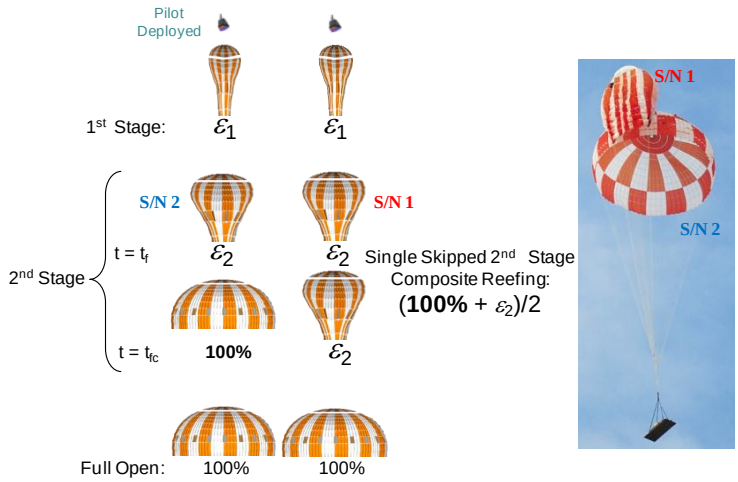


Figure 6. Sub-stage implementation of a skipped second stage for CDT-2-1.

Implementing this method resulted in better reconstruction of the test data which can be seen in Figure 8 and Figure 9. Using Main second stage inflation parameters from test data resulted in a reasonable fit between the planned disreef and the skipped disreef. An empirical fit for the fill constant and expopen were determined for the skipped portion of second stage in order to best fit the data.

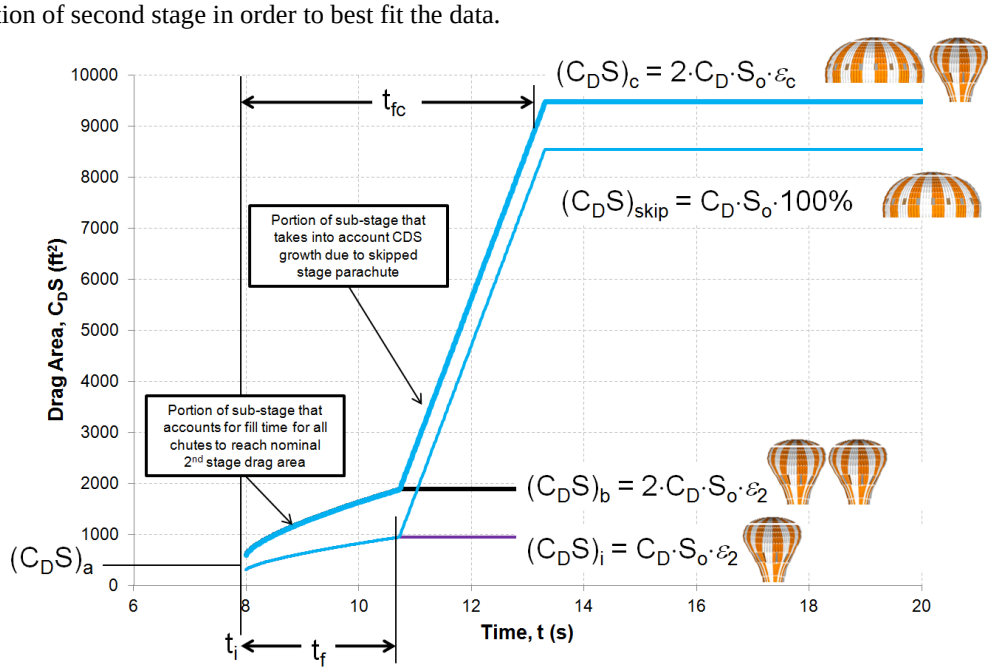


Figure 7. Generalized drag area growth curve for modeling two CPAS Mains with a skipped second stage.

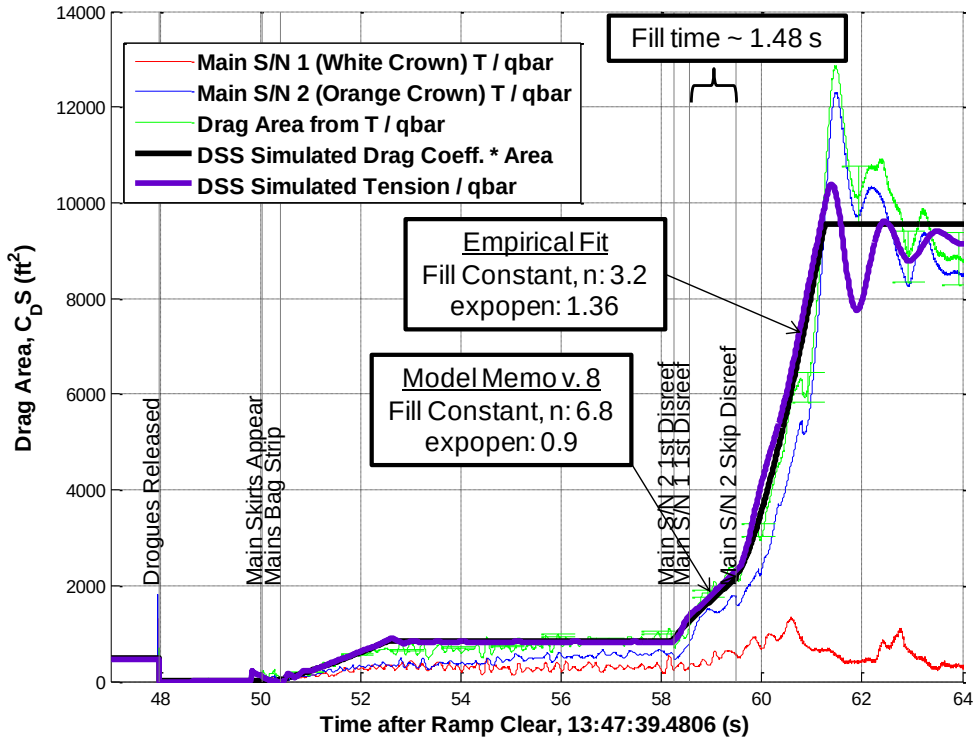


Figure 9. Improved composite reconstruction of CDT-2-1 Main second drag area.

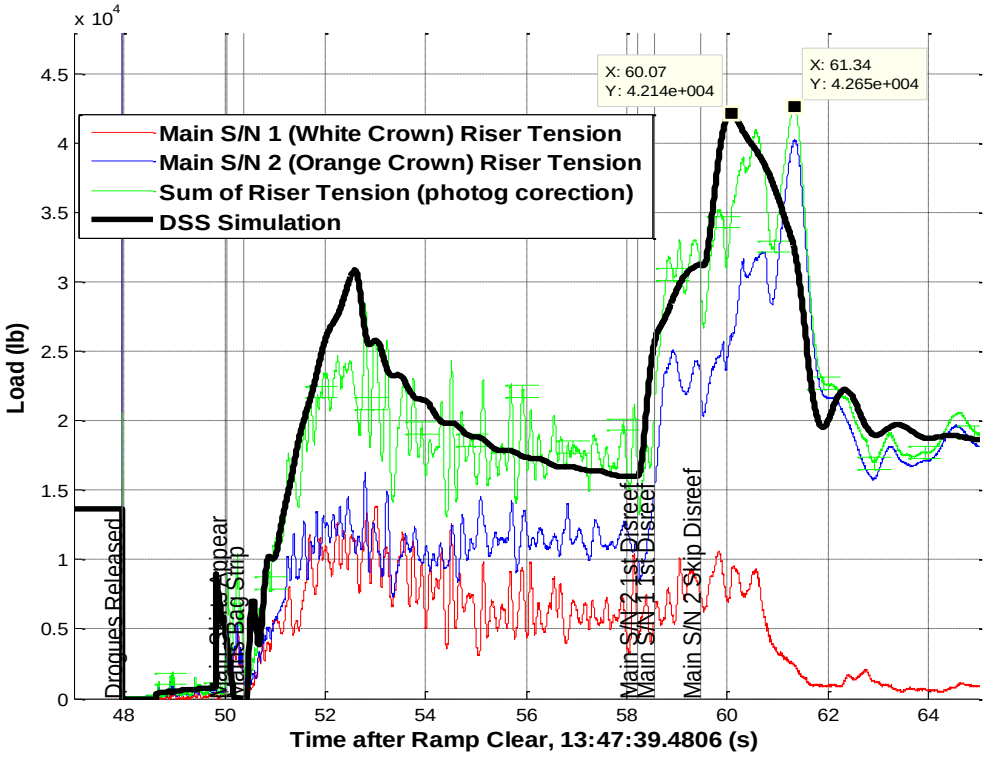


Figure 8. Improved composite reconstruction of CDT-2-1 Main second stage parachute load.

III. EDU Skipped Stage Main Parachute Testing and Performance

B. Skipped 2nd Stage Main Test: CDT-3-4

The primary test objective of CDT-3-4 was to test a skipped second stage on one of three CPAS Engineering Development Unit (EDU) Main parachutes. In order to ensure this test objective would be met, the second stage reefing line was pre-cut and the timing of the reefing line cutters were such that the non-skipping stage Mains would fire a few seconds after the skipped stage cutter. Starting from left to right in Figure 10, all three Main parachutes inflate to first stage. Then as expected the first disreef event occurs for the skipped stage Main (S/N 4) before the non-skipped stage Mains. This resulted in crowding of the non-skipped stage Mains as the skipped stage Main inflated to full open as well as an inflation lag for the non-skipped stage Mains.

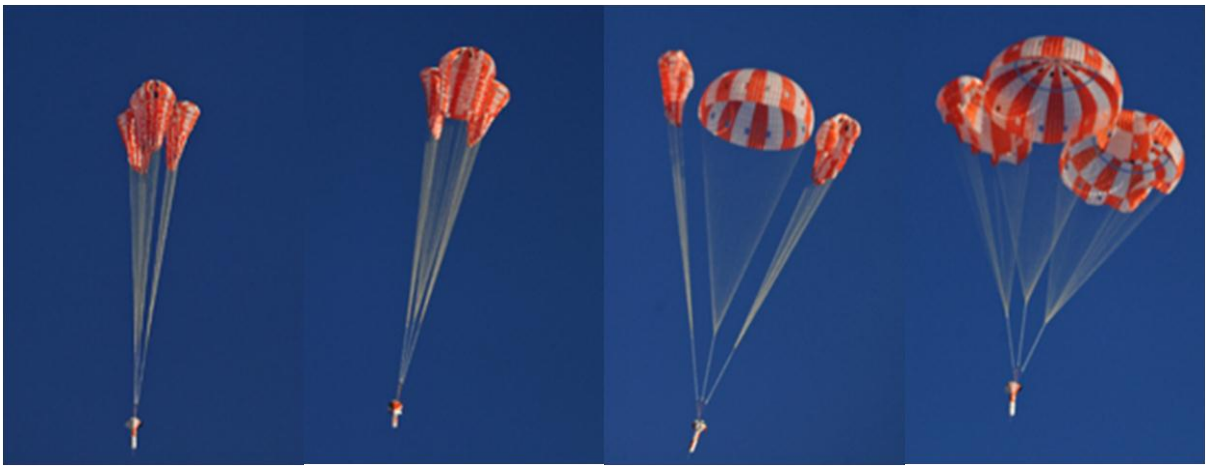


Figure 10. Progression of skipping second stage during CDT-3-4.

Predictions for the skipped stage event were made using the sub-stage drag area growth curve approach with two different methods for skipped stage inflation parameters. Both methods leveraged off of the capability of DSS to model parachute inflation individually, where the first method applied inflation parameters from the three Main cluster test CDT-2-2[2]. The second method used reconstructed parameters from the single-Main skipped second stage test MDT-2-2[2]. Using this approach resulted in a difference in the predicted peak load during the skipped stage event of approximately 20,000 lbs. Therefore, it was predicted that the loads would be bounded by these two methods. However, the more conservative method, that is using only inflation parameters derived from CDT-2-3 was chosen for the final pre-flight analysis.

The gray and black dashed traces in Figure 11and Figure 12 show the drag area growth curve and chute load for the preflight prediction and postflight reconstruction respectively. The individual Main chutes load cell data is shown by the solid red, blue and green traces. The purple trace is the summation of the individual Main data and the cyan is based upon inertial measurement unit (IMU) data. The difference in the preflight peak load prediction compared with the test reconstruction was approximately 11,000 lbf. During reconstruction an observation was made that due to the added mass effect, the peak load is proportional to the slope of the drag area curve. Any sudden, discontinuous slope increases the magnitude of the peak load.

The two non-skipped Mains were crowded out and did not exhibit an increase drag area despite the disreef cutters firing when indicated. The inflation parameters derived for the skipped stage Main fell in between the two methods employed during the preflight prediction. Although the consequence of the skipped stage Main crowding the airflow from the other two Mains resulted in an inflation lag, data necessary to update the inflation parameters of those parachutes was obtained. A generalized illustration of the process for simulating a skipped Main second stage is seen in Table 1.

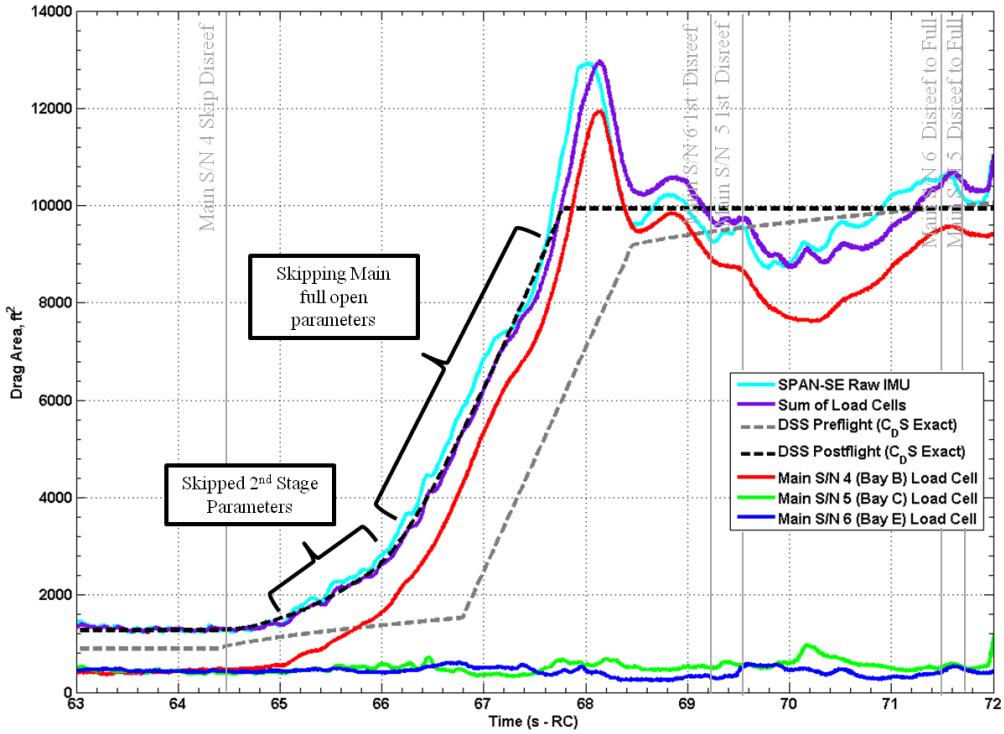


Figure 12. CDT-3-4 Main second stage drag area

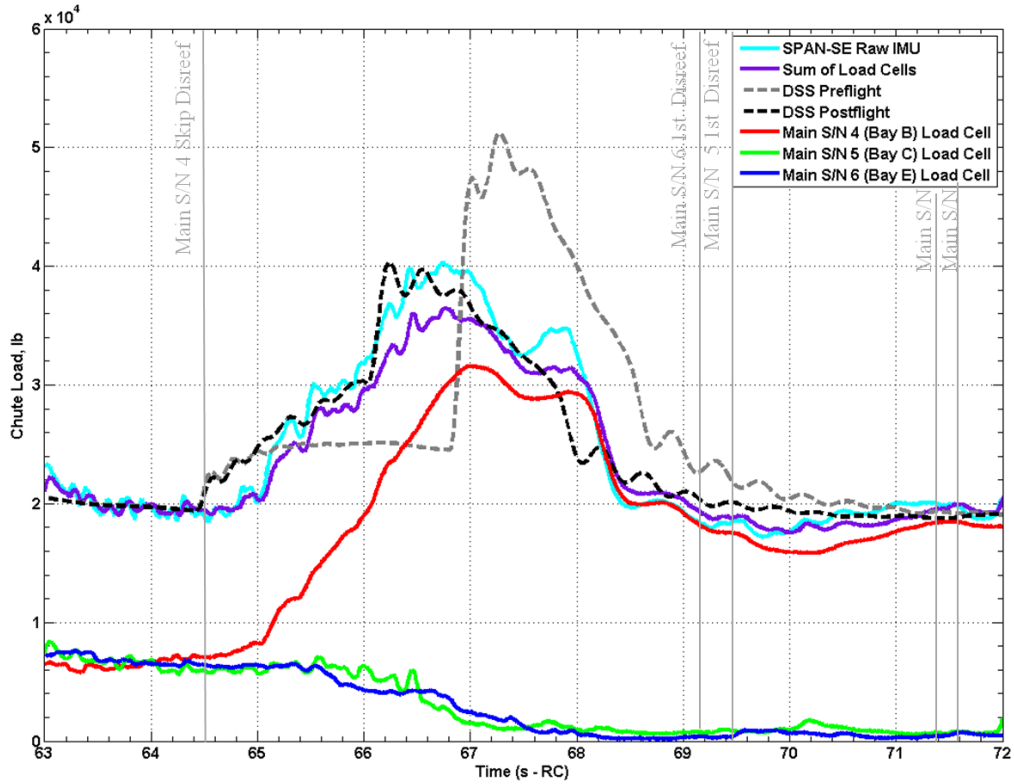


Figure 11. CDT-3-4 Main second stage parachute load

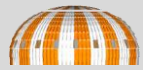
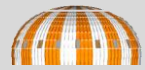
	1st Stage	2nd Stage		
		Initial phase: t_i to t_i+t_f	**Continuation**	**Full Open**
Skipping Main (A)	Nominal 1st stage parameters	Skip 2nd stage parameters (2 data points)	 Nominal full open parameters	 Already full open
Nominal Main (B)		No change	No change	Lagging full open parameters
Nominal Main (C)		No change	No change	

Table 1. Overview of inflation modeling a skipped second stage cluster of CPAS Main Parachutes.

C. Skipped 1st Stage Main Test: CDT-3-5

The primary test objective of CDT-3-5 was a skipped first stage for one of the three Main parachutes. This was again accomplished through the installation of a pre-cut first stage reefing line.

Progression of the skipped first stage is shown in Figure 13. Starting from left to right, as expected all three parachutes inflate to first stage. Then the Main with pre-cut reefing line continues to expand until reaching second stage. Next as the skipped stage Main (S/N 7) crowds out the other two parachutes, the latter's inflation to second stage lags to the point that they do not inflate fully to second stage, which also propagates into the final stage.

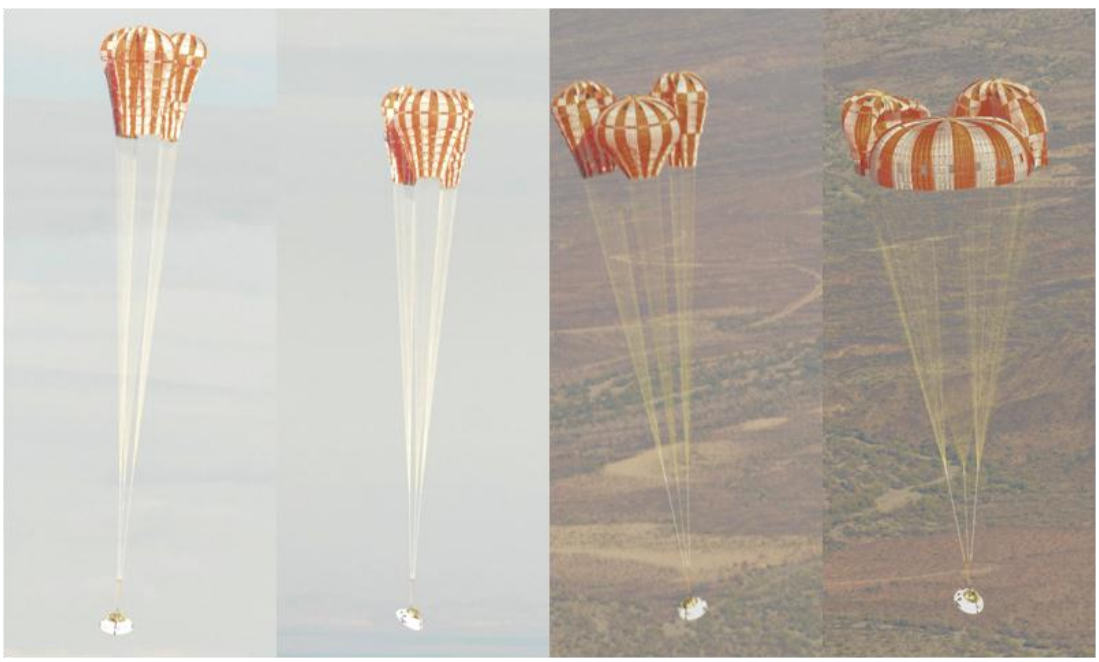


Figure 13. Progression of skipping first stage of CDT-3-5.

Preflight predictions were made using the sub-stage drag area growth curve method. Simulating the inflation of the skipped stage used inflation parameters obtained from the skipped first stage single Main test MDT-2-1[2]. The other parachutes inflate using the nominal three-Main inflation parameters which incorporated the first three-Main cluster test of the Engineering Development Unit (EDU) series, CDT-3-1.

Flight test data along with pre- and post-flight simulation runs of the drag area and chute loads for the first and second stage inflation are shown in Figure 14and **Error! Reference source not found.**. The preflight cluster drag area prediction denoted by the dashed grey trace shows a general match from t_i to t_f. The skipped stage portion of the trace, from about 79 to 81 seconds, diverges due to faster fill time experienced by the skipped stage Main. The faster fill time led to the crowding behavior as seen in other skipped stage tests. This made it difficult to determine exactly when the reefing cutters fired on the non-skipped stage Mains from the video analysis. The data indicated that those

two parachutes experienced a very slow growth, so much that completing second stage inflation did not occur. This is evident from the blue and green traces. It is only well after all three Mains disreefed completely that non-skipping Mains were able to fully inflate.

Due to the final disreef cuts occurring before the lagging Mains had time to fully inflate according to their theoretical best fit, the simulation encountered a discontinuity in the drag area. This is manifested as a jump in the drag area curve and was solved by a reset of the initial reefed drag area to match test data[5]. The reconstruction of CDT-3-5 resulted in modification in the method of simulating a cluster of EDU Mains undergoing a skipped first stage event. A generalized illustration of the process for simulating a skipped Main first stage is seen in Table 2.

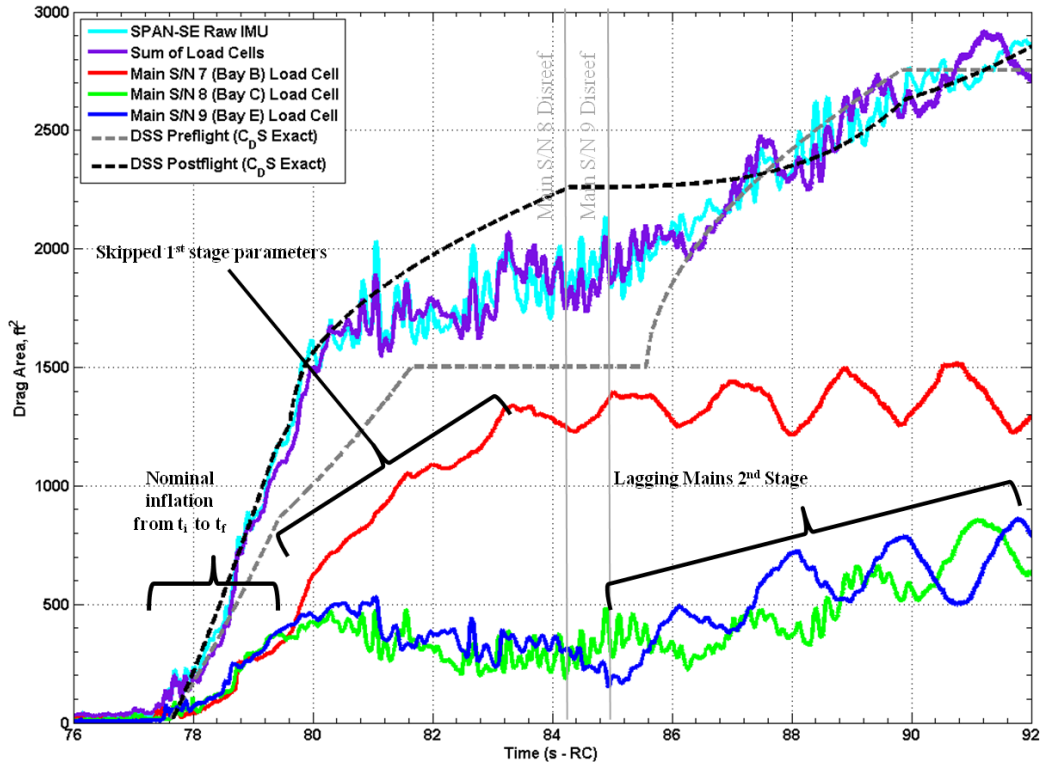


Figure 14. CDT-3-5 Main first and second stage drag area.

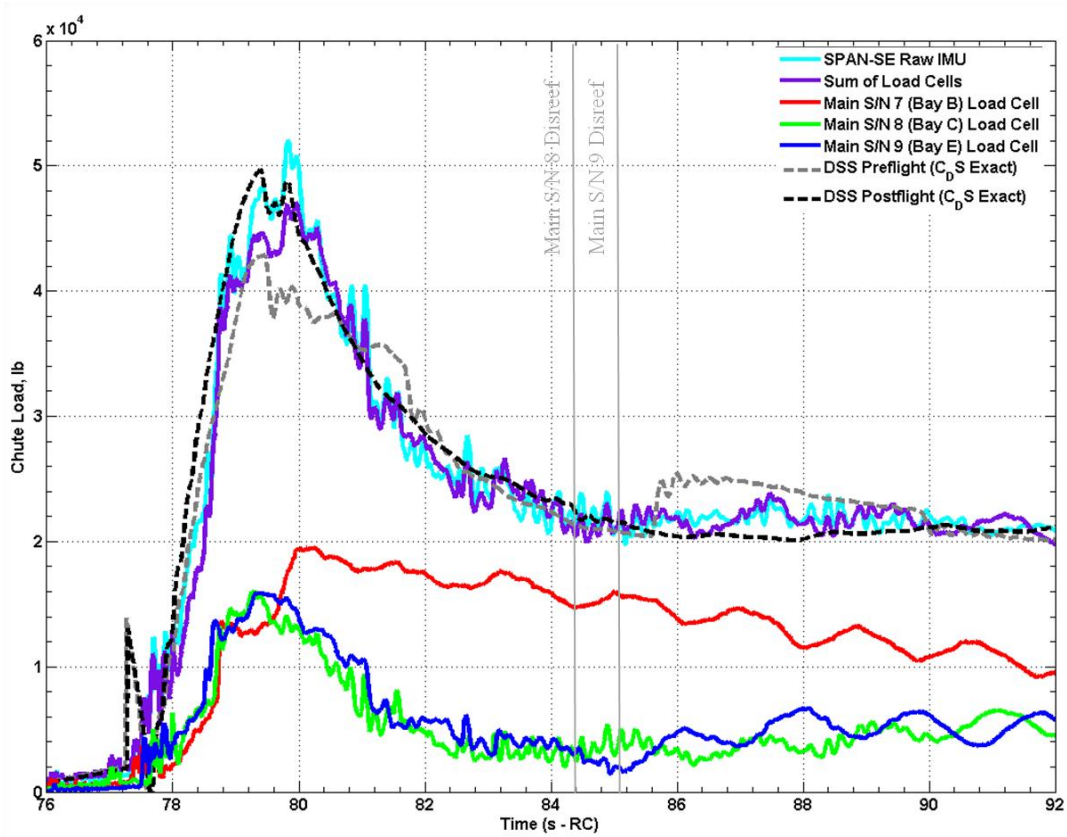


Figure 15. CDT-3-5 Main first and second stage parachute load.

	1st Stage		2nd Stage	Full Open
	Initial phase: t_i to t_i+t_f	**Continuation**		
Skipping Main (A)	Nominal 1st stage parameters	Skip 1st stage parameters (1 data point)	Already in 2nd, no change	Nominal full open parameters
Nominal Main (B)		N/A	Lagging 2nd stage parameters	Lagging full open parameters
Nominal Main (C)		N/A		

Table 2. Overview of inflation modeling a skipped first stage cluster of CPAS Main Parachutes.

IV. Conclusion

Although it is possible to simulate any finite mass skipped stage scenario with a composite simulation using the implementation of the sub-stage method, the more complex growth curve shape of finite mass inflations made this method too difficult for practical use in composite simulations. The transition to individual parachute reconstructions eliminates this limitation. Through the testing and evaluation of skipped stage events, along with the transition from modeling a cluster parachutes as a single composite to modeling each canopy, a better understanding of skipped stage behavior has resulted. The most notable effect being that canopy skipping a stage has profound effects on its neighbors by moving them out of the airflow and delaying their inflation. Additional Main skipped stage testing is currently planned and should further strengthen the understanding of this behavior.

Acknowledgments

The authors wish to acknowledge the contributions of Pete Cuthbert of NASA-JSC and James Dearman of Lockheed Martin in developing the skipped stage process.

References

[1] Knacke, T.W., "Parachute Recovery Systems Design Manual," U.S. Navy Report NWC TP-6575, Para Publishing Co., Santa Barbara, CA, 1992.
[2] Morris, A. L., et. al "Summary of CPAS Gen II Testing Analysis Results," 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011, AIAA paper 2011-2585.
[3] Ray, E. S., Bretz, D. R., and Morris, A. L., "Photogrammetric Analysis of CPAS Main Parachutes," 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011, AIAA paper 2011-2538.
[4] Cuthbert, P., "Decelerator System Simulation (DSS) Version 312," June 2010, NASA, Houston, TX.
[5] Ray, E., "Reconstruction of Inflation Loads," 22st AIAA Aerodynamics Decelerator Systems Technology Conference, Daytona, FL, March 2013, AIAA paper 2012-XXXX.