Modeling & Testing of the Capsule Parachute Assembly System (CPAS)

February 21, 2013
CPAS OVERVIEW
Capsule Parachute Assembly System (CPAS) is the parachute system for the Orion vehicle used during re-entry

- Similar to Apollo parachute design

A Government Furnished Equipment (GFE) project responsible for:

- Design
- Development testing
- Performance modeling
- Fabrication
- Qualification
- Delivery

Collaboration between NASA JSC, ESCG, and Airborne Systems
CPAS Concept of Operations

Nominal Mission and High Altitude Abort Deployment Sequence

2/22/2013
CPAS Analysis Focus

- Flow from flight performance requirements from the CPAS Project Technical Requirements Specification (PTRS) Revision
  - Meet during specified failure conditions

- Rate of Descent (ROD)
  - Crew and vehicle structure safety

- Parachute Loads
  - Drogue and Main single riser loads
    - Individual parachute failure
  - Drogue and Main cluster loads
    - Sum of individual riser loads
    - Vehicle structural failure

- Rotation Torque Limit
  - Main risers induce rotation
  - Orient vehicle edge into water for landing
Agenda

- Airdrop Testing
  - Gen I & II
  - EDU

- Parachute Analysis
  - Simulations
  - Preflight Analysis
  - Post-Flight Analysis

- Development of a Parachute Model
  - Reconstructions
  - Statistically Derived Parameters

- System Verification

- Future of CPAS
Gen I & II
EDU

AIRDROP TESTING
Evolution of Test Vehicles & Techniques

Gen I Objectives
1. Characterize single parachute inflation parameters
2. Demonstrate the system

Gen II Objectives
1. Test failure modes
2. Investigate potential design changes

Smart Separation Objectives
1. Test Smart Separation software and upgraded Avionics suite

EDU Objectives
1. Test representative parachute systems
2. Test failure modes

*All vehicles extracted from an aircraft used a Type V LVAD Platform.*
CPAS Parachutes

- **Extraction Chutes (~28 ft)**
  - Pulled the vehicle out of the aircraft. Used for testing only.

- **Programmer Parachutes**
  - Used to create the proper test conditions for the Drogue, Pilot, or Main chutes. Used for testing only.
  - Can sometimes be an identical chute as the Drogues, but the use is different.

- **Forward Bay Cover Parachutes (FBCPs) (~7 ft)**
  - Pulled off Forward Bay Cover (FBC) from vehicle

- **Drogue Parachutes (~23 ft)**
  - Stabilizes the vehicle for Main deployment.

- **Pilot Parachutes (~10 ft)**
  - Pulled out the Main chutes.

- **Main Parachutes (~116 ft)**
  - Slow the vehicle to landing
Gen I & II

EDU

AIRDROP TESTING
## CPAS Gen 1 and Gen 2 Test Progression

### Gen 1 Testing
- **Jan – Mar ‘07**
  - 4 Tests
  - Pilot Chute Tests

- **Jun – Dec ‘07**
  - 3 Tests
  - Drogue Chute Tests

- **Aug ‘07 – Jan ‘08**
  - 3 Tests
  - Single Main Chute Tests

- **Oct ‘07 – Jul ‘08, May ‘10**
  - 2 Tests, PA-1, 1 Failed Test
  - Cluster Chute Tests

### Gen 2 Testing
- **Sept ‘09 - Mar ‘10**
  - 2 Tests, 1 Failed Test
  - TSE-1 A, B, & C
    - "Smart Separation"

- **April 2010**
  - 2 Tests
  - MDT 2-1, 2-2 Skipped Stage

- **July 2010**
  - 1 Test
  - CDT 2-1
    - Main Line Length Ratio

- **Sept - Dec 2010**
  - 3 Tests
  - MDT 2-3, CDT 2-2, 2-3
    - Increased Porosity

2/22/2013
Gen I & II Test Vehicles

- Each test vehicle was designed to achieve a specific test objective
- Weight Tub
  - Test the parachute system with a representative weight
  - Significantly tested and proven operations with a quick turn around
- Small or Medium Drop Test Vehicle (SDTV or MDTV)
  - Heritage vehicle from the X-38 program
  - High dynamic pressure
- Parachute Test Vehicle (PTV & PTV2)
  - Wake similar to the Orion capsule
Gen I CPAS PTV Failure (CDT-2)

- **Cause of failure**
  - Inability of programmer to remain inflated due to test vehicle wake
    - Programmer trailing distance was insufficient
    - Stabilization parachutes caused additional, not simulated wake

- **Contributing factors**
  - Late completion of ConOps
  - Small, unproven reefing used on the programmer (20%)
  - Lack of robust extraction and separation simulations
Boilerplate Failure Recovery

- Increased knowledge regarding wake effects
  - Computational fluid dynamics (CFD) anchored to wind tunnel testing
- Improved understanding of vehicle separation
  - Smart separation algorithm was created
    - Validated on 3 Gen II tests – Test Support Equipment (TSE) series
  - Separation simulations
    - Two-body 6-Degree of Freedom (DOF)
    - Models the separation and close proximity dynamics
- Lessons learned from boilerplate failure
  - Smart separation algorithm used to separate the PTV2 from the CPSS
  - Aerodynamic databases will be based on PTV wind tunnel data
  - Stabilization parachutes will not be used
  - Simulations will account for wake effects
  - All protuberances will be eliminated or rounded
Gen II Avionics Advancements

- **Data Acquisition System (DAS) - cRIO**
  - Centralized unit for controlling and storing data from multiple instruments
  - Allowed for time-synchronization of data
  - Larger storage capacity

- **Upgraded Velocity Measurement Instrumentation**
  - NovAtel SPAN-SE
    - Accurate measurement assists in ROD
  - Crossbow Nav440
    - Higher velocity uncertainties than NovAtel
    - Triggers smart separation
  - Both are integrated GPS/IMU
    - Mitigates drop outs during extraction phase
Gen II Avionics Advancements

- **Upgraded Load Measurements**
  - Gen I used Tension Measuring System (TMS) units attached to each riser - had high uncertainty
  - Gen II used 30,000 lbf strain links attached between the riser and confluence fitting
    - Provide adequate data for the Main parachutes
    - Provided noisy data on the Drogue parachutes due to the turbulent wake environment

- **Increased Fidelity in Atmospheric Data**
  - Windpack and balloon released to travel through similar air column as test
  - Ground weather stations on the drop zone
    - Anchors windpack and balloons with ground surface winds
AIRDROP TESTING

Gen I & II

EDU
EDU Test Vehicles

- Mid-Air Delivery System (MDS) & Cradle and Platform Separation System (CPSS)
  - Allows the PCDTV and PTV to be deployed from an aircraft cargo bay

- Parachute Compartment Drop Test Vehicle (PCDTV)
  - Tests the full CPAS system utilizing a stable vehicle
  - Dart shape based on the Solid Rocket Booster and Ares booster parachute test program
    - Allows for achievement of high dynamic pressure

- PTV/CPSS
  - Tests the full CPAS system with representative vehicle aerodynamics
  - Unable to achieve high dynamic pressure with current test techniques
PCDTV Test Sequence

1. Extraction
2. Separation
3. Programmer Deploy
4. Drogue Deploy
5. Mains 2nd Stage
6. Mains 1st Stage
7. Mains Full Open
8. Pilot Deploy
PTV Test Sequence

Smart Separation after Ramp Clear

Extraction from C-17 at 25,000 ft with two 28 ft Extraction Parachutes

Two Full-Open Gen II Drogues as Programmers deployed

Programmer cut One Drogue deployed

PTV Touchdown

Smart Drogue Release using SDR

3 Pilots lift 3 Mains with nominal reefing

3/3/2013
Simulations
Preflight Analysis
Post-Flight Analysis

PARACHUTE ANALYSIS
CPAS uses numerous simulation tools for preflight predictions, mission support, and post-flight data analysis and reconstructions.

- Determine configuration design
- Ensure safety of test and personnel
- Assess test objectives and solve unexpected test results
- Parachute model development

Tools have evolved from low fidelity spread sheets to high fidelity independent parachute simulations.

End-to-end trajectories currently require use of multiple simulations.

- Desired to consolidate number of simulations

Many of the simulations are developed and maintained by NASA JSC EG.

Support and processing tools developed and maintained by ESCG.
## Evolution of Simulation & Analysis Tools

<table>
<thead>
<tr>
<th>Time</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<tr>
<td><strong>Preflight Predictions</strong></td>
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<td>DTV-Sim v.14</td>
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<td>X-38 Legacy Footprint Tool</td>
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<td>(Primary)</td>
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<td>Pressure Altitude Calculation</td>
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<td><strong>Post Flight Reconstruction</strong></td>
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<td>v.17</td>
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<td>v.1.09, v.1.10</td>
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</table>

**Gen I**

**Gen II**

**EDU**
Simulations
Preflight Analysis
Post-Flight Analysis

PARACHUTE ANALYSIS
Preflight Predictions: Dynamic Pressure & Altitude

All cases reach Main steady state above altitude limit.
Preflight Predictions: Monte Carlo – Loads

0 valid cases exceed Main cluster limit (based on 50/25/25% load share)

0 valid cases exceed Drogue DLL
Preflight Predictions: Footprint Analysis
PARACHUTE ANALYSIS
Capsule Parachute Assembly System (CPAS) - ESCG Analysis Team

Post-Flight Data Analysis

- Windpack and balloon data
  - BEA: Best Estimate Atmosphere
  - BEW: Best Estimate Winds

- Vehicle Data used to create Best Estimate Trajectory (BET)
  - Dynamic Pressure
  - Loads*
  - Drag Area (C_D S)*

- Photogrammetry
  - Fly-out angles during steady state

*completed for each phase of each parachute
Winds < 30 ft/s mostly out of SW
~11 psf lower than nominal prediction at Main deployment
Load Scaling

- Scaling due to load cells being below fairlead
  - Energy lost due to friction
- Scale loads to match IMU data

Before Scaling
- Drogue S/N 6
- Disreef to Full

After Scaling
- Drogue Release

Chute Load (lb)

- DSS Preflight (12/11/2012)
- SPAN-SE Raw IMU
- Drogue S/N 3 (Bay A)
- Drogue S/N 6 (Bay F)
Photogrammetrics

- Used to characterize Main parachute behavior in a cluster
  - Quantify fly-out angles, geometric inlet area, and twist angles
  - Understand collisions and other parachute dynamics
  - Rate of Descent (ROD)
  - Reefing line tension
- Provides insight into dynamics which is related to data gathered
Fly-Out Angles During Steady State

- Main S/N 4 (candystriped)
- Main S/N 6 (double clocked)
- Main S/N 9 (double clocked)
- Main Cluster (avg,spline)
- Time Average: 16 deg

Collisions

Mains inflating

Time (s - RC)

Fly-Out Angle (deg)

Main steady-state
Reconstructions
Statistically Derived Parameters

DEVELOPMENT OF A PARACHUTE MODEL
Capsule Parachute Assembly System

Test Reconstruction

- Use BEA/BEW/BET
- Iterate parachute parameters
  - Automated process
  - Start with latest Model Memo values
- Output parachute parameters that cause simulation to match the BET
- Parameters are published in semiannual Model Memo
  - Assess parameters through benchmarks
Finite Mass Inflation Curve Fit

1. Determine Parachute Parameters:
   - Start time, \( t_i \)
   - Initial Airspeed, \( V_i \)
   - Drag coefficient from equilibrium velocity, \( C_{D0} \)
   - Time average drag areas
     - Start Drag Area, \((C_{DS})_a\)
     - End Drag Area, \((C_{DS})_b\)
     - Full open drag area, \((C_{DS})_o\)
   - Or describe area reefing ratios, \( \varepsilon_i, \varepsilon_{i+1} \)

2. Generate inflation curve with guessed parameters:
   - Fill constant, \( n \)
   - Profile shape, \( \text{expopen} \)
   - Optional: guess \( \varepsilon_{i+1} \)

3. Compute difference between inflation curve and test data
4. Sum the difference to compute area between curves (error)
5. Iterate \( n \) and \( \text{expopen} \) to minimize the error area
   - Optional: optimize \( \varepsilon_{i+1} \)
Main Best Fit Inflation parameters

<table>
<thead>
<tr>
<th></th>
<th>Main S/N 1</th>
<th>Main S/N 2</th>
<th>Main S/N 3</th>
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<tbody>
<tr>
<td>Reefing Ratio, $c_1$</td>
<td>3%</td>
<td>4%</td>
<td>7%</td>
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<tr>
<td>Reefed Drag Area per canopy, $(C_D S)_R$ (ft²)</td>
<td>280</td>
<td>372</td>
<td>718</td>
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<td>Fill Constant, n</td>
<td>27.6</td>
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<tr>
<td>expopen</td>
<td>1.2</td>
<td>1.5</td>
<td>0.7</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Main S/N 1</th>
<th>Main S/N 2</th>
<th>Main S/N 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reefing Ratio, $c_2$</td>
<td>12%</td>
<td>10%</td>
<td>12%</td>
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<tr>
<td>Reefed Drag Area per canopy, $(C_D S)_R$ (ft²)</td>
<td>1,142</td>
<td>976</td>
<td>1,197</td>
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<td>Fill Constant, n</td>
<td>39.8</td>
<td>22.8</td>
<td>16.8</td>
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<tr>
<td>expopen</td>
<td>0.3</td>
<td>0.9</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Main S/N 1</th>
<th>Main S/N 2</th>
<th>Main S/N 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag Coefficient, $C_D$</td>
<td>0.93</td>
<td>0.93</td>
<td>0.93</td>
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<tr>
<td>Full Open Drag Area per canopy, $(C_D S)_o$ (ft²)</td>
<td>9,850</td>
<td>9,850</td>
<td>9,850</td>
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<tr>
<td>Fill Constant, n</td>
<td>3.7</td>
<td>4.2</td>
<td>3.1</td>
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<tr>
<td>expopen</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
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</tbody>
</table>

Inflation parameters from individual parachute reconstructions for each stage are recorded in a spreadsheet.
Reconstructions

Statistically Derived Parameters

DEVELOPMENT OF A PARACHUTE MODEL
Transition from Uniform to Statistical Distributions

Capsule Parachute Assembly System (CPAS)

<table>
<thead>
<tr>
<th>Left Tail</th>
<th>Right Tail</th>
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<tbody>
<tr>
<td>$Z_\sigma$</td>
<td>% Outside CI</td>
</tr>
<tr>
<td>-1$\sigma$</td>
<td>31.73%</td>
</tr>
<tr>
<td>-2$\sigma$</td>
<td>4.550%</td>
</tr>
<tr>
<td>-3$\sigma$</td>
<td>0.2700%</td>
</tr>
</tbody>
</table>

**Test Data**
- Median: 2.3
- Mean: 2.7
- Bounds: 0.9 to 6.7

Distribution bounds usually fall between 2 and 3 (equivalent) standard deviations from mean.
SYSTEM VERIFICATION
1) Design the parachute subsystem
2) Test the design thought flight and ground tests
3) Development and Qualification test data is gathered
4) Document the test data and advancements in parachute physics knowledge
5) Verify the parachute subsystem meets flight performance requirements
   a) If No, update the document for requirement clarification
   b) If No, update the design so that it can meet the requirement
6) Validate flight performance requirements at the integrated Crew Module level
7) Conduct integrated flight tests
8) Run-for-the-record simulations
## Capsule Parachute Assembly System (CPAS) - ESCG Analysis Team

### DSS Credibility Assessment Score (CAS)

<table>
<thead>
<tr>
<th>Level</th>
<th>Verification</th>
<th>Validation</th>
<th>Input Pedigree</th>
<th>Results Uncertainty</th>
<th>Results Robustness</th>
<th>Use History</th>
<th>M&amp;S Management</th>
<th>People Qualifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Numerical error small for all important features.</td>
<td>Results agree with real-world data.</td>
<td>Input data agree with real-world data.</td>
<td>Non-deterministic &amp; numerical analysis.</td>
<td>Sensitivity known for most parameters; key sensitivities identified.</td>
<td>De facto standard.</td>
<td>Continual process improvement.</td>
<td>Extensive experience in and use of recommended practices for this particular M&amp;S.</td>
</tr>
<tr>
<td>3</td>
<td>Formal numerical error estimation.</td>
<td>Results agree with experimental data for problems of interest.</td>
<td>Input data agree with experimental data for problems of interest.</td>
<td>Non-Deterministic analysis.</td>
<td>Sensitivity known for many parameters.</td>
<td>Previous predictions were later validated by mission data.</td>
<td>Predictable process.</td>
<td>Advanced degree or extensive M&amp;S experience, and recommended practice knowledge.</td>
</tr>
<tr>
<td>2</td>
<td>Unit and regression testing of key features.</td>
<td>Results agree with experimental data or other M&amp;S on unit problems.</td>
<td>Input data traceable to formal documentation.</td>
<td>Deterministic analysis or expert opinion.</td>
<td>Sensitivity known for a few parameters.</td>
<td>Used before for critical decisions.</td>
<td>Established process.</td>
<td>Formal M&amp;S training and experience, and recommended practice training.</td>
</tr>
</tbody>
</table>

**Supporting Evidence**

**M&S Operations**

**M&D Development**

**DSS Credibility Assessment Score (CAS)**

2/22/2013
FUTURE OF CPAS
Capsule Parachute Assembly System (CPAS) - ESCG Analysis Team

Future of CPAS

- **Testing**
  - **EDU** (plan as of Feb 6, 2013)
    - 2013: 3 tests – 2 PTV, 1 PCDTV
    - 2014: 5 tests – 4 PTV, 1 PCDTV
      - Includes first Forward Bay Cover (FBC) test
    - 2015: 2 tests – 2 PTV
  - EFT-1 in fall 2014

- **Simulation & Model development**
  - Transition to end-to-end simulation in an independent parachute model
  - Time varying ROD model using fly-out angles
  - Refinement of statistically derived dispersions

Lockheed Martin’s MPCV
SPECIAL THANKS

- CPAS Analysis Team
  - Pat Galvin
  - Eric Ray
  - Kristin Bledsoe
  - Usbaldo Fraire
  - Joe Varela
  - Johnny Blaschak
  - Fernando Galaviz

- Koki Machin
- Mike Frostad
- Entire CPAS team
Capsule Parachute Assembly System (CPAS)  - ESCG Analysis Team

For More Information…

- **2009 AIAA ADS Conference**
  - Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Drogue and Pilot Development Test Results, R. Olmstead
  - Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Main and Cluster Development Test Results, K. Bledsoe

- **2011 AIAA ADS Conference**
  - Summary of CPAS Gen II Testing Analysis Results, A. Morris
  - Load Asymmetry Observed During Orion Main Parachute Inflation, A. Morris
  - Challenges of CPAS Flight Testing, E. Ray
  - Verification and Validation of Requirements on the CEV Parachute Assembly System Using Design of Experiments, P. Schulte
  - Development of Monte Carlo Capability for Orion Parachute Simulations, J. Moore
  - Photogrammetric Analysis of CPAS Main Parachutes, E. Ray
  - A Hybrid Parachute Simulation Environment for the Orion Parachute Development Project, J. Moore
  - Measurement of CPAS Main Parachute Rate of Descent, E. Ray
  - Development of the Sasquatch Drop Test Footprint Tool, K. Bledsoe
  - Development of a Smart Release Algorithm for Mid-Air Separation of Parachute Test Articles, J. Moore
  - Simulating New Drop Test Vehicles and Test Techniques for the Orion CEV Parachute Assembly System, A. Morris
  - Verification and Validation of Flight Performance Requirements for Human Crewed Spacecraft Parachute Recovery Systems, A. Morris

- **2013 AIAA ADS Conference**
  - Extraction and Separation Modeling of Orion Test Vehicles with ADAMS Simulation, U. Fraire
  - An Airborne Parachute Compartment Test Bed for the Orion Parachute Test Program, J. Moore
  - Application of a Smart Parachute Release Algorithm to the CPAS Test Architecture, K. Bledsoe
  - Application of Statistically Derived CPAS Parachute Parameters, L. Romero
  - A Boilerplate Capsule Test Technique for the Orion Parachute Test Program, J. Moore
  - Testing Small CPAS Parachutes Using HIVAS, E. Ray
  - Improved CPAS Photogrammetric Capabilities for Engineering Development Unit (EDU) Testing, E. Ray
  - Reefing Line Tension in CPAS Main Parachute Clusters, E. Ray
  - Skipped Stage Modeling and Testing of the Capsule Parachute Assembly System, J. Varela
  - Reconstruction of Orion EDU Parachute Inflation Loads, E. Ray

2/22/2013
QUESTIONS?
BACKUP
Parachute Deployment Envelope

- Drogue contingency deploy envelope
- Nominal Entry Drogue Deploy
- Drogue mortar fire
- Pilot mortar fire
- Main inflation

PCDTV: CDT-3-1 (9/8/2011)
PCDTV: CDT-3-2 (12/20/2011)
PTV: CDT-3-3 (2/29/2012)
PCDTV: CDT-3-4 (4/17/2012)
PTV: CDT-3-5 (7/18/2012)
PCDTV: CDT-3-6 (8/28/2012)
Helicopter tests were simple to execute and analyze

Test Conducted

- Pilot Development Tests (PDT)
  - Vehicle used: SDTV
- Drogue Development Tests (DDT)
  - Vehicle Used: MDTV

Programmer parachute set up the desired dynamic pressure

- Poor understanding of programmer drag lead to a failure to achieve the desired test condition
Low Velocity Aerial Delivery (LVAD)
- Certified US Army cargo aircraft extraction method
- Uses a Type V platform and standard Army extraction parachute

Short Platforms (12 ft by 9 ft platform)
- Significant pitch under the programmer by ~180°
  - Pilot or Main parachute slings could have been severed
- Near-failure causes
  - Unstable & not well-characterized aerodynamics
  - Programmer trailing distance from platform
    - Changed on MDT-2 with no significant stability increase
  - Programmer size
Capsule Parachute Assembly System (CPAS) - ESCG Analysis Team

Gen I/II Missile Shaped Vehicles

- Cradle Monorail System (CMS)
  - Allowed the MDTV to be deployed by a C-130A aircraft
  - Constructed on a 32 ft by 9 ft Type V platform to use the LVAD extraction technique
- No separation simulation created
  - Used low fidelity analysis methods and engineering judgment
  - Separation occurred at the time of lowest dynamic pressure predicted in preflight simulations
  - Assumed an instantaneous separation
  - Post-test analysis proved that separation occurs in 1.5 seconds

2/22/2013
## Summary of Generation II Tests

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Number of Parachutes</th>
<th>Vehicle Type</th>
<th>Primary Test Objective</th>
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<tbody>
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<td>Programmer</td>
<td>Drogues</td>
<td>Mains</td>
</tr>
<tr>
<td>MDT-2-1</td>
<td>1 Drogue</td>
<td>1</td>
<td>1</td>
</tr>
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<td>MDT-2-2</td>
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<tr>
<td>CDT-2-1</td>
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<tr>
<td>CDT-2-2</td>
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<tr>
<td>CDT-2-3</td>
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<td>3</td>
</tr>
</tbody>
</table>

MDT – Main Development Test  
CDT – Cluster Development Test

MDTV – Medium Drop Test Vehicle  
CMS – Cradle Monorail System
MDS (Mid-Air Deployment System) Sequence

1. MDS under extraction parachutes (post separation)
2. Separation
3. Extraction
4. Stabilization Parachutes deployed
5. Recovery chutes deployed
6. Recovery chutes 1st Stage
7. Recovery chutes 2nd Stage
8. Recovery chutes disreef to Full Open
9. MDS touchdown
10. Touchdown

2/22/2013
CPSS Test Sequence

Smart Separation 2.235 s after Ramp Clear

Extraction from C-17 at 25,000 ft with two 28 ft Extraction Parachutes

Reposition to backstop 75.1 s after Ramp Clear

Extraction chute cutaway, recovery chute deploy 128 s after Ramp Clear

CPSS touchdown 330 s after Ramp Clear
Trajectory Simulations

- **CAPSIM & PalletSIM**
  - Used to independently model two-vehicle systems post separation
  - Not used in EDU test phase

- **DSS**
  - High fidelity 6-DOF trajectory simulation
  - Does not have multi-body capability
  - Uses a composite model approach to simulation parachute clusters

- **ADAMS**
  - Commercial multi-body simulation
  - Models contact forces between bodies
  - Used for EDU extraction and separation phases

- **Flight Analysis and Simulation Tool (FAST)**
  - 6-DOF multi-body trajectory simulator
  - Utilizes Lockheed Martin developed hi-fi parachute model
  - Currently being phased in as primary tool for preflight predictions

CAPSIM GUI

ADAMS Overlay
Trajectory Simulations

- **Decelerator Simulation System Application (DSSA)**
  - Provides end-to-end 6-DOF simulations of Type V LVAD tests
  - Includes an aircraft extraction model
  - Uses DSS parachute model

- **DTV-Sim**
  - 2-DOF simulation without an aircraft extraction model
  - Provides a point mass trajectory of any vehicle type
  - Uses DSS parachute model
### Parachute Parameters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_D)</td>
<td>Drag coefficient (of full open parachute)</td>
</tr>
<tr>
<td>(n)</td>
<td>Canopy fill constant</td>
</tr>
<tr>
<td>(\text{expopen})</td>
<td>Opening profile shape exponent</td>
</tr>
<tr>
<td>(C_k)</td>
<td>Over-inflation factor</td>
</tr>
<tr>
<td>(t_k)</td>
<td>Time to ramp down after stage over-inflation</td>
</tr>
</tbody>
</table>

![Diagram showing the relationship between Drag Area and Time](image-url)

- \((C_D S)_a\) at \(t_i\)
- \((C_D S)_{\text{peak}}\)
- \((C_D S)_b\)
- \(t_f\)
- \(t_{fp}\)
- \(t_k\)

- \(\text{expopen} = 0.5\)
- \(\text{expopen} = 1\)
- \(\text{expopen} < 1\)
- \(\text{expopen} > 1\)
Day of Flight Simulations & Lessons Learned

➢ Wind data
  ➢ Preflight predictions are done concerning wind contingency release altitudes
  ➢ Wind measurements gathered hourly from RAWIN balloons
    ➢ Balloon data is input into Sasquatch to determine the test article footprints
  ➢ Ground winds can cause parachute and test vehicle damage
    ➢ Tests are timed to occur immediately after sunrise when winds are at a minimum

➢ Release altitudes
  ➢ Gen I and II data showed higher than planned release altitudes
  ➢ Changes were made to provide the air crew with an indicated pressure altitude instead of the previously used geometric altitude
  ➢ Tests have shown that this procedure causes vehicles to be dropped at the planned altitude
Parachute Reconstruction Process

Computed Parachute Performance
- Steady-State Reefed Drag Area
  \((C_D S)_R\)
- Steady-State Full Open Drag Area
  \((C_D S)_o\)
- Reefing Ratios
  \(\varepsilon_i = \frac{(C_D S)_R}{(C_D S)_o}\)
- Over-Inflation Factors (infinite mass only)
  \(C_k = \frac{(C_D S)_{peak}}{(C_D S)_R}\)

Drag Area Optimization Process
- 'fminsearch' function
- Minimize error between computed and test \(C_D S(t)\)

Drag Area Simulations for Stage j in MATLAB
- Canopy fill time
  \(t_f = n \cdot D_o \cdot \sqrt{\frac{\varepsilon_{i+1} - \varepsilon_i}{V_i}}\)
- Parachute Drag Area Growth
  \((C_D S)(t) = (C_D S)_a + ((C_D S)_b - (C_D S)_a) \cdot \left(\frac{t - t_i}{t_f}\right)^{expopen}\)
- Drag Area Ramp Down Curve (infinite mass only)
  \((C_D S)(t) = (C_D S)_{peak} \cdot (C_k)_{(t_e+t_i-1)/t_k}\)

Guess Inflation Parameters (e.g. from Model Memo)
- Canopy Fill Constant
  \(n\)
- Opening Profile Shape Exponent
  \(expopen\)
- Fall Time (infinite mass only)
  \(t_k\)

Guess Inflation Parameters
- (e.g. from Model Memo)
  - Canopy Fill Constant
    \(n\)
  - Opening Profile Shape Exponent
    \(expopen\)
  - Fall Time (infinite mass only)
    \(t_k\)

DSS Input File

Stage Comparison
- Do peak parachute loads match?
- Does Altitude match?
- Does dynamic pressure match?

Modify fill constants using engineering judgment

Output Optimized Constants for Stage j
- Canopy Fill Constant
  \(n\)
- Opening Profile Shape Exponent
  \(expopen\)
- Fall Time (infinite mass only)
  \(t_k\)

Parachute Data
- Riser and Resultant Loads
  \(F_i\)
- Steady-State Drag Area
  \((C_D S)_{p,i} = \frac{F_i + W_{p,i} \cdot G}{q}\)

Initial Conditions from BET
- Altitude
  \(H\)
- Velocity & Airspeed
  \(V_{East}, V_{North}, V_{z}, V_{air}\)
- Attitudes
  \(\theta, \psi, \varphi\)
- Body Rates
  \(P, Q, R\)

\(\text{Stage Initial Airspeed}\)
\(V_i\)

\(\text{Continue to next stage}\)

\(\text{Stages Completed?}\)

\(\text{Yes}\)

\(\text{No}\)

Reconstruction Complete

DSS 6-DOF Trajectory

2/22/2013
CPAS Flight Performance Requirements

- Probability of meeting requirements
  - Loads
    - Probability per table with 50% confidence
  - ROD (planned for Rev C)
    - 99.87% probability of meeting the requirement with 90% confidence
  - Torque (planned for Rev C)
    - 99.87% probability of meeting the requirement with 90% confidence

- Necessitates the use of statistical assessments

<table>
<thead>
<tr>
<th>Chute Loads</th>
<th>Reference Mission</th>
<th>Case</th>
<th>Probability of Meeting Design Limit Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>High altitude abort/entry</td>
<td>Nominal</td>
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<td>0.9987</td>
</tr>
<tr>
<td>One-drogue failure</td>
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<td></td>
<td>0.9773</td>
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<tr>
<td>Low altitude/pad aborts</td>
<td>Nominal</td>
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<td>0.9773</td>
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<tr>
<td>One-drogue failure</td>
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<td>0.8413</td>
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<tr>
<td>Main Loads</td>
<td>High altitude abort/entry</td>
<td>Nominal</td>
<td>0.9987</td>
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<tr>
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</table>
Uniform Dispersions

- Previous Model Memos included uniform dispersions
  - Design dispersions – maximum and minimum seen in test
  - Flight test dispersions – engineer factor around design dispersions
    - 5% for $C_D S$
    - 10% for other parameters
Further Updates to Statistical Dispersions

Test Data
- logn: 0.9209 0.44781
- Bounds: 0.90063 6.7474
- Median: 2.41

Test Data
- logn: 0.14547 0.21556
- Bounds: 0.76275 1.8689
- Median: 1.17

EDU Main Stage 3 n

EDU Main Stage 3 expopen