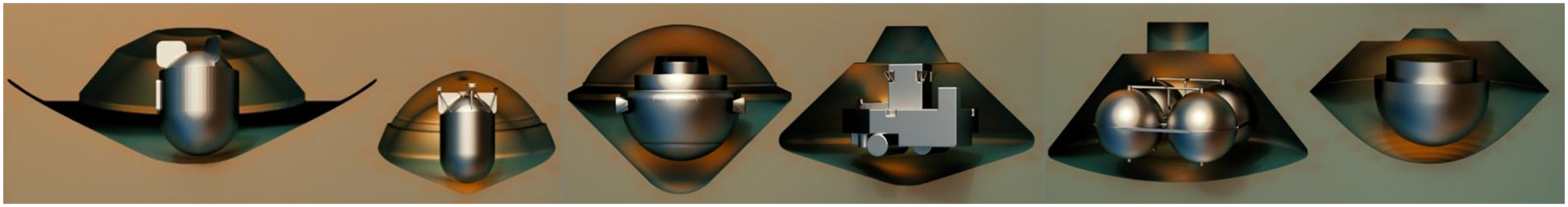

Entry, Descent, and Landing Systems Short Course

Subject: CPAS Parachute Testing, Model Development, & Verification

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JETS/Aerodyne, LLC

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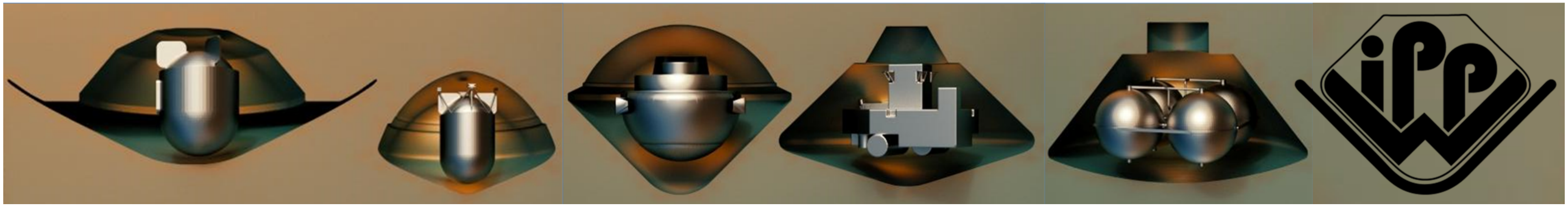
International Planetary Probe Workshop 10
June 15-16, 2013
San Jose, California



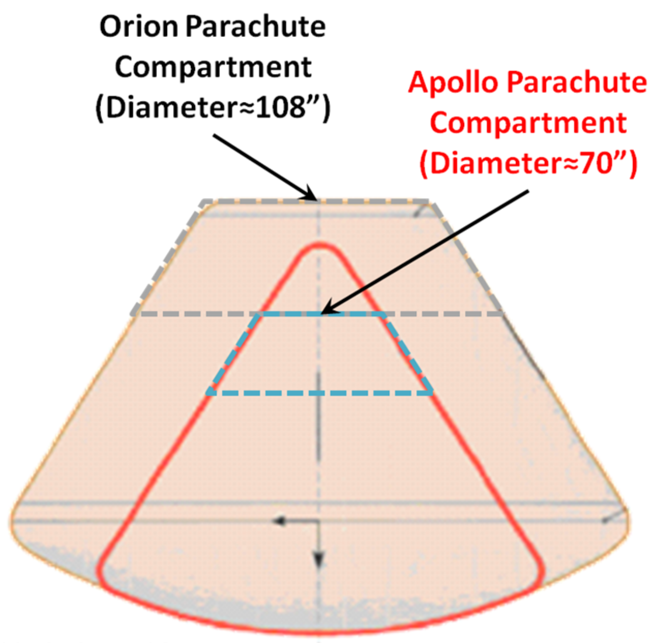
Agenda

- CPAS Overview
- Airdrop Testing
- Parachute Test Analysis
- Development of a Parachute Model
- System Verification & Validation
- Future of CPAS

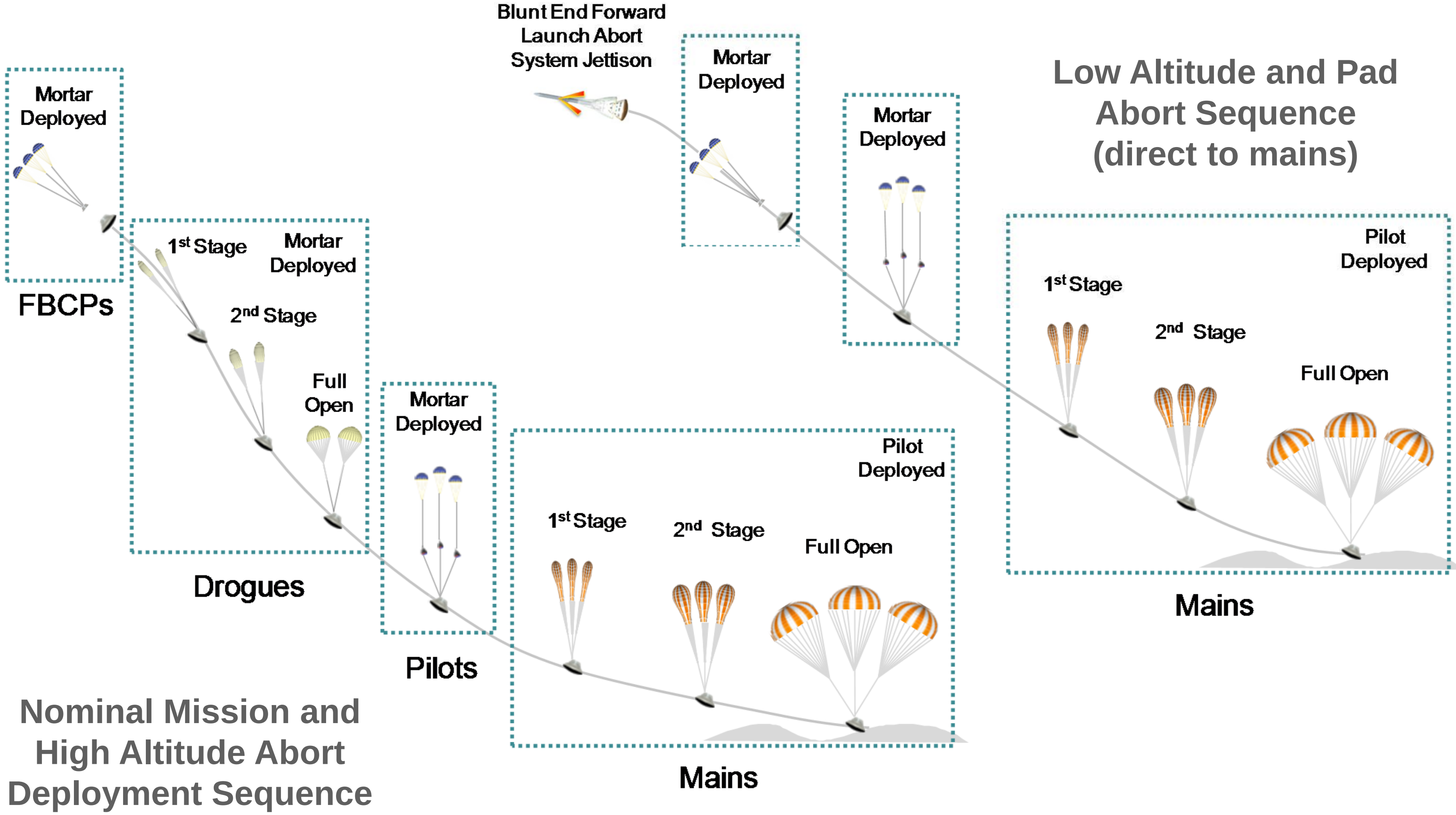
CPAS OVERVIEW

CPAS Overview

- Capsule Parachute Assembly System (CPAS) is the human rated parachute system for the Orion vehicle used during re-entry
  - Similar to Apollo parachute design
  - Human rating requires additional system redundancy
- A Government Furnished Equipment (GFE) project responsible for:
  - Design
  - Development testing
  - Performance modeling
  - Fabrication
  - Qualification
  - Delivery



CPAS Concept of Operations



CPAS Requirements

- The CPAS Project Technical Requirement Specification (PTRS) levies requirements on the system
- To verify the design and validate the requirements
  - Some system aspects are modeled
  - Some rely on demonstration
- 155 requirements total with 104 completely or partially verified by analysis
- Verification and Validation Document (V&VD)
  - Contains success criteria for verification of each requirement
  - Identifies the method and pass/fail criteria

CPAS Analysis Focus

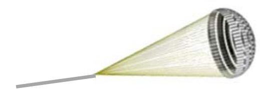
- CPAS analysis team responsible for verification and validation of 23 requirements
  - Functional and performance
    - Meet all other requirements when in deployment envelope
    - Meet all other requirements with specified vehicle mass
  - Rate of Descent (ROD)
    - Crew and vehicle structure safety
  - Parachute Loads – single riser and cluster loads
    - Individual parachute failure
    - Vehicle structural failure
  - Rotation Torque and Flyout Angle Limit
    - Main risers induce rotation
    - Orient vehicle edge into water for landing
- Develop models anchored to flight tests
- Conduct Monte Carlo analyses to examine possible failure conditions and compare results to requirements
  - Parachute canopy or riser failure
  - Failure to deploy
  - Parachute flagging or skipped stage

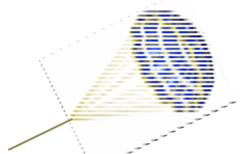
AIRDROP TESTING

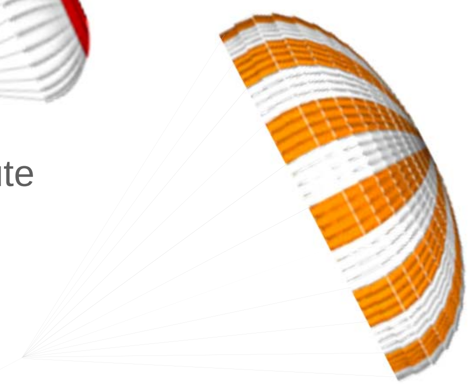
CPAS Parachutes

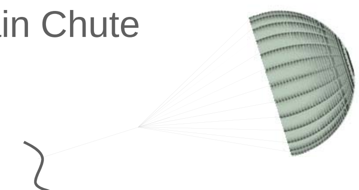
- Forward Bay Cover Parachutes (FBCPs) (~7 ft)
  - Pulls off Forward Bay Cover (FBC) from vehicle.
- Drogue Parachutes (~23 ft)
  - Stabilizes the vehicle for Main deployment.
- Pilot Parachutes (~10 ft)
  - Pulls out the Main chutes.
- Main Parachutes (~116 ft)
  - Slow the vehicle to landing.

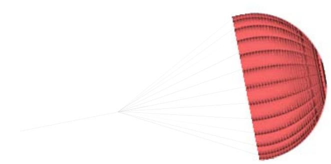
- Test Support Parachutes
  - Extraction Chutes (~28 ft)
    - Pulls the vehicle out of the aircraft. Used for testing only.
  - Programmer Parachutes
    - Used to create the proper test conditions for the Drogue, Pilot, or Main chutes. Used for testing only.
    - Can sometimes be an identical chute as the Drogues, but the use is different.







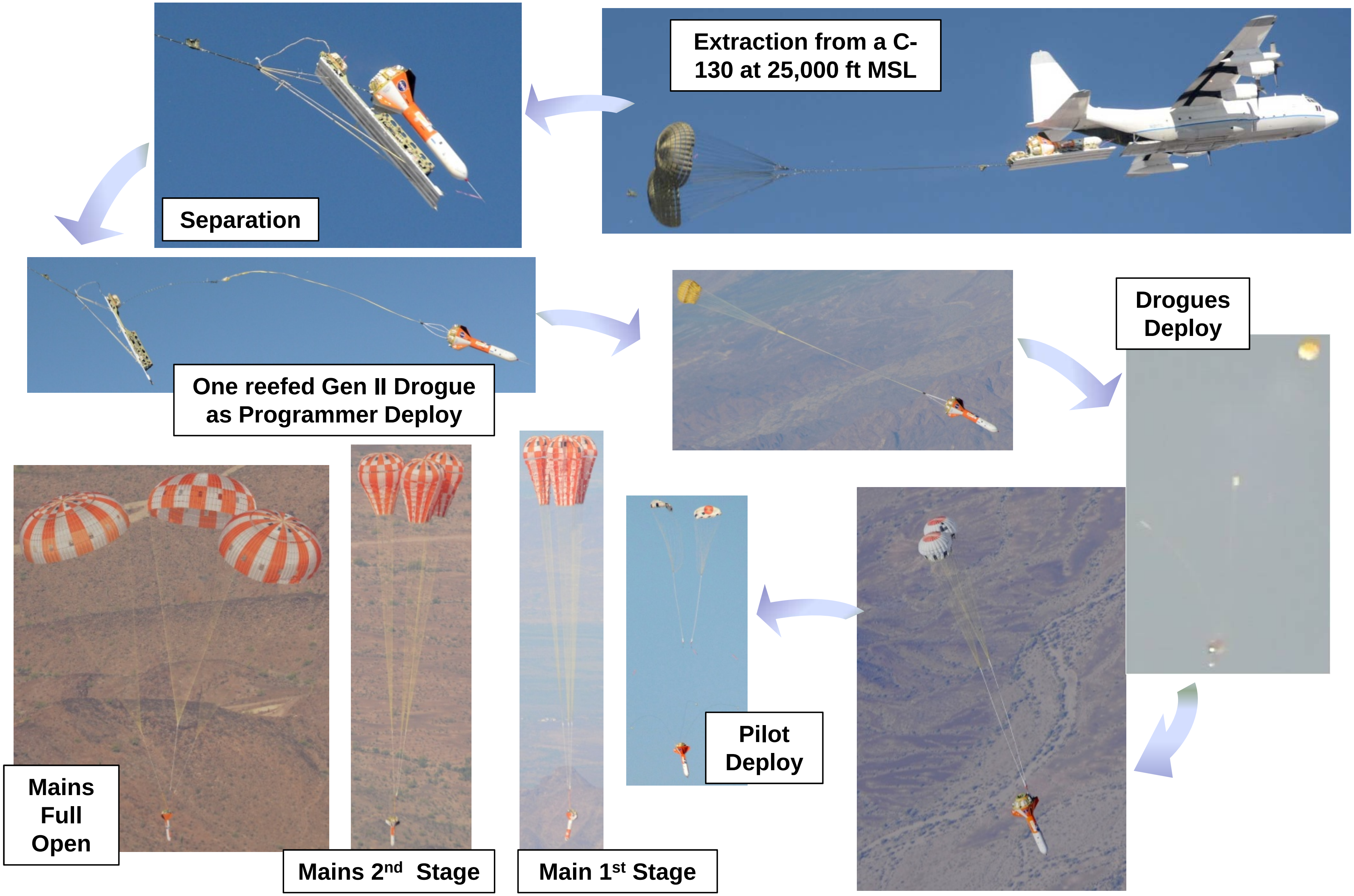




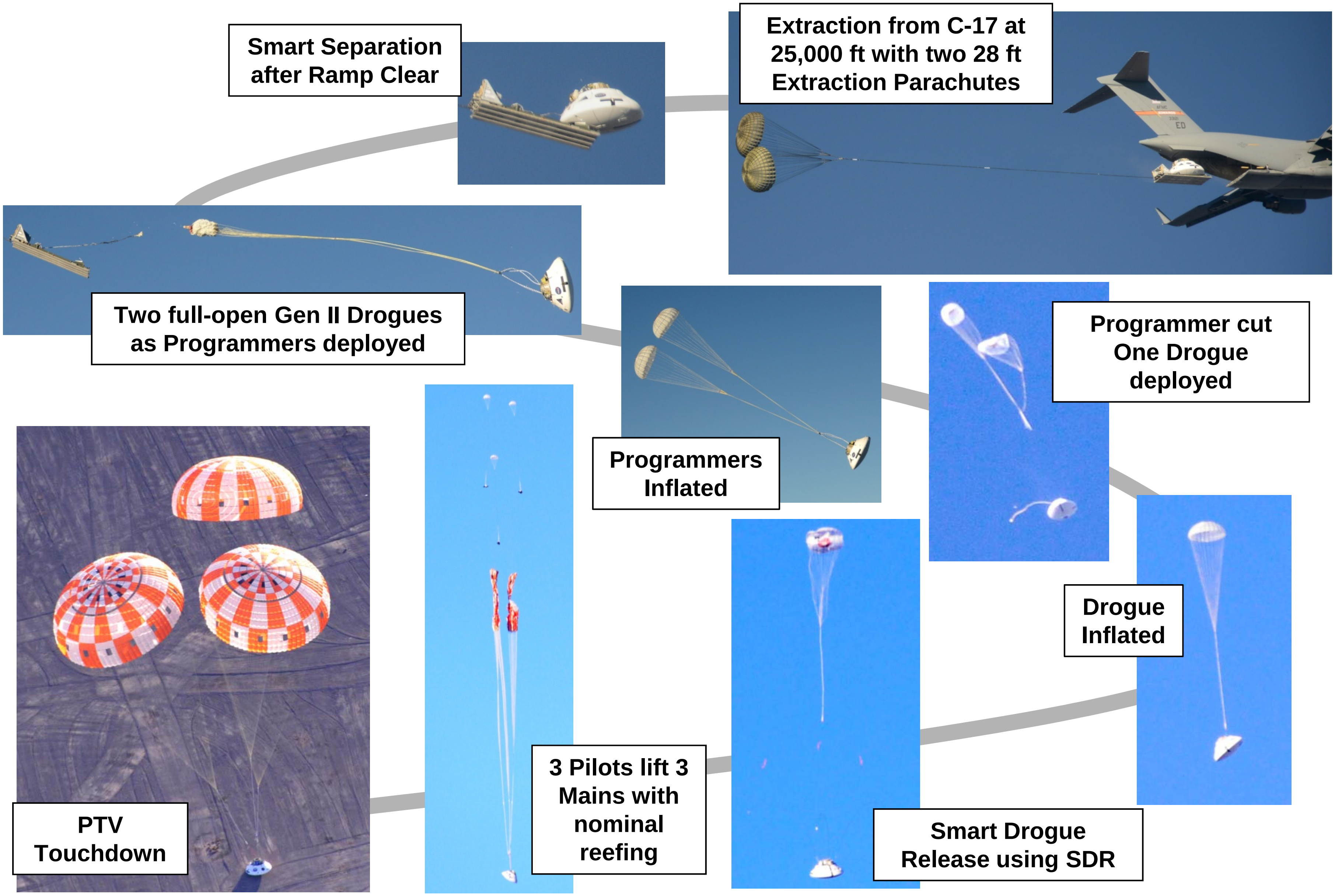
Engineering Development Unit (EDU) Test Vehicles

- Mid-Air Delivery System (MDS) & Cradle 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 an aerodynamically 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 flight like wake environment
  - Unable to achieve nominal entry environment with current test techniques

PCDTV/MDS Test Sequence



PTV/CPSS Test Sequence



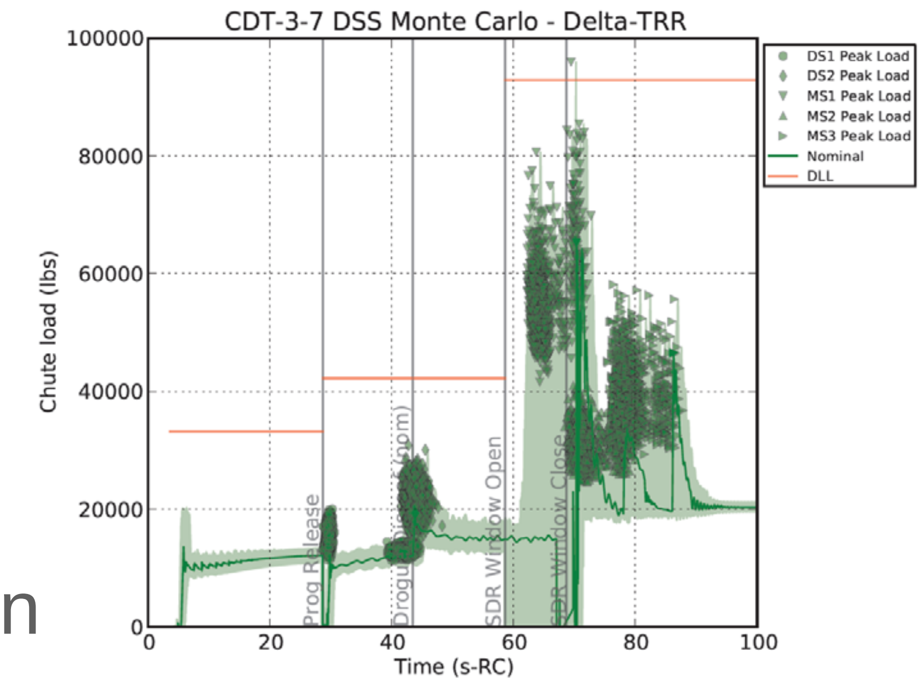
Video

- For more videos, search for NASACPAS user on YouTube

PARACHUTE TEST ANALYSIS

Parachute Analysis: Preflight

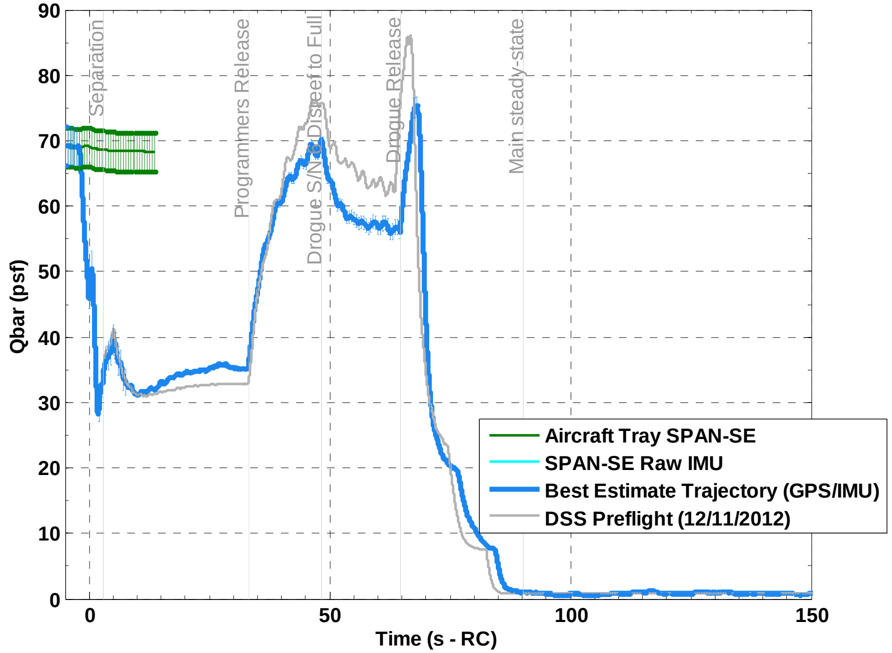
- No single end-to-end simulation available therefore multiple simulations used to model different phases
- Define test objectives: number and configuration of programmers



- Assesses risk of test through Monte Carlos: loads, altitude, range safety, etc.

Parachute Analysis: Post-flight

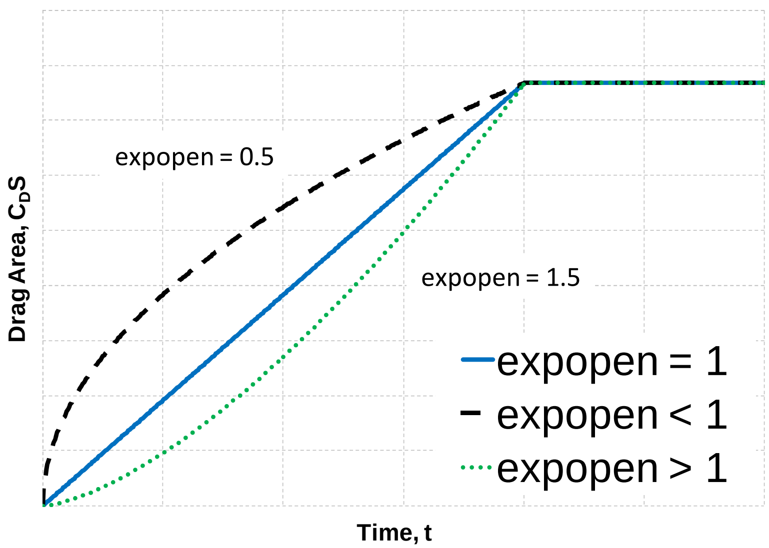
- Reduce and plot test data against prediction
- Photogrammetric analysis used to characterize parachute behavior

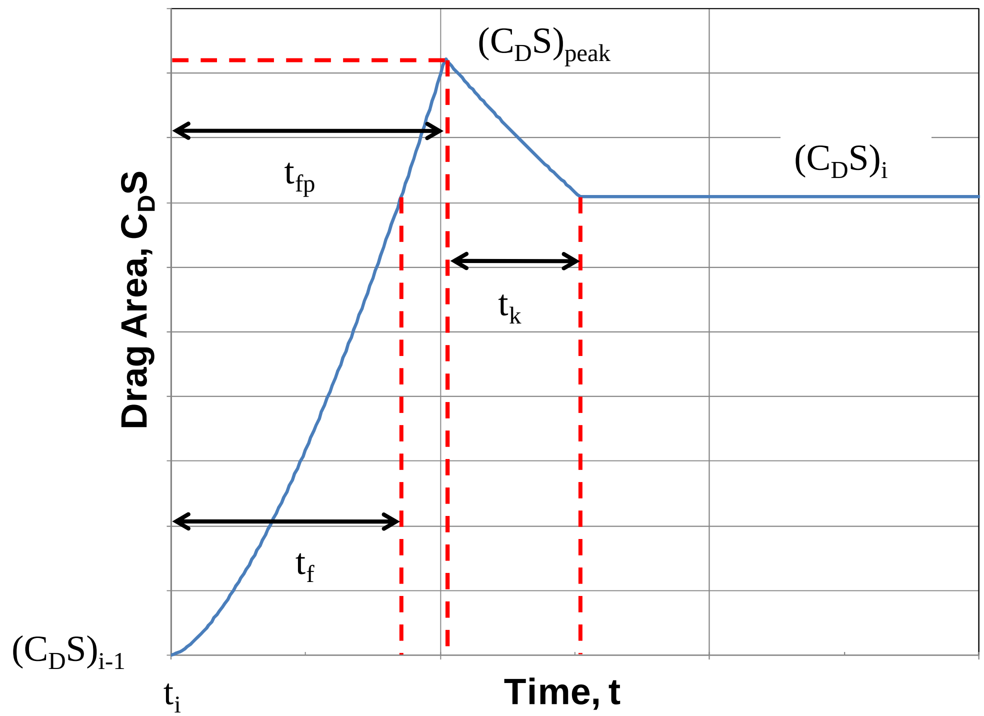


DEVELOPMENT OF A PARACHUTE MODEL

Parachute Modeling

- Parachute parameters
  - Drag area: C_DS
  - Fill constant: n
  - Opening profile shape exponent: expopen
  - Overinflation factor: C_k
  - Ramp down time: t_k





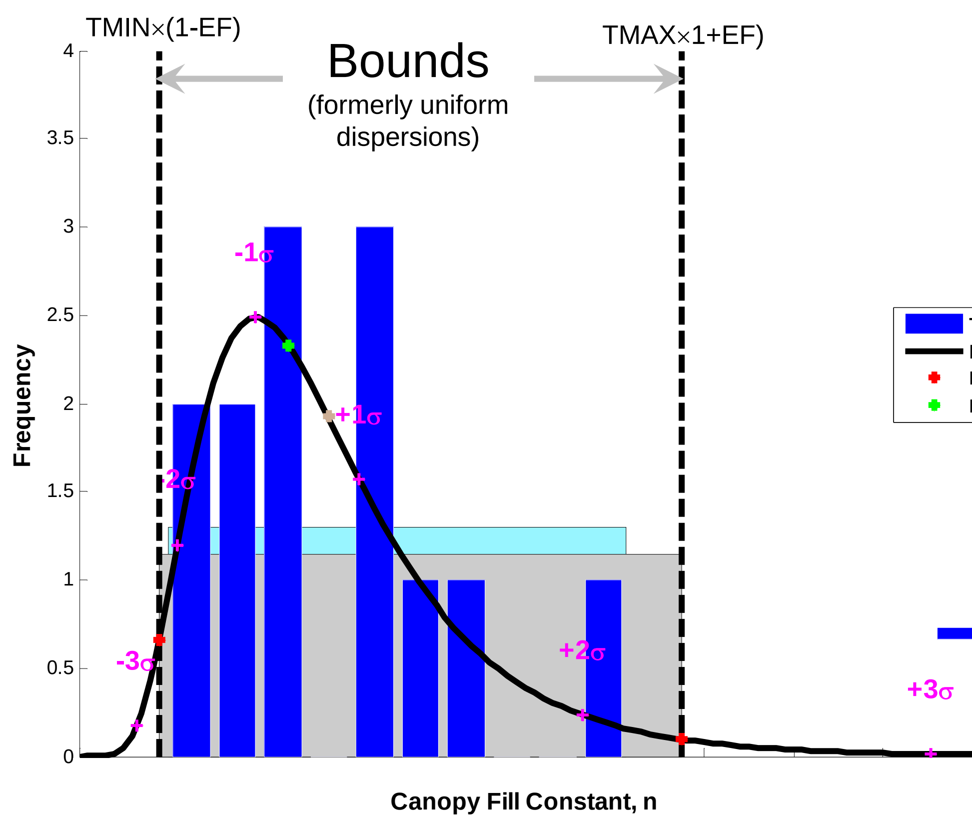
Model Development

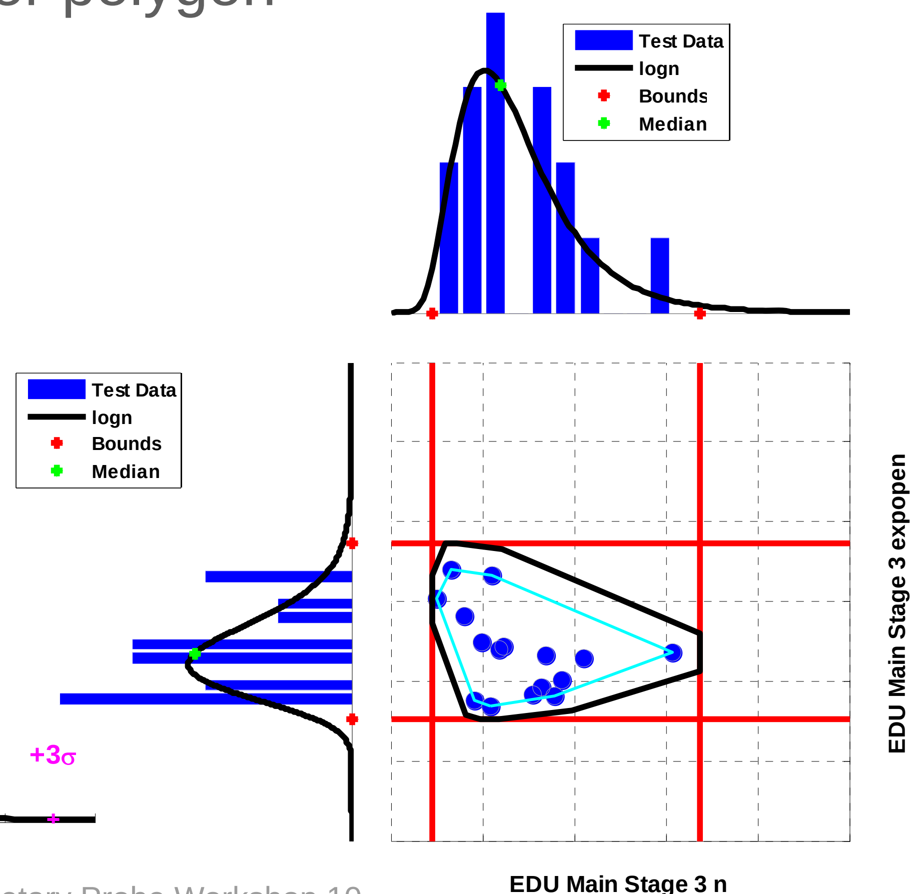
- Determine appropriate parachute parameter through test data reconstructions
  – Run simulations varying parachute parameters until test data is matched
  – Can be subjective
- Do this for each test, parachute type, and stage

	CDT-3-4		CDT-3-5		CDT-3-6	
	Drogue A	Drogue B	Drogue A	Drogue B	Drogue A	Drogue B
Clean Reefed Drag Area per canopy, $(C_DS)_R$ (ft^2)	128	128	146	158	133	134
Over-inflation Factor, C_k	1.2	1.3	1.2	1.3	1.3	1.4
Fill Constant, n	3.4	6.9	5.4	4.9	7.5	5.2
Opening profile shape exponent, expopen	0.90	2.1	2.1	2.2	2.8	1.9
Ramp down time, tk (s)	0.69	0.13	0.03	0.06	0.14	0.11

Model Development

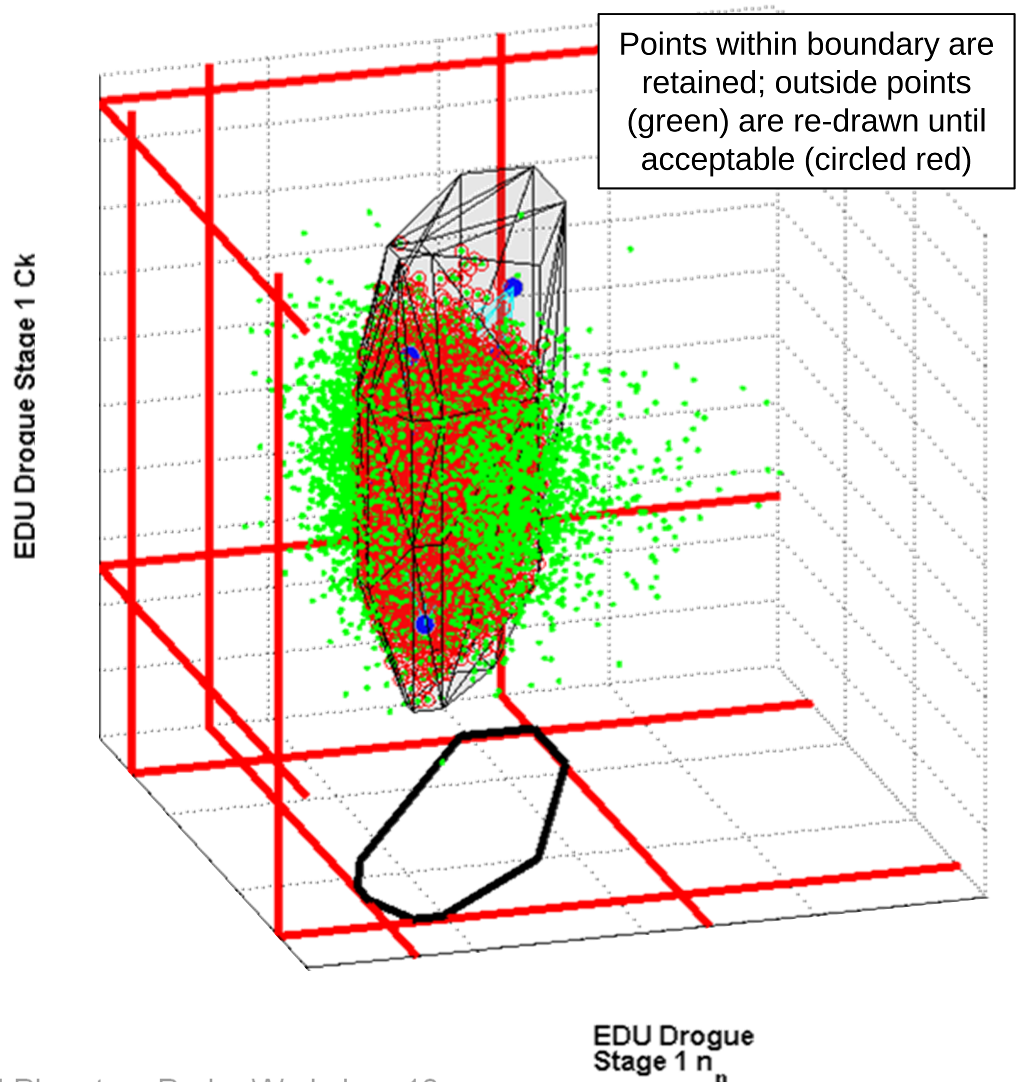
- Generate dispersions for each parachute type and stage
- Dispersion bounding: caps or polygon





Model Development

- Redraw dispersions until inside polygon
- Deliver parachute model: 200K dispersions via 21 text files



SYSTEM VERIFICATION & VALIDATION

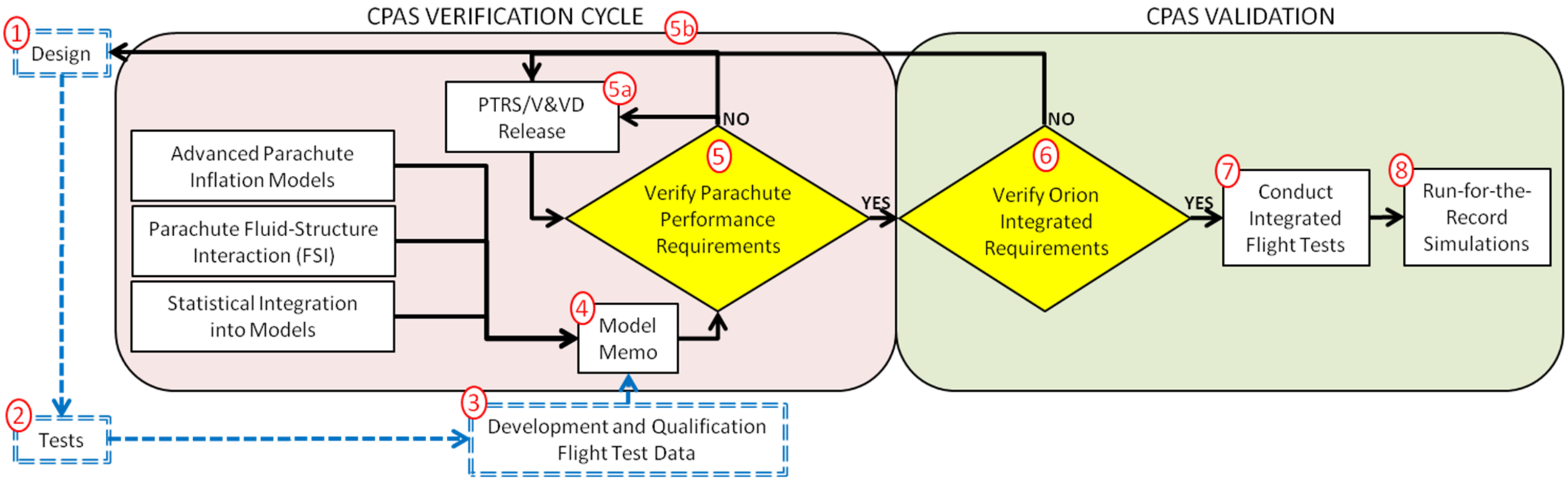
System V&V Introduction

- CPAS must meet its requirements to ensure the system functions as intended, individually and with other Orion systems
- V&V plan is a "list of activities that establishes the compliance" with the requirements
- Flight performance requirements are verified via analysis
- Instructions provided through NASA Standard 7009 "Standard for Models and Simulations"
  - Model must be credible
    - Determine through Model Credibility Scoring Guidelines
    - Completed for each model and simulation
      - Current primary simulation: Decelerator System Simulation (DSS)
      - Future primary simulation: Flight Analysis & Simulation Tool (FAST)

Model Credibility Score for DSS (January 2011)

Level	Verification	Validation	Input Pedigree	Results Uncertainty	Results Robustness	Use History	M&S Management	People Qualifications
4	Numerical error small for all important features.	Results agree with real-world data.	Input data agree with real-world data.	Non-deterministic & numerical analysis.	Sensitivity known for most parameters; key sensitivities identified.	De facto standard.	Continual process improvement.	Extensive experience in and use of recommended practices for this particular M&S.
3	Formal numerical error estimation.	Results agree with experimental data for problems of interest.	Input data agree with experimental data for problems of interest.	Non-Deterministic analysis.	Sensitivity known for many parameters.	Previous predictions were later validated by mission data.	Predictable process.	Advanced degree or extensive M&S experience, and recommended practice knowledge.
2	Unit and regression testing of key features.	Results agree with experimental data or other M&S on unit problems.	Input data traceable to formal documenation.	Deterministic analysis or expert opinion.	Sensitivity known for a few parameters.	Used before for critical decisions.	Established process.	Formal M&S training and experience, and recommended practice training.
1	Conceptual and mathematical models verified.	Conceptual and mathematical models agree with simple referents.	Input data traceable to informal documenation.	Qualitative estimaes.	Qualitative estimates.	Passes simple tests.	Managed process.	Engineering or science degree.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.
	M&S Development		M&S Operations			Supporting Evidence		

CPAS V&V Cycle



1) Design the parachute subsystem
2) Test the design through 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

FUTURE OF CPAS

Future of CPAS

- Development Testing
  - EDU (plan as of May 20, 2013)
    - 2013 (remaining): 2 tests – 1 PTV, 1 PCDTV
    - 2014: 4 PTV tests
    - 2015: 2 PTV tests
  - EFT-1 in fall 2014
- Qualification Tests
- Simulation & model development
  - Transition to end-to-end simulation in an independent parachute model
  - Refinement of statistically derived dispersions
  - Determine and document Model Credibility of simulation used for run-for-the-record V&V

Lockheed Martin's MPCV

SPECIAL THANKS

- CPAS Analysis Team
  - Pat Galvin
  - Johnny Blaschak
  - Kristin Bledsoe
  - John Davidson
  - Megan Englert
  - Usbaldo Fraire
  - Fernando Galaviz
  - Eric Ray
  - Joe Varela
- Koki Machin
- Entire CPAS 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
  - Proposed Framework for Determining Added Mass of Orion Drogue Parachutes, U. Fraire
  - 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

For Even More Information…

- 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

QUESTIONS?