

Analysis Methodology Developed During the Orion Parachute System Airdrop Campaign

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The general objective of any given Orion Capsule Parachute Assembly System (CPAS) airdrop test was to improve the understanding of system behavior and performance. In the analysis space, the objectives were to collect model development and validation data. As the program progressed, it was discovered that the collection of this data required distinct types of analysis efforts: test specific analysis and parachute system analysis. While these efforts were closely related and overlapped at times, the end goal of each drove unique considerations. Parachute system analysis focused on model development, data reduction, and performance reconstruction for CPAS components while test specific analysis focused on minimizing test risks while maximizing the likelihood of achieving test objectives. With every test being unique in some form, whether it be due to test article, setup, or specific objectives, analysts were frequently faced with novel questions and charged with defining bounds and determining optimal solutions. To overcome these challenges, the CPAS program established an analysis methodology for the execution of parachute airdrop testing. This methodology can be used to identify key items of interest, and find their solutions, within a test specific analysis effort for an Aerodynamic Decelerator Systems (ADS) test campaign.

I. Nomenclature

AESM	=	ADAMS Extraction-Separation Model	FBCP	=	Forward Bay Cover Parachute
ADAMS	=	Automatic Dynamic Analysis of Mechanical Systems	ft-AGL	=	feet above ground level
ADS	=	Aerodynamic Decelerator System	ft-MSL	=	feet above mean sea level
BET	=	Best Estimate Trajectory	GL	=	Green Light
CARP	=	Computed Air Release Point	IMU	=	Inertial Measurement Unit
CdS	=	drag area	LVAD	=	Low-Velocity Airdrop
CDT	=	Cluster Development Test	MDS	=	Mid-Air Delivery System
ConOps	=	Concept of Operations	MoS	=	Margin of Safety
CQT	=	Cluster Qualification Test	PCDTV	=	Parachute Compartment Drop Test Vehicle
CPAS	=	Capsule Parachute Assembly System	PSA	=	Parachute System Analysis
CPSS	=	Cradle and Platform Separation System	psf	=	pounds per square foot
DSS	=	Decelerator System Simulation	PTV	=	Parachute Test Vehicle
DSSA	=	Decelerator System Simulation Application	RSS	=	root-sum-squared
EDU	=	Engineering Development Unit	SMG	=	Spaceflight Meteorology Group
EFTC	=	Extraction Force Transfer Coupling	TSA	=	Test Specific Analysis
EPJD	=	Extraction Parachute Jettison Device	TSE	=	Test Support Equipment

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II. Introduction

The objective during CPAS testing was to demonstrate system functionality while collecting system behavior and performance data. Analysts were primarily concerned with the performance data. The exact performance data needed was dependent on program requirements and test-specific objectives. This process is highlighted by the certification approach chosen by the CPAS program which leveraged Monte Carlo simulations validated during a test campaign to verify compliance with system requirements.¹ To validate the CPAS models, the test data was compiled in a database of inflation parameters used to seed predictive Monte Carlo simulations.

To gather this data, there were two primary types of analysis efforts for the CPAS program: test-specific analysis (TSA) and parachute system analysis (PSA). The specifics of these efforts have been extensively published by the CPAS analysis team in papers discussing the preflight analysis process², multi-body dynamic simulations³, debris modeling⁴, imagery processing⁵, and reconstruction process⁶.

Based on the purpose of the testing and the use of the collected data, one might assume that the PSA efforts would have dominated analysis efforts. While PSA efforts for the CPAS program were substantial, the program discovered that TSA efforts were close to being equivalent. During the qualification phase of the CPAS test campaign, the final eight airdrop tests, approximately half of the CPAS analysis team's resources were devoted to test execution. While this may seem counterintuitive initially, the reason becomes apparent when one views the scope of work that was required for TSA and PSA efforts. While there was crossover between TSA and PSA, particularly during model and test technique development, the analysis activities could be separated based on two primary over-arching objectives:

- Test Specific Analysis: Completing the analysis necessary to execute a test which achieved program objectives with an acceptable level of risk.
- Parachute System Analysis: Completing the analysis of test results necessary to build and validate CPAS models.

The primary objective during PSA was to inform parachute system performance models by calibrating deployment parameters, inflation parameters, and vehicle performance parameters. The extensive process of extracting these parameters was documented by Ray in Reference 6. This objective was complex, challenging, and required substantial effort to achieve. The general process involved reducing test data to parameters of interest, seeding a simulation with the extracted parameters, then comparing the output to the test articles' actual trajectories and measured parachute inflation performance.

PSA focused on CPAS performance model development refinement. It was a highly iterative task driven by a need to deliver a robust and validated model at the conclusion of the drop test program. This process was a program-long effort culminating with the delivery of final products at the CPAS System Acceptance Review in June of 2019.⁷ This program-long objective was distinctly different than the test-specific objectives that were considered as part of TSA activities.

The primary objective during TSA was to successfully deliver a test article to required test conditions at an acceptable level of risk to system hardware and test vehicles without compromising personnel, aerial assets, and surface assets. This was inherently a short-term objective. It was test specific. The test-to-test variations experienced by the CPAS program were substantial. Over the course of the full test campaign, 3 different aircraft types were used to drop 5 different test articles, at altitudes ranging from 10,000 to 35,000 feet above mean sea level (ft-MSL).⁸ During the program, test techniques were iterated to gradually expand the domain of knowledge.

This dynamic environment had direct impacts to TSA efforts as simulations had to be developed, modified, and calibrated iteratively as the test techniques changed. While PSA efforts could focus on extracting system-specific performance and a long-term life cycle, TSA efforts had to consider short-term deadlines in a highly dynamic environment. The CPAS analysts leveraged an incremental approach to completing TSA within this dynamic environment.² As test-specific planning occurred, multiple milestones were used to iterate the analysis products. Over the course of the program, as test techniques evolved, analysis techniques evolved.⁹

Along with a dynamic environment, the TSA activities also had to model and analyze items and events that were critical to testing but were not CPAS program deliverables. These efforts were frequently expansive in scope and duration such as payload extraction modeling discussed by Davidson³ or debris hazard analysis discussed by Bledsoe and Bernatovich⁴.

Both TSA and PSA activities were expansive efforts that were critical to the successful CPAS test program and system certification. The individual priorities for the efforts frequently lead to dramatically different challenges for engineers during the CPAS test campaign. The focus of this paper is to explain the challenges posed by TSA activities and the methodology employed by CPAS analysts to ensure the successful execution of a complex drop test program.

III. Extraction Analysis

While the U.S. military regularly executes Low-Velocity Airdrops (LVAD) with various payloads, extracting an engineering payload like the CPAS test articles from an aircraft was found to be a highly complex activity. CPAS engineers found a robust modeling capability was required to successfully model the extraction of test vehicles.

The CPAS Parachute Test Vehicle (PTV) and CPAS Platform Separation System (CPSS) test article required a complex extraction and separation sequence. The Cluster Qualification Test (CQT) 4-8 extraction and separation sequence of the PTV and CPSS can be seen in Figure 1. During the CPAS test campaign, the program was extracting not just a single vehicle, but two mated vehicles with a novel separation method.⁸ As such, the CPAS program spent substantial resources to reliably predict the extraction and separation of test vehicles.³ During the qualification phase of the CPAS program, approximately 25% of the analysis team was focused purely on modeling the extraction and separation of the two CPAS test articles - the PTV and CPSS combination and the Parachute Compartment Drop Test Vehicle (PCDTV) and Mid-Air Delivery System (MDS) combination. Figure 2 shows the CQT 4-7 extraction and separation sequence of the PCDTV and MDS.

When modeling the extraction, an analyst's primary goal was to ensure a safe and predictable extraction of the payload from the aircraft. On the surface, this may seem an obvious primary goal; a successful test requires a successful extraction. This is an area that could have easily been overlooked by engineers due to the aforementioned LVADs executed by the military. Readers can benefit from lessons learned by the CPAS program which experienced several anomalies related to vehicle extraction. These anomalies drove TSA efforts to improve modeling capabilities to ensure the CPAS program was able to certify Orion's parachute system and its associated models. The following subsections first describe the CPAS approach used to model extraction of the test article, followed by a discussion of several extraction related in-flight anomalies.

A. Extraction Modeling Approach

The first CPAS payload extraction model used was a FORTRAN based simulation named Decelerator System Simulation (DSS). As the test campaign progressed, DSS evolved into a tool called Decelerator System Simulation Application (DSSA); this evolution improved the user interface and allowed for rapid analysis of various test configurations. Rapid analysis capability was useful within the dynamic testing environment. Limitations within the DSSA simulation architecture led to its retirement from program use. The final simulations used by CPAS were high-fidelity multi-body dynamic simulations called the CPAS Automatic Dynamic Analysis of Mechanical Systems (ADAMS) Extraction-Separation models (AESM). The complexities of the AESM simulation architecture required separate simulations for the PTV/CPSS article and the PCDTV/MDS article.

While extraction models for any given test or program are likely to be unique, there are several common events that were important to CPAS engineers: Extraction parachute inflation, test article first motion, time of ramp clear,

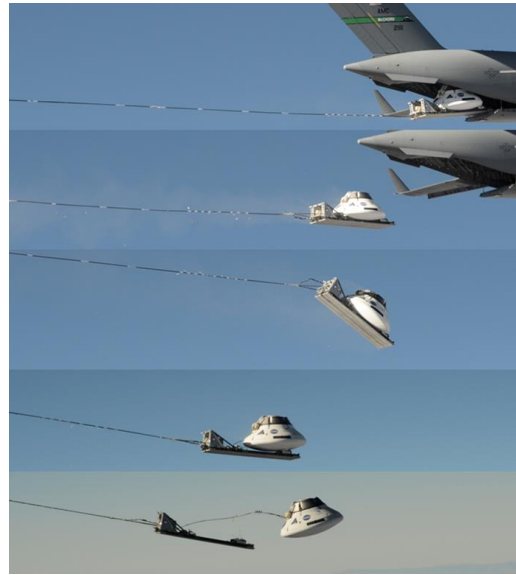


Figure 1. CQT 4-8 Extraction and Separation



Figure 2. CQT 4-7 Extraction and Separation

and dynamics at ramp clear. These events are likely to be critical points within the extraction of any payload from any aircraft.

A drop test can be viewed as a cascading sequence of events starting at “Green Light” (GL), the time when a given extraction was initiated. As such, errors and uncertainties in the prediction of initial events can propagate through the entire trajectory of any specific test. With extraction parachute inflation being the first event following GL, CPAS leveraged prior test data and tow testing to optimize inflation timing and performance.¹⁰ Imagery played a critical role in the analysis process as it provided data on both inflation timing and extraction parachute behavior.

First motion occurred after extraction parachute inflation when sufficient loads were generated to break the locks holding the test article to the floor of an aircraft. The timing of this event was directly related to extraction parachute inflation loads and dynamic loads within the extraction line. Accurate modeling of first motion allowed for subsequent modeling of a test article’s acceleration as it moved down the carrier aircraft’s deck.

The carrier aircraft’s pitch (deck angle), pitch rate, and deck friction all influenced the test article’s acceleration down the deck and off the aircraft ramp. As the test article approached ramp clear, contact forces and gravity drove additional pitch rates into test article. The CPAS AESMs were tuned using data collected by Inertial Measurement Units (IMU). By combining IMU data with imagery derived timelines, the CPAS AESMs were calibrated to predict the motion of the test article accurately.³

Accurate modeling of test article dynamics at cramp clear were critical to the CPAS program. Immediately following ramp clear, was the separation of the PTV from the CPSS, or the separation of the PCDTV from the MDS. Both test articles required a narrow range of dynamics to achieve a stable separation of the vehicle from its cradle.³

A stable separation was required to ensure a successful test. An unstable separation would have elevated uncertainties that would cascade into in programmer deployment, Forward Bay Cover Parachute (FBCP) deployment, Droogie deployment, and even Pilot and Main parachute deployment. In the worst case, an unstable separation could cause a loss of the test article by inducing dynamics that the vehicle would be unable to recover from.

While any CPAS demand provided an opportunity to learn about the system, CPAS certification required performance demonstrations at explicit initial deployment conditions. To confidently achieve these test points, CPAS spent substantial time, effort, and resources on modeling the extraction and separation phase of drop tests. The modeling process was iterative with test data being compared to simulation output. Test imagery was leveraged to define event times and observe system behavior, while recorded loads, accelerations, and vehicle state data were compared directly to model outputs. A reconstruction was then completed to calibrate the pre-test model and improve predictions for the next test. As more data was gathered, and the test complexity increased, models were modified and improved.

While the U.S. military has developed a framework to execute LVAD extractions, it is the experience of CPAS engineers that extracting novel test vehicles and Aerodynamic Decelerator Systems (ADS) from an aircraft is a complex engineering challenge. The challenges of modeling payload extraction should not be overlooked as they will have a direct impact on the success of a drop-test program.

B. Test Support Equipment (TSE)-1C

TSE-1C was the third test in a series which extracted a weight tub test article from a C-130 at approximately 20,000 ft-MSL and was conducted to test the CPAS test avionics systems.⁸ The Concept of Operations (ConOps) for the tests was to use a delayed release of an Extraction Force Transfer Coupling (EFTC) to transition from an attach point at the base of the platform to attach points on the weight tub’s backstop. Subsequently, the extraction parachute would be cut from the backstop and a static line would deploy a programmer parachute. After the programmer phase, the programmer parachute would then deploy the two CPAS mains using a static line. The TSE-1C test article and attach points can be seen in Figure 3.

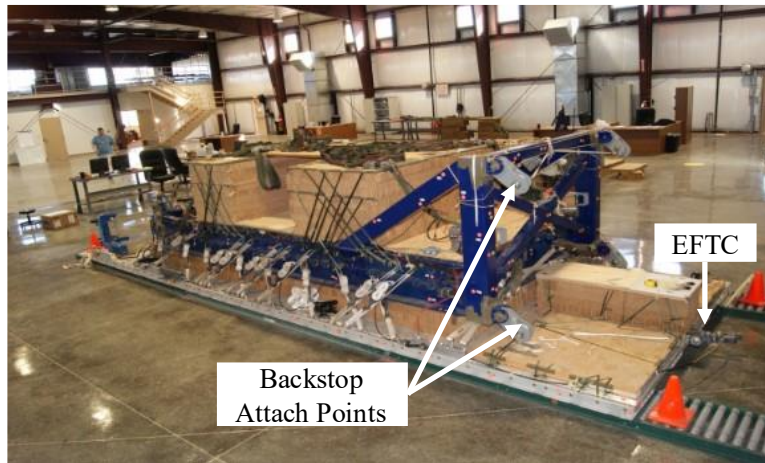


Figure 3. TSE-1C Test Article

During the test, the EFTC failed to release, thereby preventing all subsequent parachutes from being deployed. This resulted in a loss of the test article when it impacted the Arizona desert.

After exiting the aircraft, the vehicle pitched down, and the EFTC was bent downwards by the extraction parachute. The accident investigation determined that the bending of the EFTC was the probable cause for the anomaly as it likely pinched the 24-foot cable which ran between the Extraction Force Transfer Actuator and the Coupling Link Assembly thereby preventing the EFTC from releasing.¹¹

TSE-1C was a partial success as it validated the smart separation algorithm

but, the test article was lost due to an anomaly that occurred immediately after extraction from the aircraft.¹² Following the accident, CPAS redesigned tests to avoid bending the EFTC.¹³ This redesign effort had direct impacts to pre-test analysis as test Concept of Operations (ConOps) were a substantial consideration for CPAS analysts who carefully considered vehicle dynamics throughout the entire test sequence. ConOps efforts are discussed in Section IV.

C. Cluster Development Test (CDT) 3-11

CDT 3-11 was the first high altitude (35,000 ft-MSL) extraction of the PTV/CPSS test article. Due to the high energy environment associated with the test, pre-test analysis drove the decision to use a novel extraction parachute configuration. Rather than the nominal package of two full open 28 feet diameter extraction parachutes, the two extraction parachutes targeted a 70% reefing ratio.¹⁰

An anomaly occurred during the inflation of the extraction parachutes when a traveling wave along the length of the extraction parachute line was created. This wave caused a whipping effect that slammed the extraction line attachment mechanism into the carrier aircraft deck. This event resulted in damage to the aircraft's deck.¹⁰ Although this phenomenon was previously seen on prior drop tests, the severity was determined to be the result of a higher true airspeed imparting increased energy into the system during extraction parachute deployment. In addition to the whipping anomaly, the test experienced an increase in extraction loads and negative angles of attack at extraction.³ In a fashion similar to the TSE-1C EFTC damage, these increases resulted in damage to test hardware when a bracket connecting the CPSS to a device known as an Extraction Parachute Jettison Device (EPJD) was bent.

Following the tests, the packing and rigging of the extraction parachutes was modified to attenuate the energy during parachute deployment and inflation thereby mitigating the “whipping” action.³ The analysis team analyzed subsequent test data to ensure the mitigation was effective.

To mitigate the EPJD bracket bending, the program again committed to adjusting ConOps to limit negative angles of attack. For the PTV and CPSS architecture, this required implementing a backstop reposition event immediately after ramp clear. Changes to ConOps resulted in substantial modeling efforts as the new reposition event introduced a dynamic load event that would result in a major anomaly on CDT 3-16.

D. CDT 3-16

CDT 3-16 was the third 35,000 ft-MSL extraction of the PTV/CPSS test article. Following CDT 3-11, static line testing and hardware modifications led to the CPAS analysis team concluding “there was minimal risk to the test vehicle during the backstop reposition phase of the flight.”¹⁴ This conclusion was incorrect. During the test, a Kevlar line known as the Reposition Deployment Line (RDL) experienced substantial damage. This damage can be seen in Figure 4 which was taken from Reference 14. Post-Test analysis determined asymmetric loading due to a split attachment configuration in concert with a poorly understood dynamic loading environment led to significant RDL damage.



Figure 4. CDT 3-16 Reposition Deployment Line Damage

While the test was successful, the near failure of the RDL was a sobering anomaly. A complete RDL failure could cascade into a loss of the test article via uncontrolled PTV and CPSS separation immediately after extraction from the aircraft. Because of this, the program altered the remaining CDT test matrix with CDT 3-17 being executed from 30,000 ft-MSL instead of 35,000 ft-MSL. To achieve Cluster Qualification Test (CQT) objectives, significant ground testing and modeling efforts were required before testing from 35,000 ft-MSL could continue.³

IV. ConOps Design

ConOps design was a core tenant of the CPAS TSA activities. While the test matrix prescribed the CPAS configuration, test vehicle, and objectives, it did not specify how to accomplish a test.⁸ CPAS analysts designed ConOps using an iterative process.² For a given test, multiple design phases were used as checkpoints leading to a test. These check points provided opportunities to review details with the hardware team, avionics team, and test management. Following each review, analysis products were iterated to incorporate changes requested by other teams to accommodate hardware challenges, avionics limitations, or programmatic changes. This iterative process is explained in depth by Englert et al in Reference 2. Within this process however, CPAS analysts employed a methodology to first design a ConOps, and then “dial in” a trajectory. This methodology used Selective Design to minimize error and uncertainty and Objective-Led Design to maximize the likelihood of a successful test.

A. Selective Design

The cascading nature of a drop test sequence drove the need for selective design. As a test progresses, the end state of one phase becomes the initial state for the subsequent phase. The accumulation of uncertainties and performance variabilities within Monte Carlo simulations of test sequences caused the range of results to increase as the simulations progressed. As such, a selective-design approach which considered prediction uncertainty and variability was crucial to designing successful ConOps.

When designing ConOps, consideration to distributed results was critical. Distributed results were necessary to evaluate both test risk and the likelihood of achieving test objectives. The distributed trajectories were particularly sensitive to a buildup of dispersed inputs, uncertainties, and performance variations over the course of an entire drop-test sequence.

Over the course of the program, CPAS analysts improved the accuracy of trajectory predictions through simulation tuning of both TSA and PSA models. By reconstructing a flight, both nominal and dispersed inputs could be tuned for a specific test configuration. Examples of this approach can be seen in extraction model publications³ and the process used to reconstruct CPAS deployment and inflation demands.⁶ A key limitation of simulation tuning, however, is the availability of applicable test data.

Inherent in the CPAS test approach was for tests to vary in configuration and objective. This variability limited applicable test data when designing a new ConOps. To combat the uncertainty in a new configuration or objective, analysts selectively built ConOps from components of prior tests. While a ConOps sequence could represent a unique test, the ConOps could be compiled from individual phases taken from prior tests. To accurately predict trajectory bounds with limited uncertainty, analysts built ConOps using as many previously tested phases as possible. By the end of the CPAS program, analysts had many test phases that could be pulled from and combined in unique ways while having confidence in the pre-test simulation results.

Over the course of the test program, however, there were instances where a novel phase was required. In these instances, prior test data provided limited ability to tune a simulation or inform a compilation of sequences into a new ConOps. While simulations and models generally improved, any phase outside of the calibrated domain increased uncertainty and elevated risk to test success. When these cases arose, analysts worked parallel paths to mitigate the

risks. The initial, and short term, priority was to bound the potential trajectories within Monte Carlo simulations. The primary method to accomplish this was by selectively choosing ConOps such that uncertainties within the simulation architecture were understood and limited. The longer-term priority was to improve models and simulations of the sequence on subsequent tests. To do this, they frequently worked with avionics and hardware teams to collect additional test-specific data.³

In addition to limiting the uncertainty a new ConOps phase might introduce, analysts also built ConOps to reduce distributed simulation results. Independent from uncertainties in a sequence was the predicted variability of both individual and combined sequences. This variability was driven primarily by parachute and vehicle performance. Different parachute configurations inherently had different distributed performance and vehicle performance was coupled with initial conditions and parachute performance. Analysts leveraged prior test data and Monte Carlo simulations to compile ConOps which reduced the distributed performance of test articles. The success of these efforts was directly tied to the availability of prior test data and calibrated simulations. CQT 4-8 provides an example of how selective design was used to reduce uncertainty and distributed performance when designing a ConOps.

Consider the Cluster Qualification Test (CQT) 4-8 ConOps, shown in Figure 5, which used a programmer-parachute cluster followed by a freefall to achieve a targeted dynamic pressure at FBCP deployment. Engineers could vary two parameters to achieve the desired dynamic pressure initial condition: programmer cluster drag area (C_dS) and freefall time.

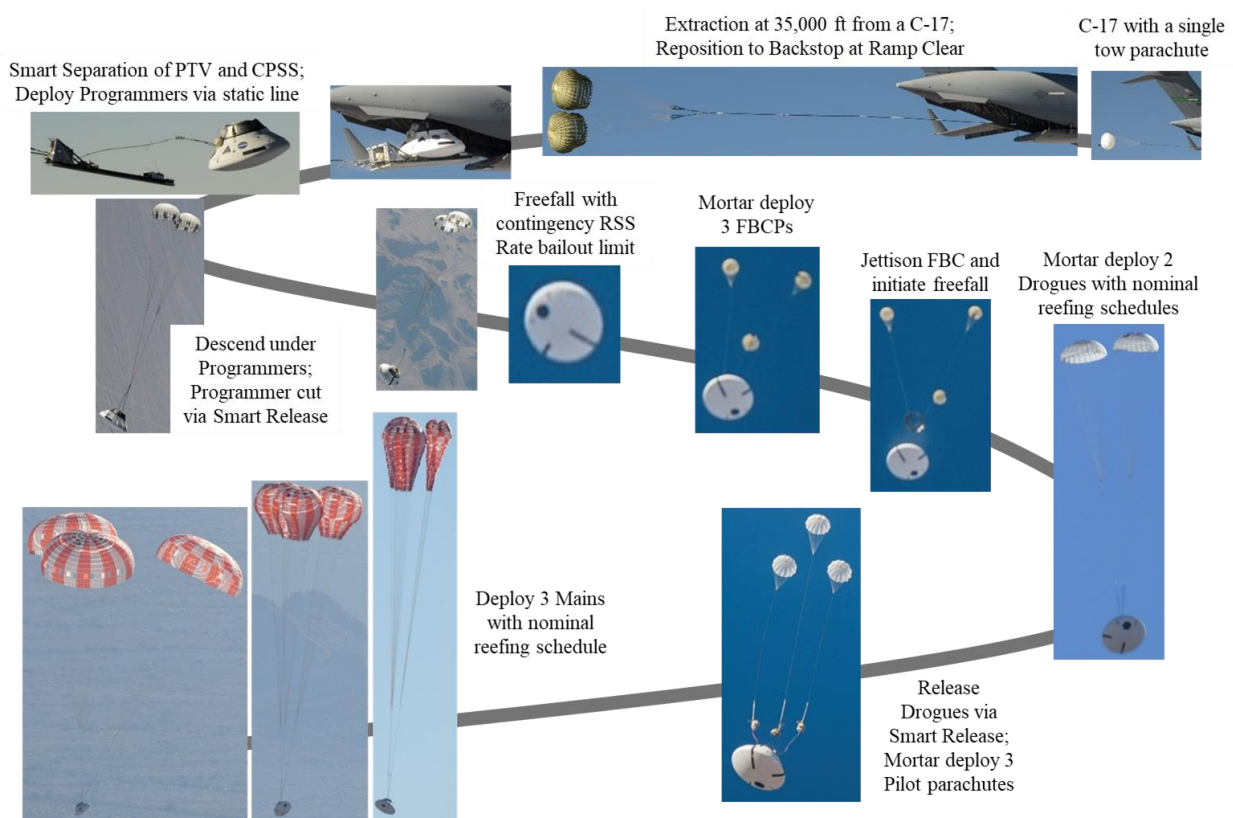


Figure 5. CQT 4-8 Concept of Operations

A low programmer-cluster C_dS would have allowed for a shorter freefall. Brief freefalls are desired as they minimize the time the PTV is in uncontrolled flight where there is a potential to lose stability. The lower cluster C_dS , however, would be slower to stabilize the PTV after separation from the CPSS. An unstable PTV at programmer release would result in elevated uncertainty and distributed performance during the freefall phase thereby impacting the range of FBCP deployment conditions.

Alternatively, a high programmer-cluster C_dS could have been combined with a longer freefall phase to achieve the targeted dynamic pressure. This ConOps would increase the stability of the PTV at programmer release thereby reducing uncertainty and distributed performance during the freefall phase. The disadvantage of this approach was a longer freefall increasing the amount of time the PTV would be in uncontrolled flight. The uncertainty and distributed

performance associated with the longer duration freefall phase would impact the range of FBCP deployment conditions.

When comparing the two options, both had limited ability to mitigate the uncertainty and distribution of FBCP deployment initial conditions caused by the freefall phase. Models could predict vehicle dynamics during the freefall, but the controlling factor was the initial conditions at programmer release. While vehicle dynamics could not be mitigated with simulations, they could be mitigated with an onboard algorithm to bailout of the freefall if the root-sum-squared (RSS) of vehicle rates hit a pre-determined limit. With this algorithm in place, the high programmer CdS option had lower overall uncertainty and distributed performance. The ConOps selected and used for CQT 4-8 were thus: 2 CPAS Engineering Development Unit (EDU) Drogues disreefed to full open four seconds after deployment to stabilize the vehicle; the programmers were then cut via a Smart Release mechanism to trigger a 12 second freefall with an RSS rate limit bailout enabled.

As the final test of the CPAS certification campaign, the CQT 4-8 ConOps and test execution benefited greatly from Selective Design. Models and simulations were iterated and tuned using data collected during prior tests - both test specific data and parachute system data. Selective Design then worked in conjunction with tuned simulations to further mitigate uncertainty propagation and trajectory variability.

B. Objective Led Design

Efforts to mitigate uncertainty and variability were primarily aimed at improving the accuracy of pre-test predictions by limiting the distribution of the Monte Carlos simulation results. While this assists with “dialing in” a ConOps, it does not optimize a ConOps to achieve specific test objectives. Optimization of ConOps for specific objectives was an iterative process tied to a pre-test review cycle. This cycle nominally consisted of four analysis phases and a test week phase.² In each phase, analysis was completed, and trajectory predictions were compared to test objectives. Details of the test setup were discussed and compared to the completed analysis. As the phases progressed, analysis products were refined. In the initial phase, the goal was for a trajectory to approach the objectives. In the final phase, the goal was to have a trajectory with the highest likelihood of achieving all stated objectives. Throughout these phases, parameters of the test were adjusted to maximize the likelihood of test success. This was done by considering the intent of a test, test objectives, and test limitations.

Consider the CQT 4-7 ConOps, shown in Figure 6, which shows a high dynamic pressure test using the PCDTV/MDS test article. The intent of the test was to target a high dynamic pressure deployment for the FBCPs, Drogues, Pilots, and Mains.⁸ Out of the 12 test objectives noted by Evans in Reference 8, there were five objectives that were critical to the pre-test analysis workflow:

1. “Execute a safe and successful nominal system PCDTV airdrop test from 35,000 MSL with no significant damage to test hardware”⁸
2. “Analyze system performance of a cluster of three static line deployed FBCPs used as programmer parachutes”⁸
3. “Analyze system performance of two mortar deployed FBCPs in a high dynamic pressure environment”⁸
4. “Analyze system performance during mortar deployment of two drogue parachutes above the 155 psf dynamic pressure Deployment Envelope Limit. Target Mortar-Fire dynamic pressure is nominal 165 psf; minimum of 155 psf”⁸

5. “Analyze system performance during deployment of three Main parachutes above the 105 psf dynamic pressure Deployment Envelope Limit at Main line stretch. Target dynamic pressure is: nominal 116 psf; minimum of 105 psf”⁸

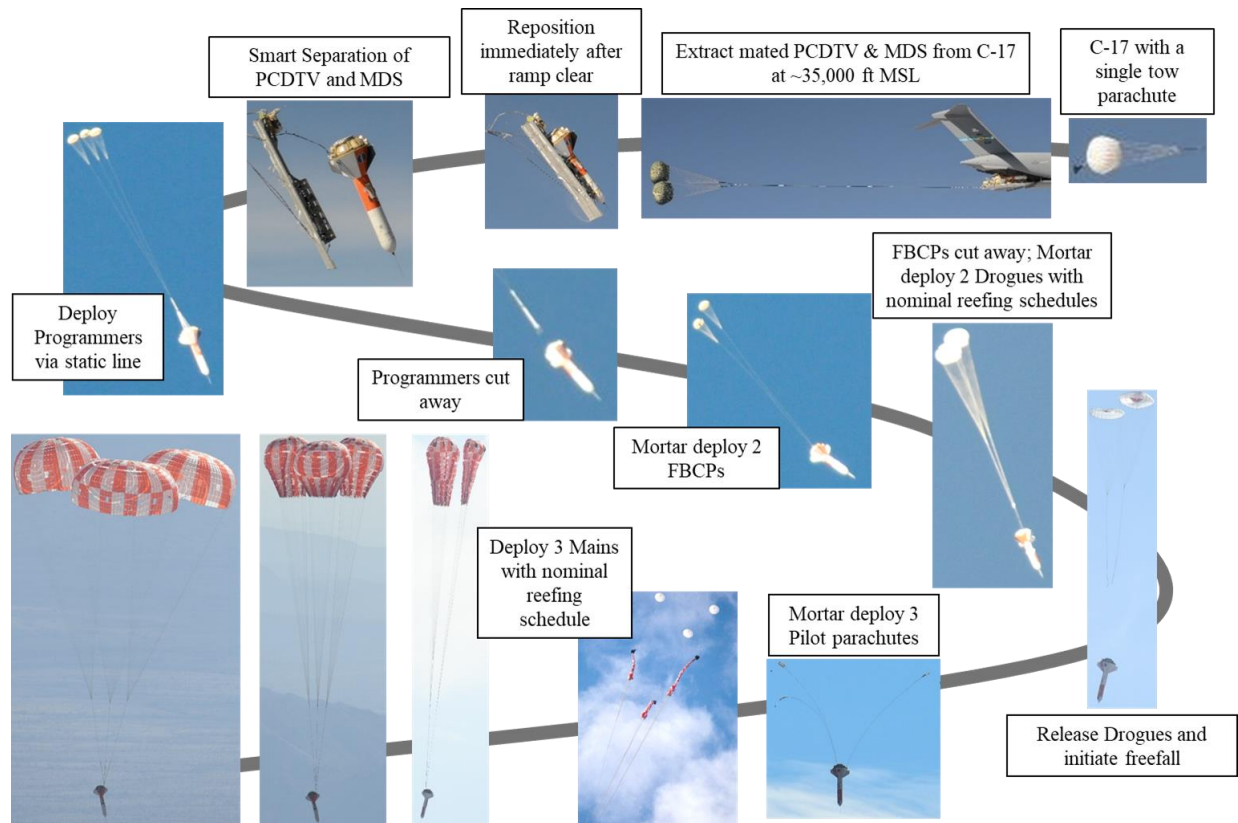


Figure 6. CQT 4-7 Concept of Operations

A review of the objectives listed above shows that the objectives worked in conjunction to apply constraints to the design space available to the trajectory designers. Objectives one and two limited choices on test setup to achieve the desired test points while objectives three, four, and five controlled the CPAS parachute test configuration. Objectives four and five additionally specified both the nominal test targets and the minimum test conditions. With these objectives, the analysts were able to begin to define the tests ConOps.

The objectives listed above primarily define the initial configuration and sequence of events: CQT 4-7 was to be a 35,000 ft-MSL extraction with three FBCPs as programmers followed by two FBCPs, two Drogues, three Pilots, and three Mains. While not explicit objectives, two other program restrictions were used to limit conditions. While the test was meant to be an overpressure test to demonstrate margin, the program did not want to overpressure beyond the hardware’s capabilities. As such, hardware Margin of Safety (MoS) implicitly set an upper limit for dynamic pressures at deployment events. Additionally, for the Main parachutes, there was a hard altitude limit; the test vehicle needed to be at steady state prior to reaching an altitude of 1,250 ft-above ground level (ft-AGL). It should be noted that 1,250 ft-AGL was the limit at the end of the qualification campaign when pre-test models and simulations were mature, verified, and validated; CQT 4-7 was eighth test using the PCTV test article and the second to last test of the CPAS program.

With these objectives and constraints applied, the iterative process of designing a trajectory was completed. Starting with the vehicle and system configuration, analysts estimated sequencing times which would produce a trajectory which approached the specified objectives. Previous test configurations and data were heavily used in these initial estimates. In these initial iterations, a review of the trajectory only considered the broad test objectives and constraints and analysis of the objectives, program constraints, full element wise MoS, and debris were not considered. After a few iterations, a potential trajectory was selected to proceed with comprehensive TSA in a subsequent phase.

Following an initial phase, the full domain of trajectory analysis was considered which included element wise MoS for all CPAS components, vehicle dynamics, MoS for test support hardware, dynamic loading analysis, and

debris footprint analysis. The use of Objective-Led Design was highly successful within the CPAS program. By building trajectories to meet specific objectives via analysis phases, analysts were able to maximize the likelihood of a successful test.

The specifics of these TSA efforts are outside of the scope of this paper, but many are documented in prior CPAS publications. Analysis of vehicle dynamics and dynamic loading is discussed in the series titled *Extraction and Separation Modeling of Orion Test Vehicles with ADAMS Simulation*.^{3,14,15,16} Analysis of debris footprints and simulation is discussed in a series of papers for the CPAS debris tool known as Sasquatch.^{4,17} The complete analytical techniques developed and used by the CPAS analysis team was compiled into a CPAS internal document by Ray in the *Capsule Parachute Assembly System (CPAS) Simulation of Drop Test Vehicles and Test Techniques Version 18*.¹⁸

V. Other Aspects of Test Specific Analysis (TSA)

While the core of TSA efforts was focused on extraction analysis and ConOps design, every test had potential for unique, and one-off analysis. These could be caused by a specific test configuration, review of previous test data, or an improved understanding of a test event or component. While these efforts could be highly variable, they were frequently related to dynamic loads, data collection, and test execution

A. Dynamic Loads

Dynamic loads, frequently referred to as “Snatch Loads,” were a concern for the duration of the CPAS test program. Whenever two or more masses were connected and subjected to a velocity differential, there was potential for a high dynamic load that posed a risk to test hardware.

The fidelity of dynamic load analysis varied throughout the drop test program. The simplest approach was to estimate a dynamic load by modeling the rope, cord, or webbing that connected components as a spring. The relative kinetic energy of the objects was estimated, then used to solve for spring elongation and force using equations for elastic potential energy and Hooke’s Law.

The program found that this approach broke down in high energy environments where textiles did not behave as simplified springs.¹⁴ The approach also broke down when multiple point masses were in series with multiple textile components. The program concluded that accurate dynamic load predictions needed high fidelity finite element models coupled with well-defined boundary conditions.

It was cost and schedule prohibitive to model all dynamic loading events with this level of sophistication. Analysts instead used a targeted approach to recommend whether the program accept a less-analytical solution. In the case of a component known as the RDL, mentioned in Section III.D, a high fidelity model was required to ensure success.^{3,14} This was driven by the criticality of the event and because a bounding hardware configuration was not readily available.

In other cases, however, when a bounding hardware configuration could be easily implemented, analysis efforts could focus on other tasks at hand. In these cases, analysts worked with hardware designers to develop components that mitigated the risk of uncertain loads predictions as it was more efficient to expend resources, both time and cost, on hardware procurement rather than advanced modeling efforts. Examples of this approach were the extensive use of Energy Modulators when deploying programmer parachutes or the design of a reinforced deployment bag for the CPSS and MDS recovery Main parachutes. Using estimates from the analysis team, design engineers were able to develop hardware solutions that mitigated, or even eliminated, the risk. While the solutions may not have been elegant analytical solutions, there were highly effective and efficient uses of program resources.

Future test programs are likely to have test techniques that include dynamic loading events. These loads are likely to be different than those experienced by CPAS, and the optimal solutions will be dependent both on the event in question and the program’s priorities. It is the CPAS experience, however, that dynamic loading events should be carefully considered when designing a test technique and ConOps.

B. Instrumentation and Data Collection

Both TSA and PSA relied on test instrumentation and data collection in areas related to component loading, event timing, vehicle state, atmospheric conditions, and imagery. Many of these data sources were related. For instance, vehicle state data, event timing, and parachute cluster loads were collected through an onboard IMU.⁶ When atmospheric data was combined with the IMU and individual riser load measurements, an accurate Best Estimate Trajectory (BET) could be created. This BET was then used to complete reconstructions of a test.

The collection and use of imagery during the CPAS test campaign, both onboard and external, was a particular focus of test planning, test analysis, and publication efforts for CPAS analysts. Details on specific imagery analyses

have been published in broad a range of papers such as *Improved CPAS Photogrammetric Capabilities for Engineering Development Unit (EDU) Testing*⁵, *Pendulum Motion in Main Parachute Clusters*¹⁹, *Photogrammetric Analysis of CPAS Main Parachutes*²⁰, and *Photographic Volume Estimation of CPAS Main Parachutes*.²¹ The imagery efforts pursued by CPAS in testing ultimately drove considerations for the role imagery plays in the surveillance of spacecraft parachute systems.²² The analysis team defined what data was needed from a given test and worked with the avionics and hardware teams to implement instrumentation and data collection solutions. As technology evolved, the ability to collect higher fidelity data also increased. In Reference 12, Evans et al. discuss the evolution of imagery and avionics systems during the CPAS test campaign. Just as CPAS's instrumentation evolved, future programs should consider the current state of technology when building instrumentation and data collection packages.

C. Test Execution

External factors such as weather, debris, airspace, and aircraft operations posed frequent test execution challenges during the CPAS test campaign. TSA was completed to maximize a drop test's test-day opportunities through accurate pre-test simulations and weather-related risk mitigation. These efforts were critical to the execution of CQT-4-5 following several unsuccessful attempts.

CQT 4-5 was a test of the PTV/CPSS system extracted from a C-17 at 35,000 ft-MSL. The first attempt was made on morning of December 13th, 2017. As the test progressed towards GL, all assets were in place for test execution and hardware recovery. When executing dry pass run ins, the C-17 crew was unable to fully open the aircraft's door and lower the ramp. Aircraft depressurization time constraints and test article size limited trouble shooting efforts while aloft, forcing the crew to call off the test and return to base.

As airdrop testing always had potential for delays, the program had secured three consecutive days on the range. Preliminary weather forecasts from the Johnson Space Center's (JSC) Spaceflight Meteorology Group (SMG) looked unfavorable for the following day. Due to the limited options, the NASA test director decided that the test would be attempted. On December 14th, 2017, analysts used data from an early morning weather balloon to complete a debris analysis with Sasquatch that concluded that upper-level winds were too severe for safe execution of the drop test. Ultimately, CQT 4-5 was successfully executed on December 15th.

The causes of delays in the CQT 4-5 test were all known CPAS engineers before test week. While completing TSA activities, analysts considered whether the 35,000 ft-MSL extraction was required and how to minimize the test execution risks it posed. As the test was one of the final qualification tests, CQT 4-5 required a 35,000ft-MSL extraction to demonstrate the functionality of all CPAS parachutes in sequence. The extraction and ConOps were carefully analyzed to maximize the accuracy of pre-test predictions. These predictions were then used to seed the Sasquatch debris tool.

While weather itself was beyond the control of CPAS analysts, careful collection of hardware landing locations on prior tests and weather data allowed for footprint reconstructions that optimized the Sasquatch simulation and reduced weather-related test risks. These efforts culminated in accurate hazard assessments on the morning of the test which the NASA test director could have high confidence in. By extensively working to optimize ConOps, trajectories, vehicles, debris footprints, flight paths, and day of test operations, analysts were able to maximize the likelihood of test execution. CPAS analysts recommend test execution challenges be carefully considered by TSA efforts for future programs.

VI. Conclusions

The successful execution of CPAS drop tests was directly related to extensive TSA and PSA activities. To maximize the chance of test execution and test success, the CPAS analysis methodology was to complete robust extraction and separation analysis while leveraging available datasets to complete Selective and Objective-Led test ConOps design. This methodology was developed gradually as the complexity of test vehicles and ConOps increased. Development frequently occurred as the result of difficult test findings such as the EFTC failure on TSE-1C or the RDL failure on CDT 3-16. Any drop test program of a novel ADS is likely to experience challenges unique to the system and test technique chosen. The CPAS program learned that the solution to, or mitigation, of these challenges required substantial TSA efforts. Without these efforts, a successful design, development, qualification, and ultimately the safe return of the Artemis-II crew would not have been possible.

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References

- ¹ Morris, A. L., Olson, L. M., “Verification and Validation Plan of Flight Performance Requirements for Human Crewed Spacecraft Parachute Recovery Systems,” 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011, AIAA Paper 2011-2560.
- ² Englert, M., E., et al, “CPAS Preflight Drop Test Analysis Process,” 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona Beach, FL, March 2015, AIAA Paper 2015-2178
- ³ Davidson, J. Y., “Extraction-Separation Performance and Dynamic Modeling of Orion Test Vehicles with Adams Simulation: 4th Edition,” AIAA Aviation 2019 Forum, Dallas, TX, AIAA Paper 2019-3375
- ⁴ Bledsoe, K. J., Bernatovich, M., Galvin, P. J., “Development and Overview of CPAS Sasquatch Airdrop Landing Location Predictor Software,” 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona Beach, FL, March 2015, AIAA Paper 2015-2122
- ⁵ Ray, E. S., Bretz, D., “Improved CPAS Photogrammetric Capabilities for Engineering Development Unit (EDU) Testing,” 22nd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona, FL, March 2013, AIAA Paper 2013-1258
- ⁶ Ray, E., “Updated Reconstruction Methods for Modeling Orion Parachute Loads,” AIAA Aviation 2019 Forum, Dallas, TX, AIAA Paper 2019-3143
- ⁷ Ray, E., “CPAS Operating Modeling Parameters Version 18 (System Acceptance Review),” NASA JSC 65914 Rev. M, June 2019.
- ⁸ Evans, C. T., “Orion Capsule Assembly System (CPAS) Test Program Summary,” AIAA Aviation 2019 Forum, Dallas, TX, AIAA Paper 2019-3021
- ⁹ Manning, S., Galvin, P., “CPAS Analysis and Simulation Improvements Throughout Testing,” AIAA Aviation 2019 Forum, Dallas, TX, AIAA Paper 2019-3145
- ¹⁰ Ray, E. S., Varela, J. G., “Inflation of Unreefed and Reefed Extraction Parachutes,” 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona Beach, FL, March 2015, AIAA Paper 2015-2180
- ¹¹ Zipay, J., “CPAS TSE-01C Failure Investigation Report”, November 2010, NASA JSC 66097
- ¹² Evans, C. T., et al, “Orion Capsule Parachute Assembly System (CPAS) Airdrop Test Program Avionics, Imagery, and Instrumentation Systems,” AIAA Aviation 2019 Forum, Dallas, TX, AIAA Paper 2019-3024
- ¹³ Evans, C. T., “Orion Capsule Parachute Assembly System (CPAS) Airdrop Test Program Techniques, Challenges, and Solutions,” AIAA Aviation 2019 Forum, Dallas, TX, AIAA Paper 2019-3023
- ¹⁴ Varela, J. G., et al, “Extraction-Separation Performance and Dynamic Modeling of Orion Test Vehicles with Adams Simulation: 3rd Edition,” 24th AIAA Aerodynamic Decelerator Systems Technology Conference, Denver, CO, June 2017, AIAA Paper 2017-3233
- ¹⁵ Fraire, U., Anderson, K., Cuthbert, P. A., “Extraction and Separation Modeling of Orion Test Vehicles with ADAMS Simulation,” 22nd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona, FL, March 2013, AIAA Paper 2013-1394
- ¹⁶ Fraire, U., Anderson, K., Varela, J. and Bernatovich, M., “Extraction and Separation Modeling of Orion Test Vehicles with ADAMS Simulation: 2nd Edition”, 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona, FL, March 2015, AIAA Paper 2015-2161
- ¹⁷ Bledsoe, K., Morris, A., “Development of the Sasquatch Drop Test Footprint Tool,” 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011, AIAA Paper 2011-2601
- ¹⁸ Ray, E. S., “Capsule Parachute Assembly System (CPAS) Simulation of Drop Test Vehicles and Test Techniques,” JETS-JE11-13-SAIP-MEMO-0021 REV H, July 2019.
- ¹⁹ Ray, E. S., Machin, R. A., “Pendulum Motion in Main Parachute Clusters,” 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, Daytona Beach, FL, March 2015, AIAA Paper 2015-2138
- ²⁰ Ray, E. S., Bretz, D. R., Morris, A. L., “Photogrammetric Analysis of CPAS Main Parachutes,” 21st AIAA Aerodynamics Decelerator Systems Technology Conference, Dublin, Ireland, May 2011, AIAA Paper 2011-2538.
- ²¹ Ray, E., “Photographic Volume Estimation of CPAS Main Parachutes,” 24th AIAA Aerodynamic Decelerator Systems Technology Conference, Denver, CO, June 2017, AIAA Paper 2017-3229
- ²² Janssen, S. A., Ray, E. S., Morris, A. L., “Video Analysis for Surveillance of Spacecraft Parachute Systems,” AIAA Aviation Forum and Ascend, 2024, Las Vegas, NV, July 2024, AIAA paper 2024-4330