A Multidisciplinary Analysis Approach for the Cygnus Cargo Resupply to ISS

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Unlocking the Potential of MBSE with ModelCenter
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Orbital ATK Overview

Orbital — Innovation You Can Count On®

Orbital ATK — The Partner You Can Count On

ATK — Aerospace Systems, Defense Systems — Innovation… Delivered

- Global Aerospace and Defense Systems Company Established by Merger of Orbital and Alliant Techsystems in 2015

- Leading Developer and Manufacturer of Innovative, Reliable and Affordable Products for Government and Commercial Customers
  - Launch Vehicles, Rocket Propulsion Systems and Aerospace Structures
  - Tactical Missile Products, Armament Systems and Ammunition
  - Satellites, Space Components and Technical Services

- More Than 13,000 Employees, Including About 4,200 Engineers and Scientists

Flight Systems Group

Defense Systems Group

Space Systems Group

Orbital ATK SSG MDAO/MBSE Experience

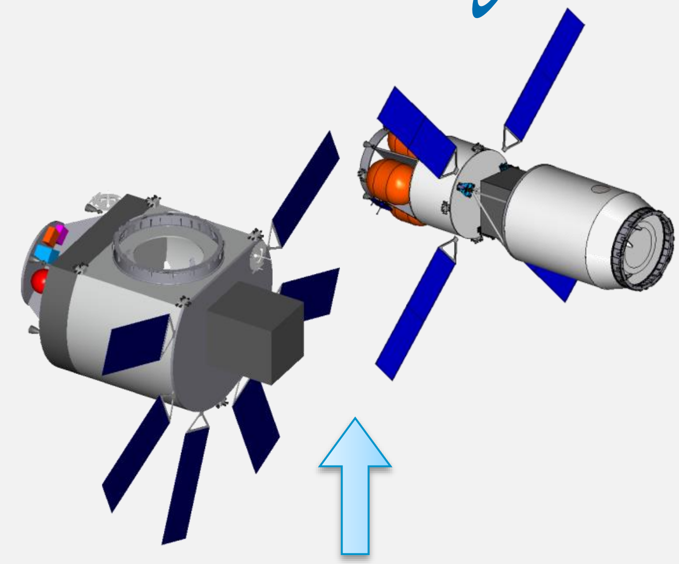
"A standardized and robust modeling language is considered a critical enabler for MBSE. The Systems Modeling Language (OMG SysML™) is one such general purpose modeling language …" *- A Practical Guide to SysML, 2012*

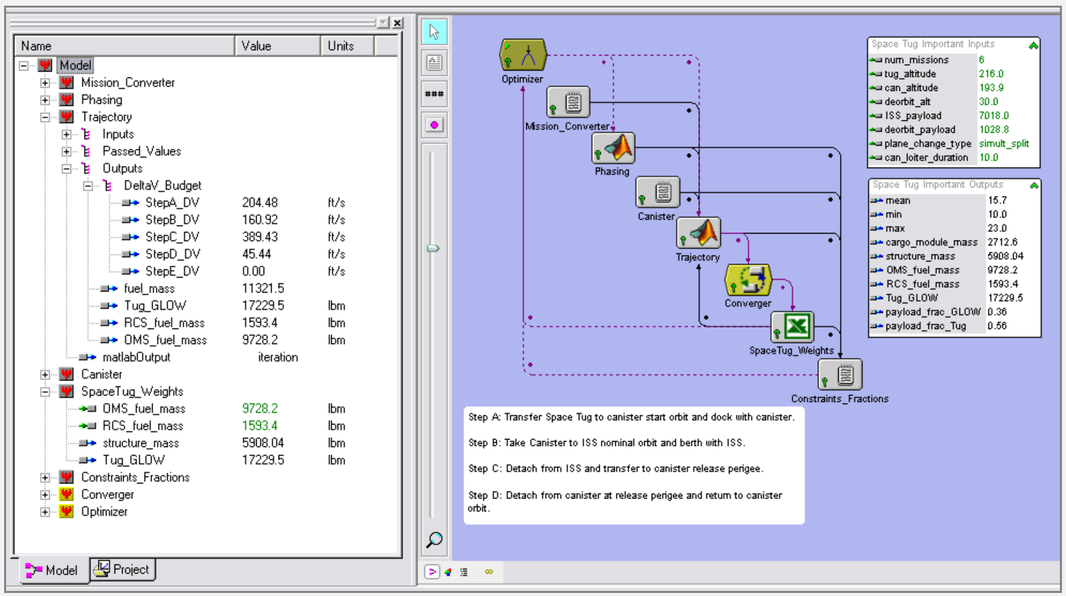
- MBSE ≠ SysML
  - SysML Is NOT a methodology or tool; it is a language that is tool/methodology-independent
  - SysML Is NOT meant to replace modeling investments in other engineering disciplines
  - SysML IS designed to *support* MBSE, but MBSE does not *require* SysML
- Orbital ATK has significant MBSE experience developing integrated analysis models to explore & evaluate large design space, generate robust designs, & integrate/automate complex analyses
- SSG has extensive experience performing multi-disciplinary analyses using Phoenix Integration ModelCenter®
  - Integrate & automate analysis models across different software programs & platforms
  - Optimize design with many optimization methods
  - Explore design space sensitivity w/ parametric trade studies & Design of Experiment tools
  - Assess/verify design robustness with probabilistic analysis tools (Monte Carlos)
- Many programs have used ModelCenter (Orion, Antares, CRS, Heavy Lift Study, …)

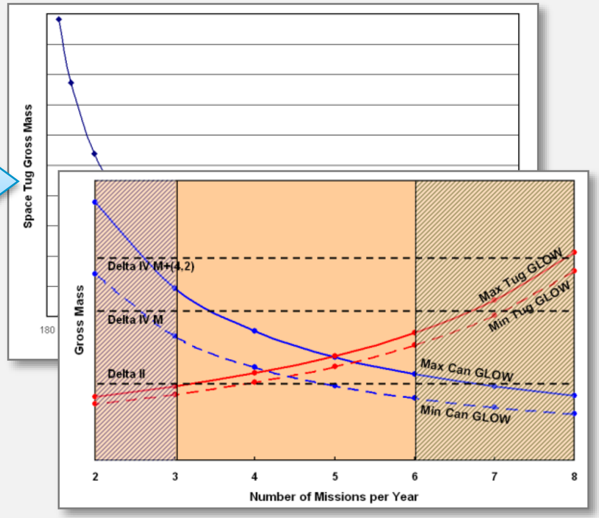
Daniel Dvorak, "Model-Centric Engineering, Part 1: An Introduction to Model-Based Systems Engineering", JPL

ICCS/COTS Proposal (2005-2006)

- Integrated Visiting Vehicle sizing & mission analysis to support ICCS/COTS proposal
  - Architecture study focused on developing spacecraft that maximizes on-orbit missions capabilities without exceeding existing launch vehicle payload constraints
  - Parametric trade studies conducted to explore sensitivity of Space Tug mass to variation in payload mass, number of missions, and CONOPS
  - Convergence/optimization of spacecraft design gross mass between FSG + SSG trajectory tools (MATLAB) & SSG spacecraft sizing tools (MS Excel)



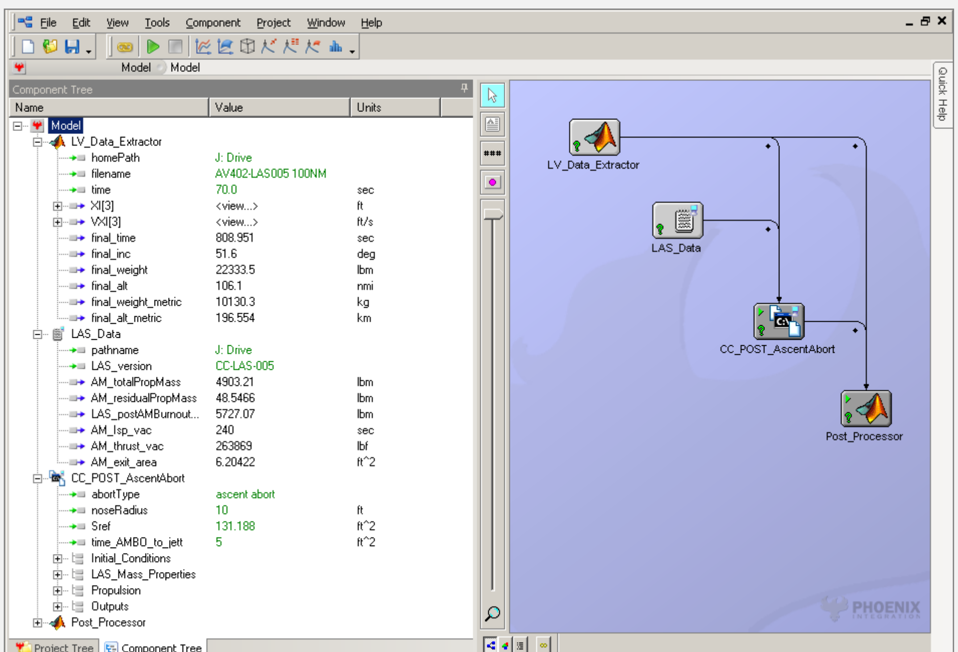


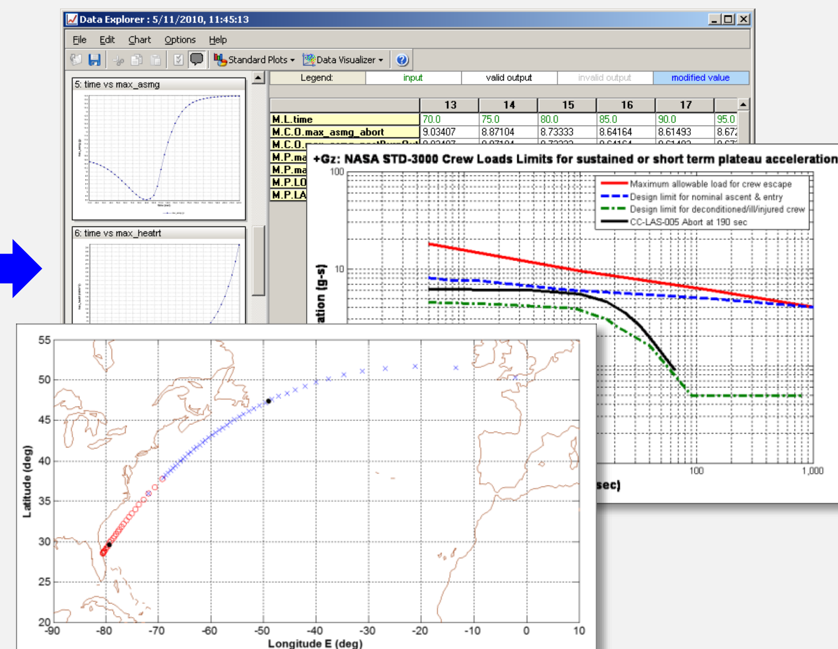


"Space Tug: An Alternative Solution to ISS Cargo Delivery," AIAA 2009-6519

CCDev2 Proposal (2010)

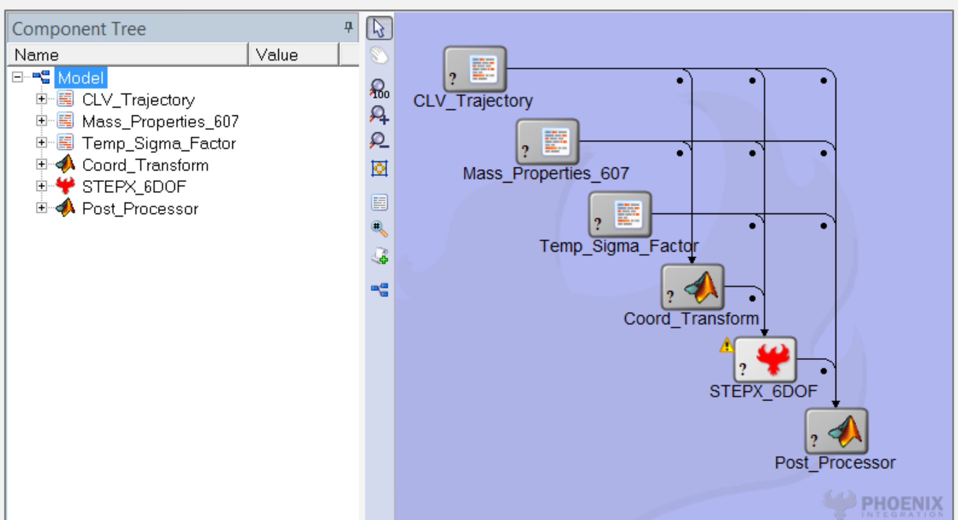
- Discipline tools integrated in ModelCenter for analysis of Abort Black-Out Zones
  - Abort initial conditions extracted from LV trajectory MATLAB data file
  - LAS mass properties & abort motor propulsion data extracted from spreadsheet
  - Initial conditions, masses, and propulsion data passed to POST 3-DOF
  - POST 3-DOF trajectory data post-processed to generate crew load limits & abort instantaneous impact points using MATLAB
- Parametric Trade Study: Performed abort simulation at intervals of LV trajectory
- Post-abort accelerations compared to NASA STD-3000 crew load limits

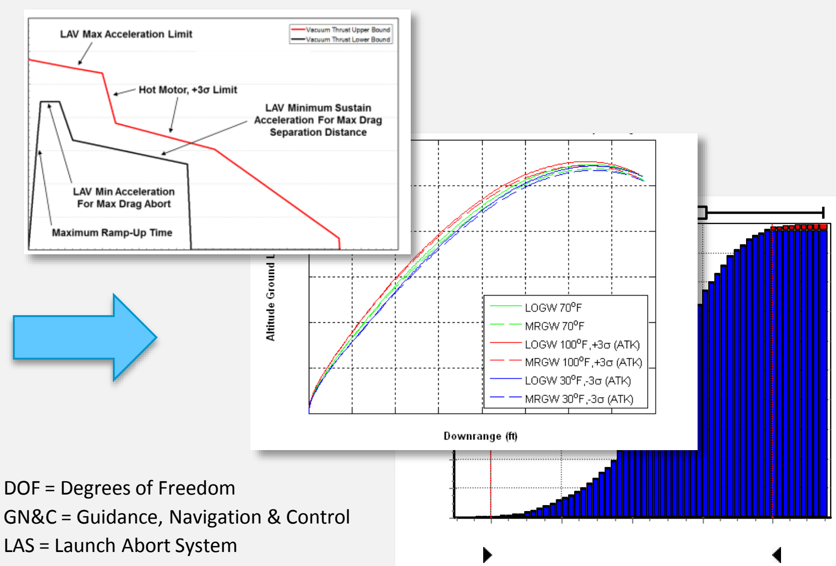




Orion LAS PA-1 Validation/Verification (2006-2008)

- PA-1 flight test integrated mission analysis conducted in ModelCenter
  - Rapid turnaround customer-requested analyses
  - Optimization of abort motor thrust profile
  - Perform GN&C 6-DOF trajectory analysis for configuration, initial conditions, and motors performance variations
- Validation & verification of performance requirements with Monte Carlo analysis within ModelCenter
- Analysis traceability back to requirements database (Cradle via Excel)

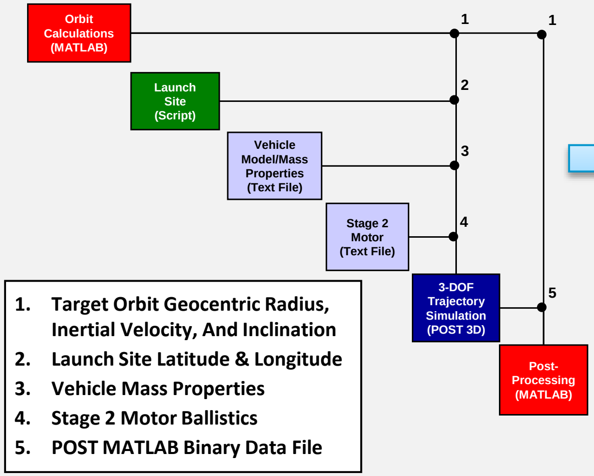




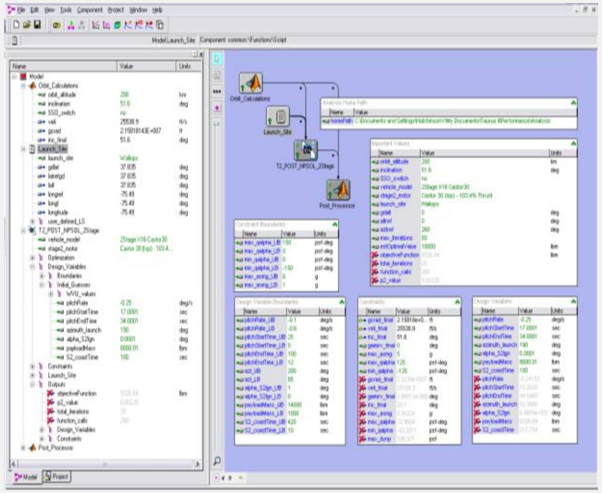
DOF = Degrees of Freedom
GN&C = Guidance, Navigation & Control
LAS = Launch Abort System
PA-1 = Pad Abort 1

Antares Performance Analysis (2008-2010)

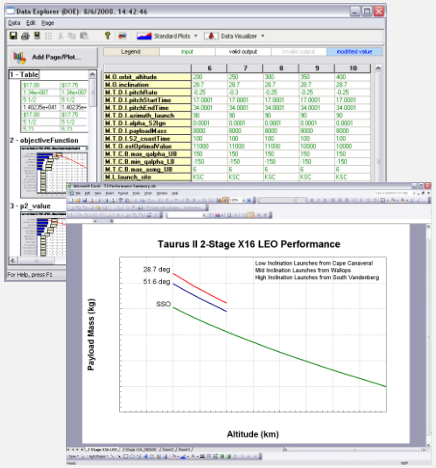
- Antares Payload Performance conducted in ModelCenter collaborative environment
  - Integrated analysis model automatically updates and evaluates POST 3DOF trajectory for changes in mass properties, upper stage motor ballistics, launch site, & target orbit
- ModelCenter parametric trade study tools conducted payload performance analysis autonomously based on matrix of input values & switches
  - Parametric trade studies were conducted to explore sensitivity of payload performance to variation in orbit altitude, inclination, and launch site



Antares Performance Design Structure Matrix



Antares Performance ModelCenter Model

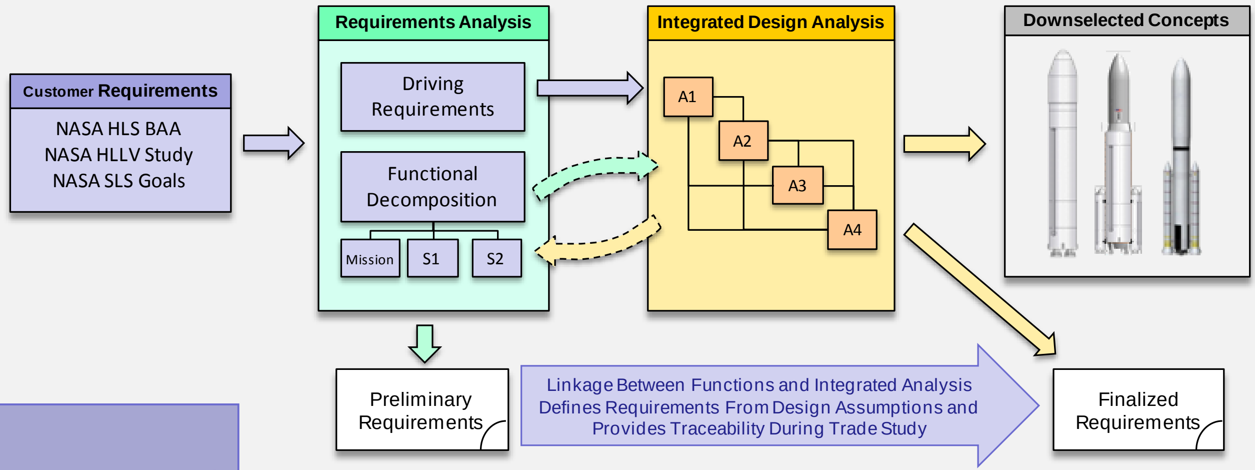


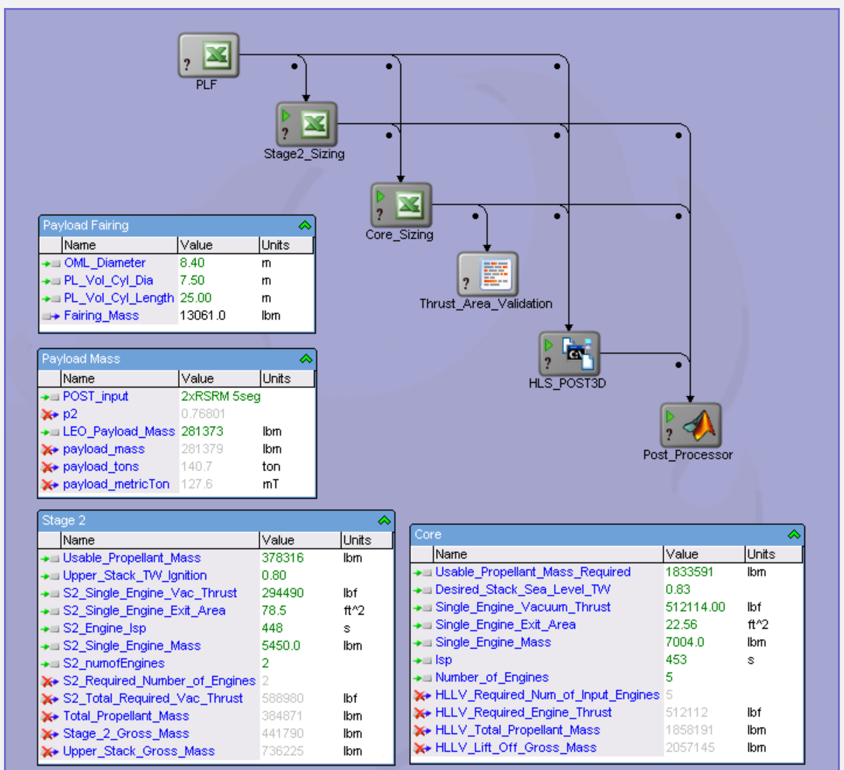
Performance Analysis Results

NASA Heavy Lift & Propulsion Systems Analysis & Trade Study (2010-2011)

Orbital ATK

- MBSE processes utilized with the Integrated Design Analysis to define top-level requirements and provide traceability during the NASA Heavy Lift Study



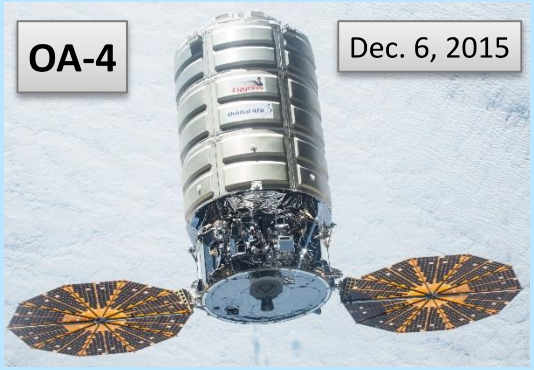


- Orbital ATK's Integrated Systems Analysis Model within ModelCenter® Collaborative Design Environment
  - ➢ Model provides data transfer between tools & system-level MDO, and enforces constraints
  - ➢ Facilitated MBSE linkage between the integrated analysis and design requirements
- Preliminary reliability and cost analyses performed outside integrated model

"A Multidisciplinary Approach to the Heavy Lift System Architecture Study," AIAA 2013-5373

BAA = Broad Agency Announcement
HLLV = Heavy Lift Launch Vehicle
HLS = Heavy Lift System
MBSE = Model-Based Systems Engineering
MDO = Multi-Disciplinary Optimization
SLS = Space Launch System

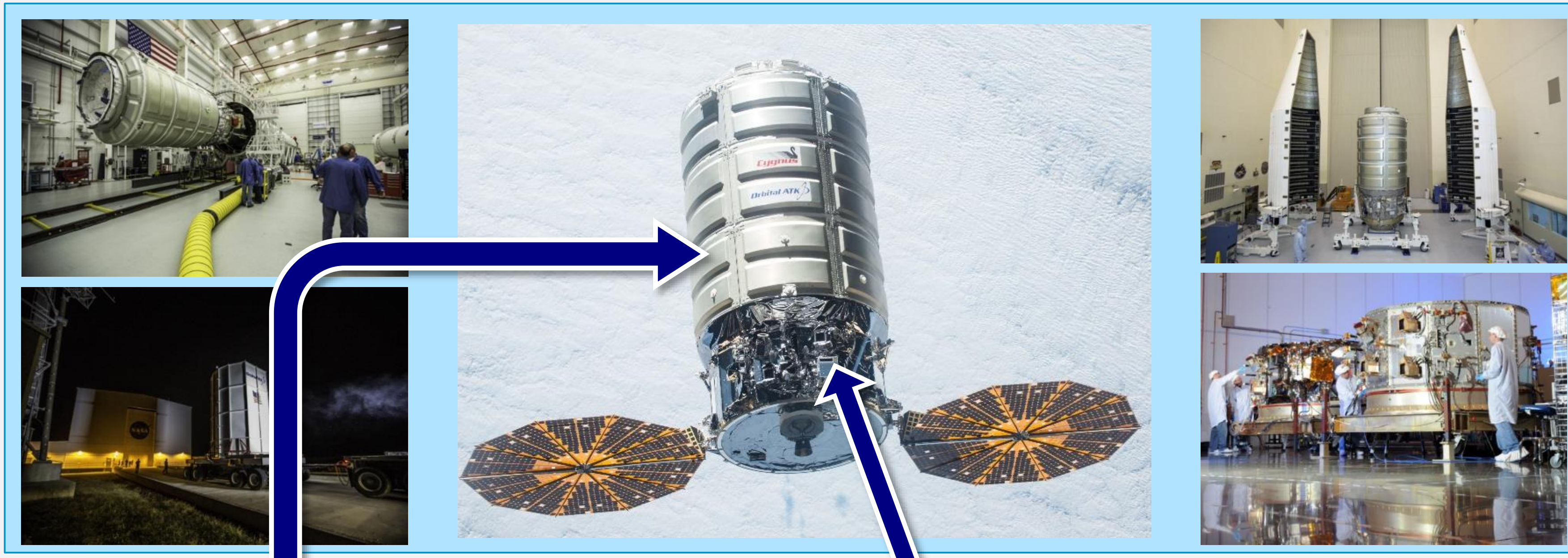
ISS Cargo Resupply with Orbital ATK Cygnus



- Cygnus carries crew supplies, spare equipment & scientific experiments to the ISS
- 16.5 mT of Cargo Delivered to ISS in 7 Flights
- 4 CRS Flights from 2017 to 2019
- 6 CRS2 Flights starting in 2019

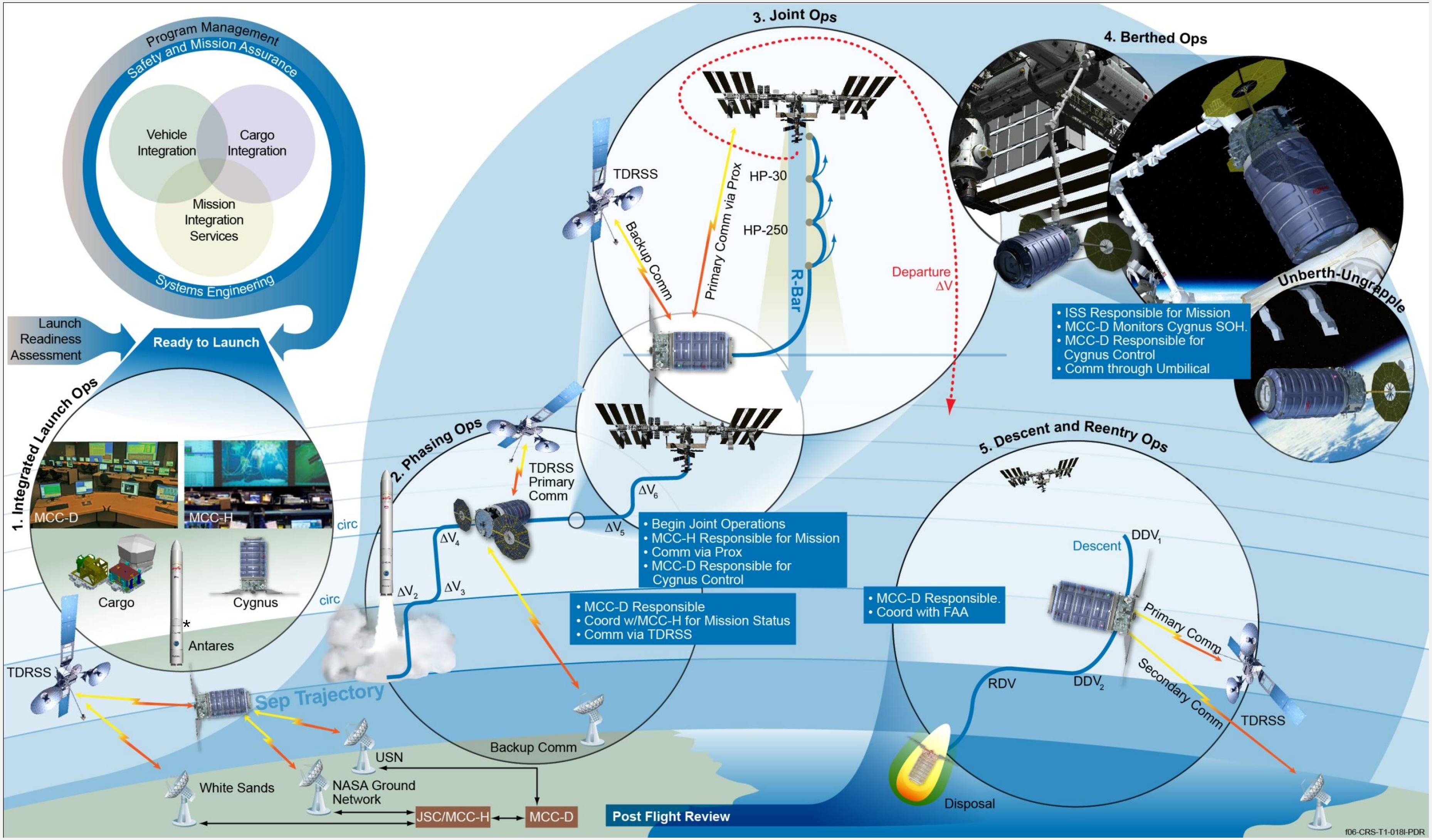
Cygnus Spacecraft Overview

Cygnus consists of two modules: Service Module & Pressurized Cargo Module



- **Pressurized Cargo Module (PCM)**
  - Heritage: Multi-Purpose Logistics Module
  - Produced by Thales Alenia Space
  - Total Cargo Mass: 3,200 - 3,500 kg
  - Pressurized Volume: 26.2 m^3
  - Berthing at ISS: Node 2 Common Berthing Mechanism (CBM)
- **Service Module (SM)**
  - Heritage: Orbital ATK Flight Proven GEOStar^{TM} & LEOStar^{TM} satellites
  - Power Generation: 2 Fixed Wing Solar Arrays, ZTJ GaAs cells
  - Power Output: 3.5 kW (sun-pointed)
  - Propellant: Dual-mode N_2H_4/MON-3 or N_2H_4

Cygnus ISS Resupply Mission Overview



*OA-4, OA-6, and OA-7 Mission Launches on Atlas V

Performance Analysis Motivation & Objective

Motivation

- CRS Performance Enhancement with Mission Optimization
  - Mission optimization opportunities selected to improve cargo performance & minimize mission impact
  - Opportunity: Improved propellant consumption analysis & provide statistical estimation for total mission
    - Increase fidelity of analyses for further system/subsystem developments & improvements
    - Improve tool/process to easily generate statistical data to validate propellant usage during the mission
    - End Goal: Provide statistical impact of each $+3\sigma$ propellant budget line item on total mission propellant

- Develop process to integrate subsystem discipline tools for accurate mission propellant usage estimation
  - Integrate existing discipline tools: Flight Dynamics, Propulsion, GN&C, & Systems
  - Enable rapid turn around of analyses for changing mission design, cargo accommodations & spacecraft configuration
  - Support significant reuse: enable increased fidelity without major work; explore propellant impact for contingencies
  - Perform Robust V&V of propellant load for each mission; results support propellant loading & ops thresholds

Objective

- Assess Cygnus propellant usage during CRS Mission to validate fuel load & oxidizer load
  - Propellant usage calculated for each maneuver during mission
- Calculate propellant usage for each maneuver during CRS mission
- Perform Monte Carlo analysis of propellant budget
  - Provide statistics for fuel & oxidizer usage during CRS Mission
  - Compare mission $+3\sigma$ vs. sum of maneuver $+3\sigma$ propellant usage

Mission Performance Optimization Process

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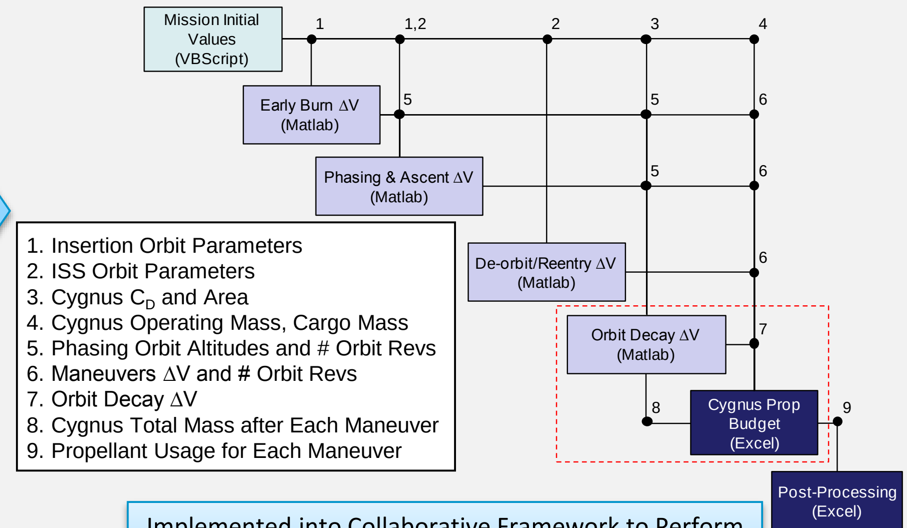
Assumptions & Dispersions Spreadsheet

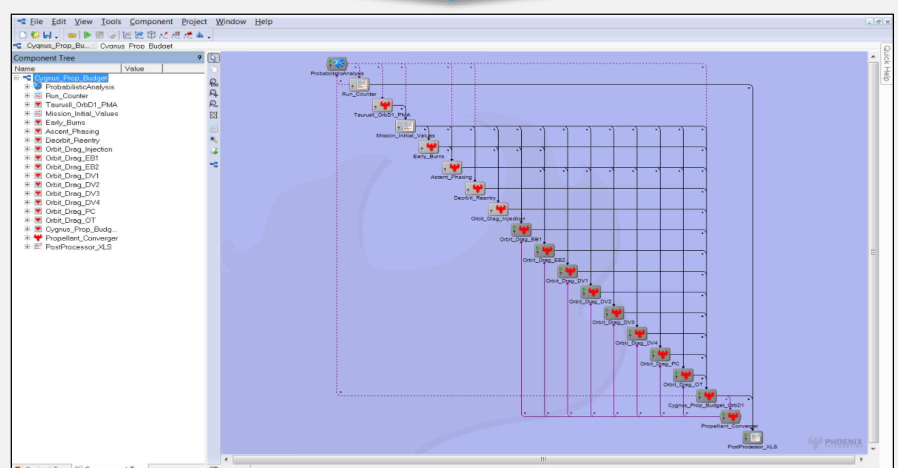
Antares	• Launch Mass • Insertion Orbit Parameters
PSS	• DVE & REA Propulsion Parameters • Pressurant & Residual Propellant Data
GN&C	• Effective DVE + REA Isp vs. C.G. • 6-DOF propellant usage distributions for attitude control, slews, JOPS, Aborts, and Departure • Early Burn Algorithm
FDS	• ISS reference trajectory • Ascent Phasing Plan • Deorbit/Reentry Trajectory Plan
Systems	• Mass Properties • Mission Cargo Manifest

Integrated Analysis of End-to-End Mission Performed using Inputs/Models across Cygnus Subsystems

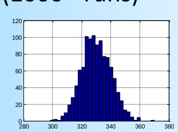
Integrated Analysis N^2 Diagram



Implemented into Collaborative Framework to Perform Probabilistic Analysis

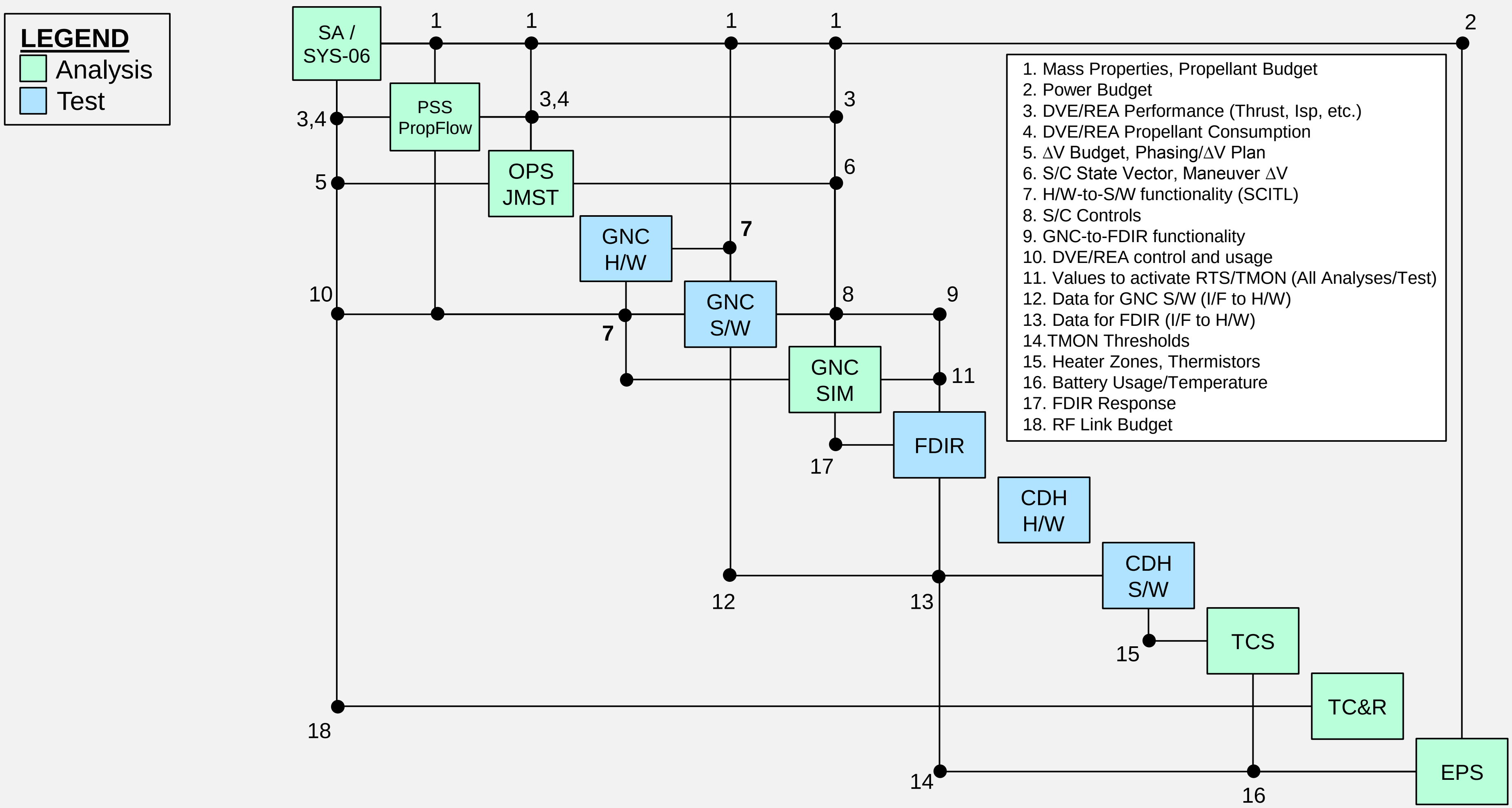


Propellant Budget Calculated from Probabilistic Analysis Statistics (1000+ runs)



Orb-4 Propellant Budget		
Maneuver	**mean**	**+3σ**
Ascent Propellant		
Prox-Ops Propellant		
Deorbit/Reentry Propellant		
Residual Propellant		
Total Mission Propellant		

Cygnus Integrated Analysis N^2 Diagram



Integrated N2 Diagram Identified Interactions & Data Needs for Analyses & Tests

Performance Analysis Assumptions & Dispersions

- Analysis Assumptions for System, Mission, GN&C, and Propulsion variables
- Dispersions based on data from GN&C verification analyses and Propulsion analyses & tests
- Assumptions & dispersions reviewed and approved by CRS Program for each mission

Analysis Assumptions (units)		
• ISS Circular Orbit Altitude (km) • Final Ascent Orbit Altitude (km) • Atmospheric Model • Launch Date • Launch Time • Target ECI RAAN (deg) • Target Inclination (deg) • Insertion Latitude (deg) • Insertion Longitude (deg) • Insertion Perigee Altitude (km) • Insertion Apogee Altitude (km) • Duration from Insertion to JTRP (days) • Insertion Δ Orbit Rev	• Insertion Absolute Orbit Rev • Early Burn 1 Δ Orbit Rev • Early Burn 1 Absolute Orbit Rev • EB2 to JTRP Δ Orbit Rev • JTRP DV Absolute Orbit Rev • Number of Slews per Maneuver • Number of Slews for Initial Sun-Pointing • Aborts Type • Abort Racetrack Type • Early Burn Slew Propellant Usage Rate (kg/slew) • Mission Slew Propellant Usage Rate (kg/slew) • Deorbit DV1 Burn Δ Orbit Rev • Deorbit DV2 Burn Δ Orbit Rev • Deorbit DV Apogee Altitude (km)	• Deorbit DV1 Perigee Altitude (km) • Deorbit DV2 Perigee Altitude (km) • Cygnus Area (m^2) • LV Payload Capability (kg) • Delivered Cargo Mass (kg) • Disposal Cargo Mass (kg) • Cygnus Operating Mass (kg) • Cygnus Total Propellant Mass (kg) • Number of Fuel Tanks • Number of Oxidizer Tanks • DVE Vacuum Isp (s) • DVE O/F Ratio • Number of Contingency Aborts • Number of Contingency Racetracks
Analysis Dispersions (units) - Distribution		
• F10.7 Solar Flux (SFU) - Triangle • Geomagnetic Index - Triangle • ISS Phase Angle (deg) - Uniform • Insertion Inclination (deg) - Triangle • Insertion ECI RAAN (deg) – Triangle	• Orbit Trim ΔV (m/s) - Uniform • Cygnus Drag Coefficient - Uniform • REA Isp (s) - Uniform • Fuel Residual Mass (kg) - Uniform • Oxidizer Residual Mass (kg) - Uniform	• JOPS Maneuvers ΔV (m/s) - Normal • Racetrack Maneuvers ΔV (m/s) - Normal • Post-Departure Burn Δ Orbit Rev - Uniform • Deorbit Error/Finite Losses ΔV % - Triangle • Ascent DVE + REA Effective Isp - Uniform • Descent DVE + REA Effective Isp - Uniform

DV = Delta Velocity (ΔV)
DVE = Delta Velocity Engine
EB = Early Burn
ECI = Earth-Centered Inertial
Isp = Specific Impulse
ISS = International Space Station
JOPS = Joint Operations
JTRP = Joint Trajectory Reference Point
LV = Launch Vehicle
O/F = Oxidizer/Fuel
RAAN: Right Ascension of the Ascending Node
REA = Reaction Engine Assembly

Propellant Consumption Analysis Approach

- Cygnus propellant budget generated by calculating propellant usage for each maneuver during the CRS mission
  - ➢ Maneuvers and mission CONOPS provided by several reference documents listed in analysis assumptions & dispersions
- Propellant usage for ΔV maneuvers calculated using rocket equation

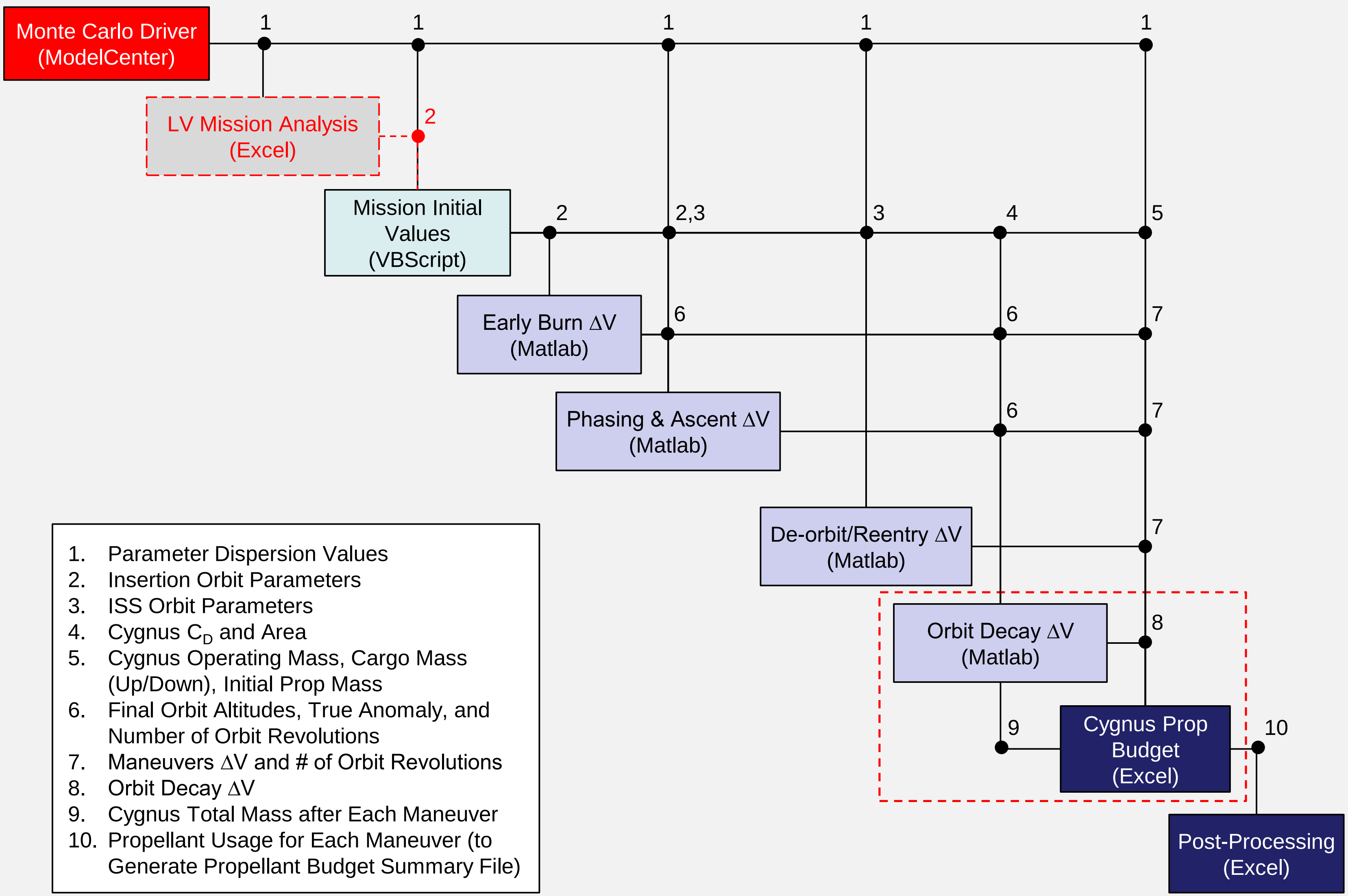
  $\Delta V = I_{sp}\, g_0\, ln(MR)$, where

  $MR = (m_{prop\_used} + m_{prop\_remain} + m_{inert} + m_{cargo}) / (m_{cargo} + m_{inert} + m_{prop\_remain})$

  - ➢ Apse raising/lowering & plane change ΔVs calculated using 2-body orbital mechanics
  - ➢ Orbital decay ΔV from atmospheric drag calculated based on MSISE 2000 atmospheric density and number of orbit revolutions
  - ➢ JOPS, abort, and racetrack ΔVs provided from analysis documentation
- Attitude control propellant usage calculated based on # of orbit revolutions
- Propellant usage for slews calculated based on #of slews and REA set

ΔV = Delta Velocity
g_0 = Standard Gravity
Isp = Specific Impulse
ln = Natural Logarithm
m_{cargo} = Cargo Mass
m_{inert} = Inert Mass
m_{prop_remain} = Propellant Mass Remaining
m_{prop_used} = Propellant Mass Used
MR = Mass Ratio
REA = Reaction Engine Assembly

Performance Integrated Analysis N^2 Diagram



1. Parameter Dispersion Values
2. Insertion Orbit Parameters
3. ISS Orbit Parameters
4. Cygnus C_D and Area
5. Cygnus Operating Mass, Cargo Mass (Up/Down), Initial Prop Mass
6. Final Orbit Altitudes, True Anomaly, and Number of Orbit Revolutions
7. Maneuvers ΔV and # of Orbit Revolutions
8. Orbit Decay ΔV
9. Cygnus Total Mass after Each Maneuver
10. Propellant Usage for Each Maneuver (to Generate Propellant Budget Summary File)

Performance Integrated Analysis Breakdown

Monte Carlo Driver (ModelCenter) — **ModelCenter Probabilistic Driver** facilitates Monte Carlo assessment of the propellant budget. **ModelCenter Converger Driver** converges between orbit decay & propellant mass.

LV Mission Analysis (Excel) — **Spreadsheet** retrieves Cygnus insertion orbit parameters based on LV data run number. Insertion orbit parameters include perigee altitude, apogee altitude, inclination, and ECI RAAN.

Mission Initial Values (VBScript) — **Script** provides input for ISS orbit parameters, Cygnus vehicle characteristics (CD, area), and Cygnus initial masses at the start of the mission.

Early Burn ΔV (Matlab) — **Matlab** script calculates the required ΔV for each Early Burn maneuver, along with the perigee/apogee altitudes and true anomalies of the orbit after each Early Burn.

Phasing & Ascent ΔV (Matlab) — **Matlab** script calculates phasing orbit perigee/apogee & # of orbit revs required to transfer from insertion orbit to ISS JTRP for specified duration. Calculates required ΔV for each orbit transfer maneuver.

De-orbit/Reentry ΔV (Matlab) — **Matlab** script calculates required ΔV for each deorbit / reentry maneuver, along with the perigee/apogee altitudes and true anomalies of the orbit after each burn.

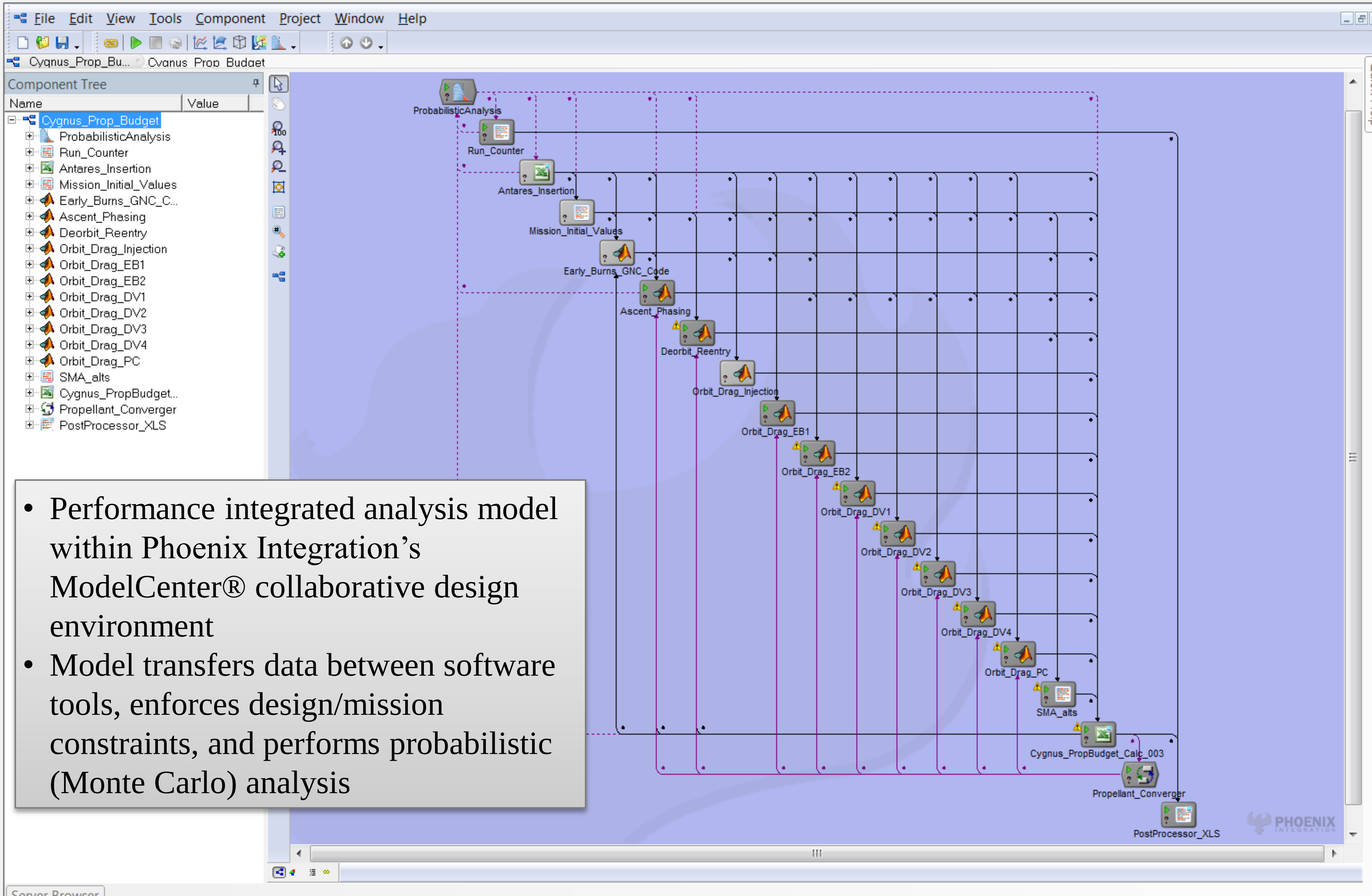
Orbit Decay ΔV (Matlab) — **Matlab** script calculates ΔV resulting from atmospheric drag acting on Cygnus while orbiting after each orbit transfer maneuver. Orbit decay ΔV calculation based on the initial orbit parameters, Cygnus vehicle characteristics (mass, area, CD), and # of orbit revs.

Cygnus Prop Budget (Excel) — **Spreadsheet** calculates propellant, fuel, & oxidizer usage to perform each maneuver during the mission. Maneuver propellant usage during orbit transfers, JOPS, and demonstrations based on their ΔV values. ΔV dispersions for JOPS nominal, abort, and racetrack maneuvers maintained within spreadsheet. Statistical data provides attitude control propellant usage per orbit revolution and slew propellant usage per slew.

Post-Processing (Excel) — **Spreadsheet** generates summary and detailed breakdown of propellant, fuel, and oxidizer usage for each maneuver during the mission from Cygnus Propellant Budget analysis. Spreadsheet also generates summary of ΔV values for orbit transfer, orbit decay, and JOPS (nominal, abort, racetracks) maneuvers.

CD = Coefficient of Drag

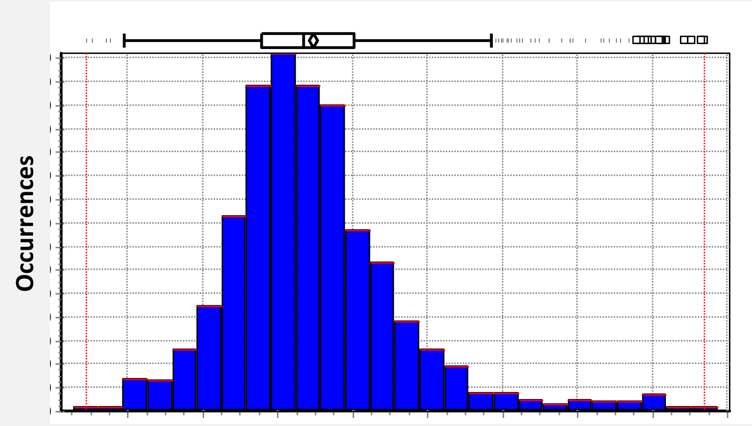
Performance Integrated Analysis ModelCenter

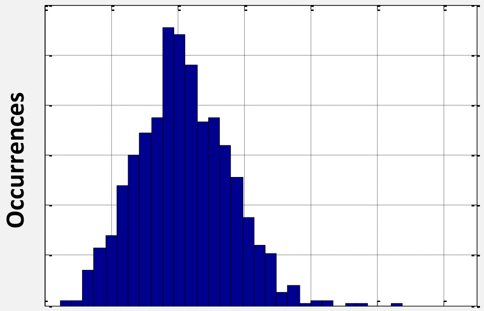


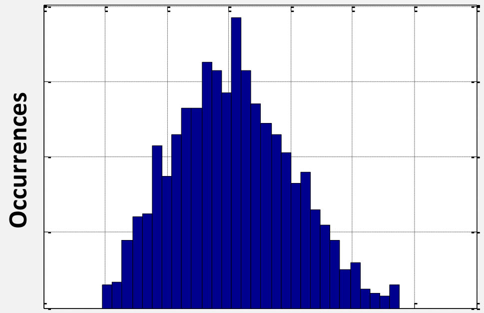
- Performance integrated analysis model within Phoenix Integration’s ModelCenter® collaborative design environment
- Model transfers data between software tools, enforces design/mission constraints, and performs probabilistic (Monte Carlo) analysis

Statistical Validation of Propellant Load

- Propellant load validated from CRS Performance Integrated Monte Carlo analysis
- Analysis calculated total mission +3σ propellant, fuel, and oxidizer consumption
  - Total mission +3σ propellant results in 7-9% reduction vs. sum of budget +3σ line items
- Propellant load has positive margin to analysis +3σ propellant usage for CRS missions to date







Maneuver +3σ Consumption	*Fuel*	*Oxidizer*	*Propellant*
Early Burns			
Phasing Burns			
RAAN/Inclination Plane Change			
Orbit Trim Burns			
Ascent Attitude Keeping			
Ascent Slews			
Ascent Consumption			
1st Approach Prox Ops			
1st Abort + Racetrack			
2nd Approach Prox Ops			
Departure			
Prox Ops Slews			
Prox Ops Consumption			
Descent Burns			
Descent Attitude Keeping			
Descent Slews			
Descent Consumption			
Residuals			
Total Mission +3σ Consumption			
Sum of +3σ Consumption			

Summary

- MBSE ≠ SysML: MBSE is also developing integrated analysis models to explore & evaluate trade space, generate robust designs, integrate & automate complex analyses
- SSG has extensive experience performing multi-disciplinary analyses using Phoenix Integration ModelCenter
- Orbital ATK Cygnus spacecraft continues to successfully deliver cargo to ISS
- ModelCenter used to develop multi-disciplinary integrated analysis to optimize propellant usage during the CRS missions and validate the Cygnus propellant load
- ModelCenter integrated analysis performed for every CRS mission to validate the Cygnus propellant load

Acknowledgement

Thanks to the Orbital ATK Cygnus Program for allowing me to participate on this great human spaceflight endeavor and continuing to successfully support human space exploration by resupplying cargo on the International Space Station.