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Realizing the Potential of Model-Based Systems Engineering Through the Product Life Cycle

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AIAA Complex Aerospace Systems Exchange
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What Is Our Motivation For Using MBSE?

- Strengthen the quality of formulation products by allowing exploration of a more comprehensive option space and more rapid analysis of alternatives
- Perform early validation of system designs
- Give systems engineers time to do more engineering analysis and less paper management
- Significantly improve the quality of communications and understanding among system and subsystem engineers
- Achieve greater design reuse
- Align with the expectations and work habits of the next generation of engineering talent
  - this is the way new engineers are being trained and the way many of our early career engineers want to work

But the bottom line is to…

- **Reduce the number of product and mission defects in the face of growing complexity**
- **And increase productivity/reduce costs**

Status of MBSE at JPL

JPL has been:

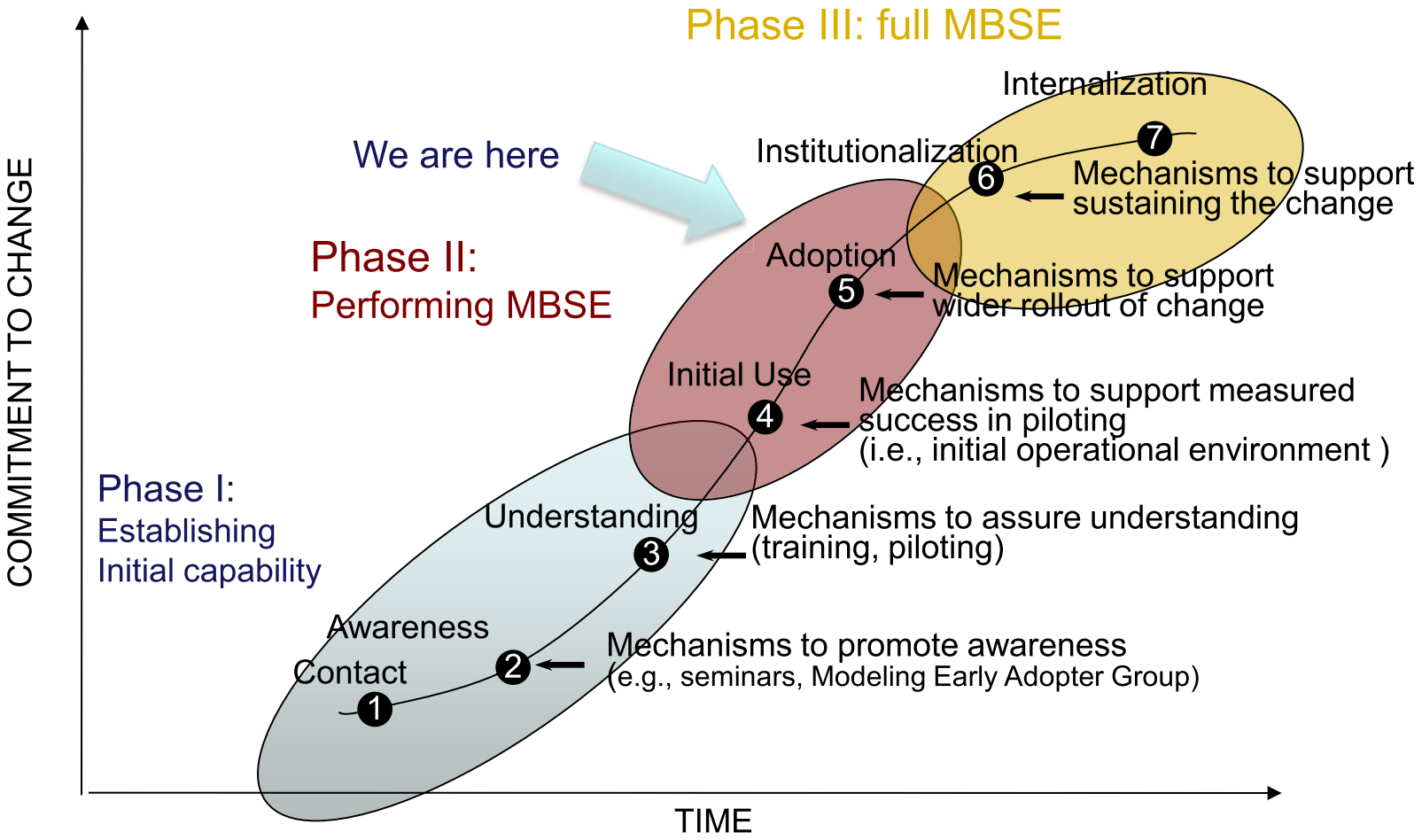
– Developing a Model-Based Systems Engineering infrastructure consisting of:

- Foundational elements of ontologies and recurring modeling patterns
- Tooling, consisting of interoperable solutions for a comprehensive modeling approach and document generation approach
- A community of practice nurtured via education and sharing experiences and solutions

– Applying MBSE to real project systems engineering problems across a wide landscape of project types, activities and lifecycle phases

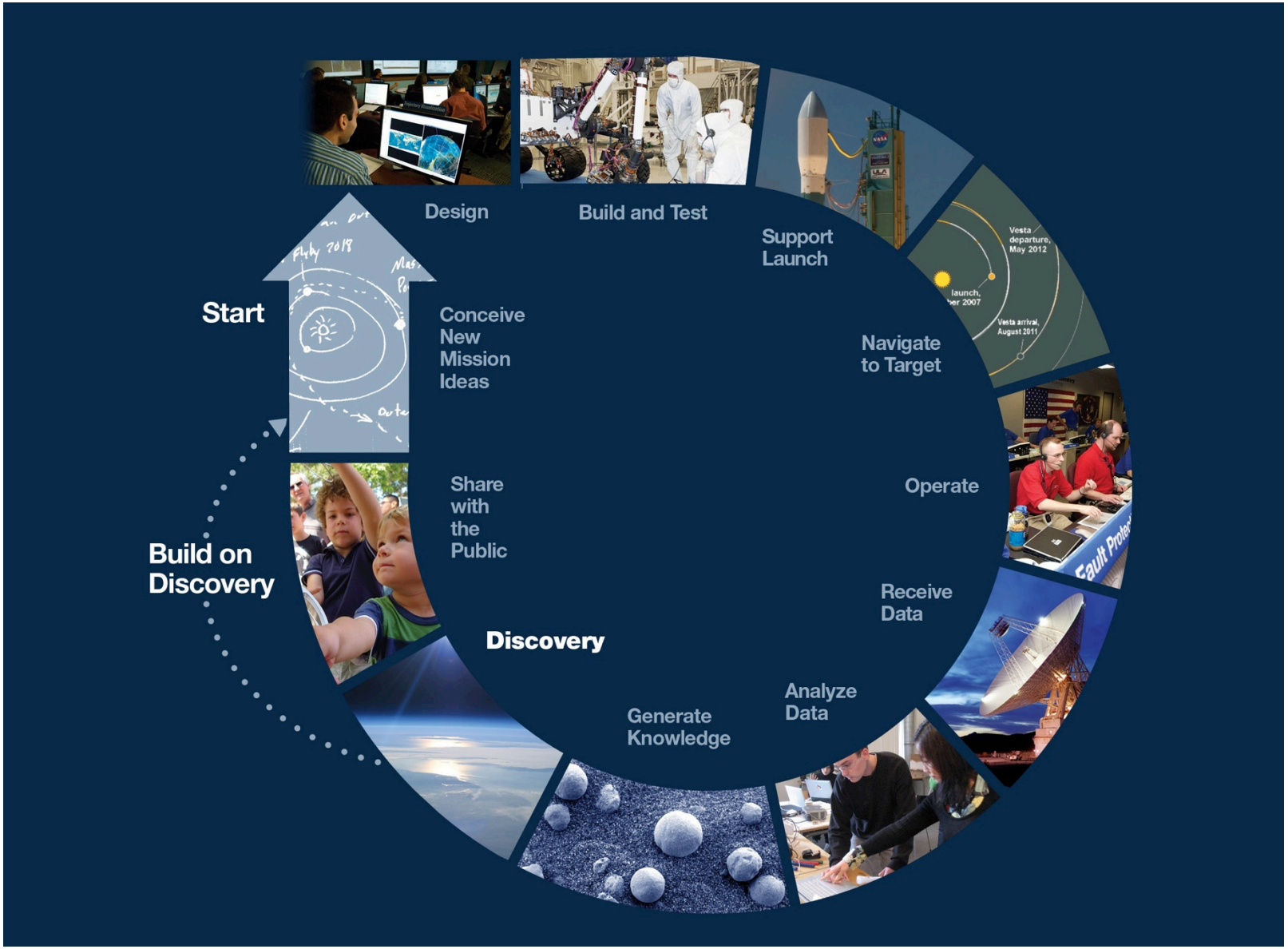
- Approximately 20 development tasks are applying MBSE at JPL across the full lifecycle

MBSE Infusion Model and Where We Are



Adapted from Out from Dependency: Thriving as an Insurgent in a Sometimes Hostile Environment, SuZ Garcia and Chuck Myers, SEPG Conference, 2001

The JPL Product Life Cycle



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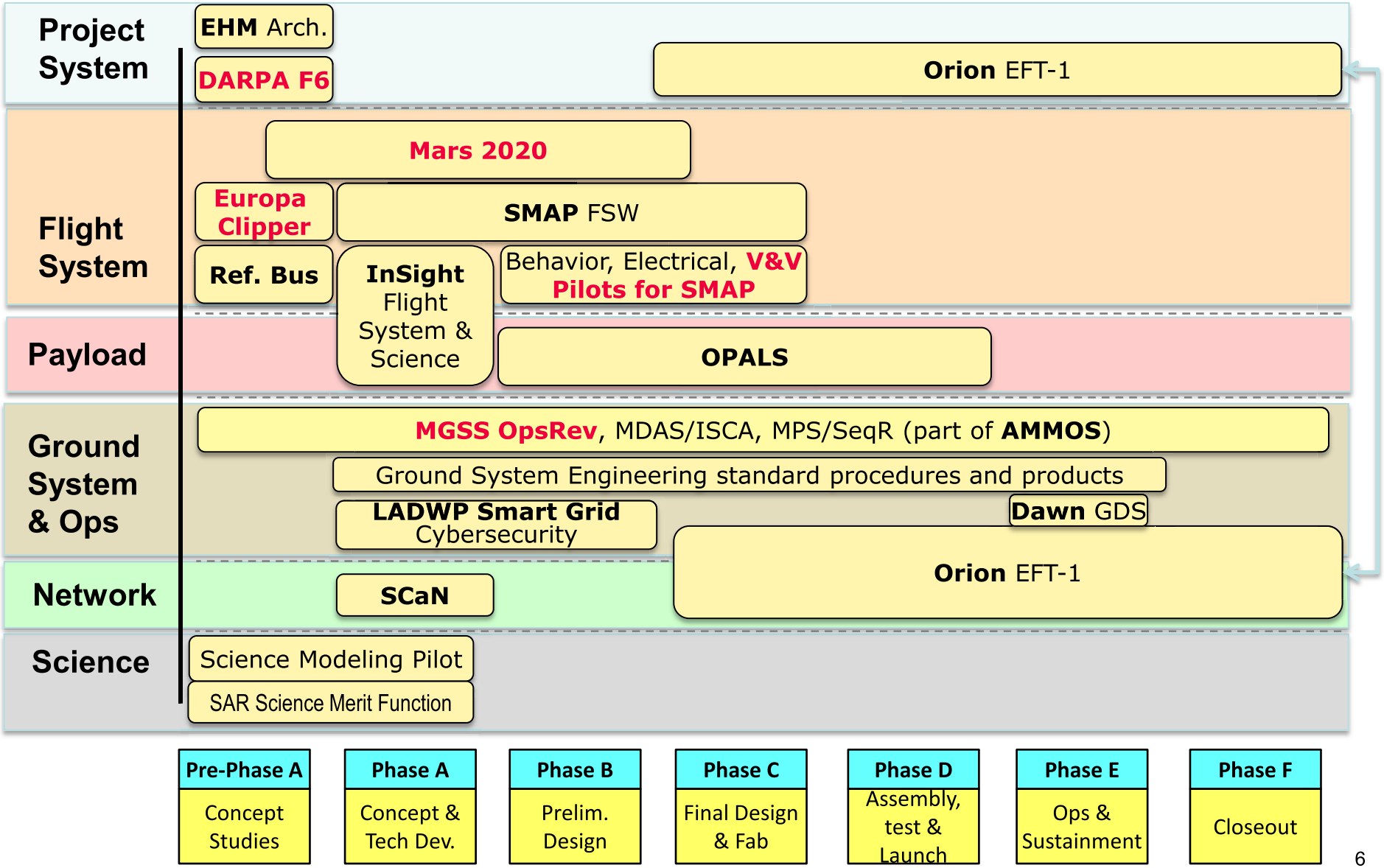
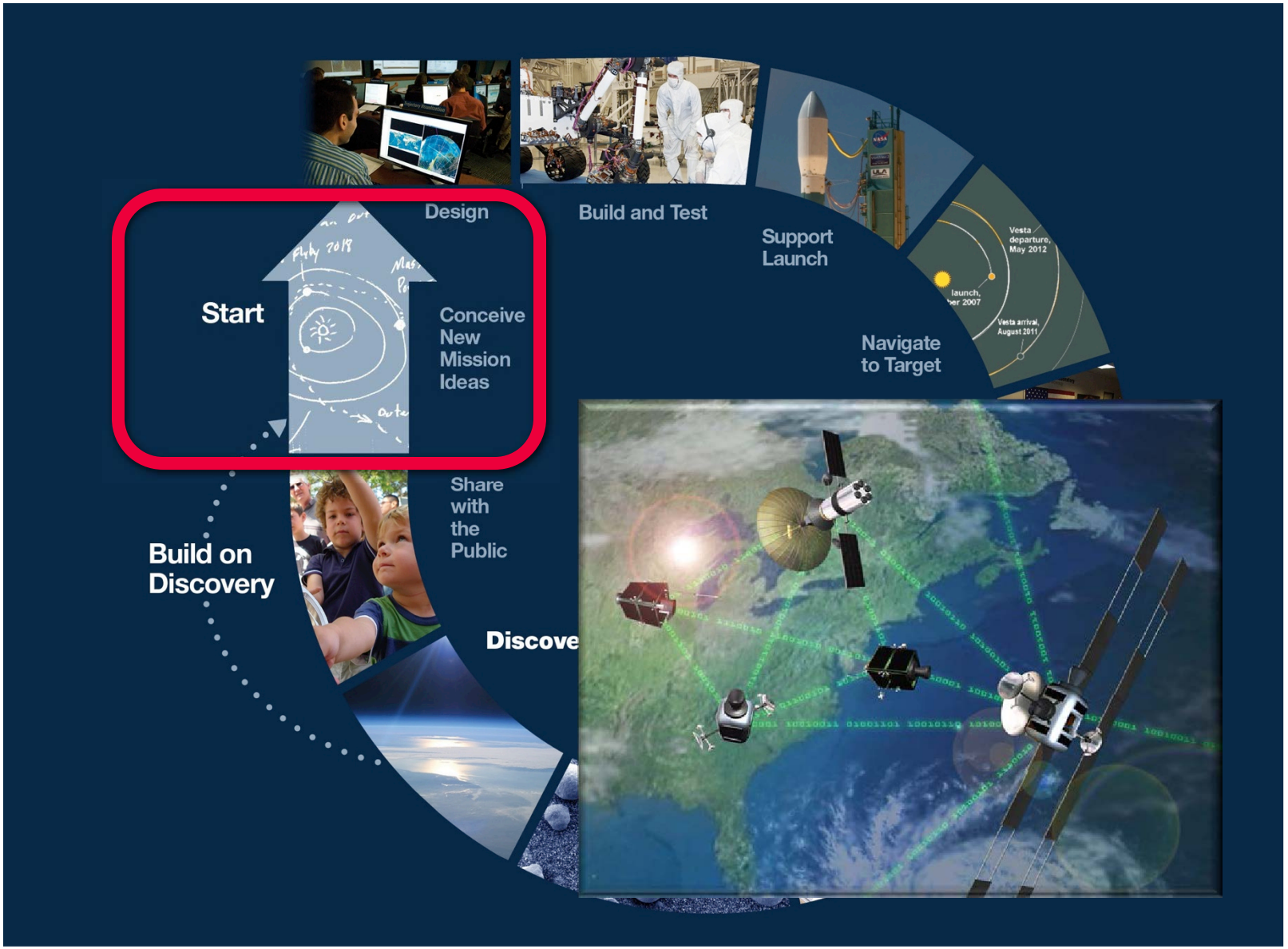
Landscape of MBSE Applications at JPL



Pre-Phase A	Phase A	Phase B	Phase C	Phase D	Phase E	Phase F
Concept Studies	Concept & Tech Dev.	Prelim. Design	Final Design & Fab	Assembly, test & Launch	Ops & Sustainment	Closeout

Mission Formulation: Trade Space Exploration



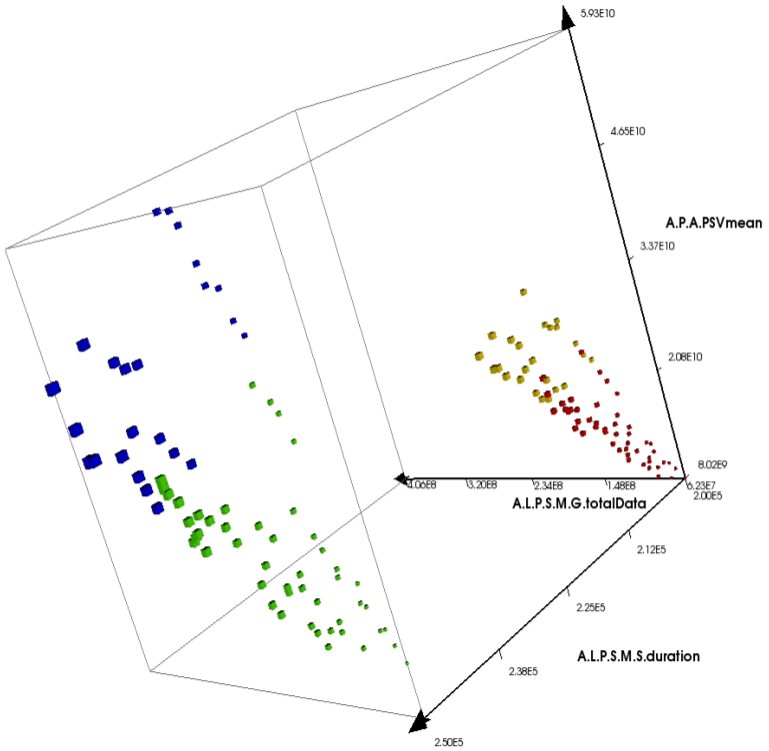
Tradespace Exploration for Fractionated Satellite Architectures

Objective: Understand and define the business case for fractionated spacecraft

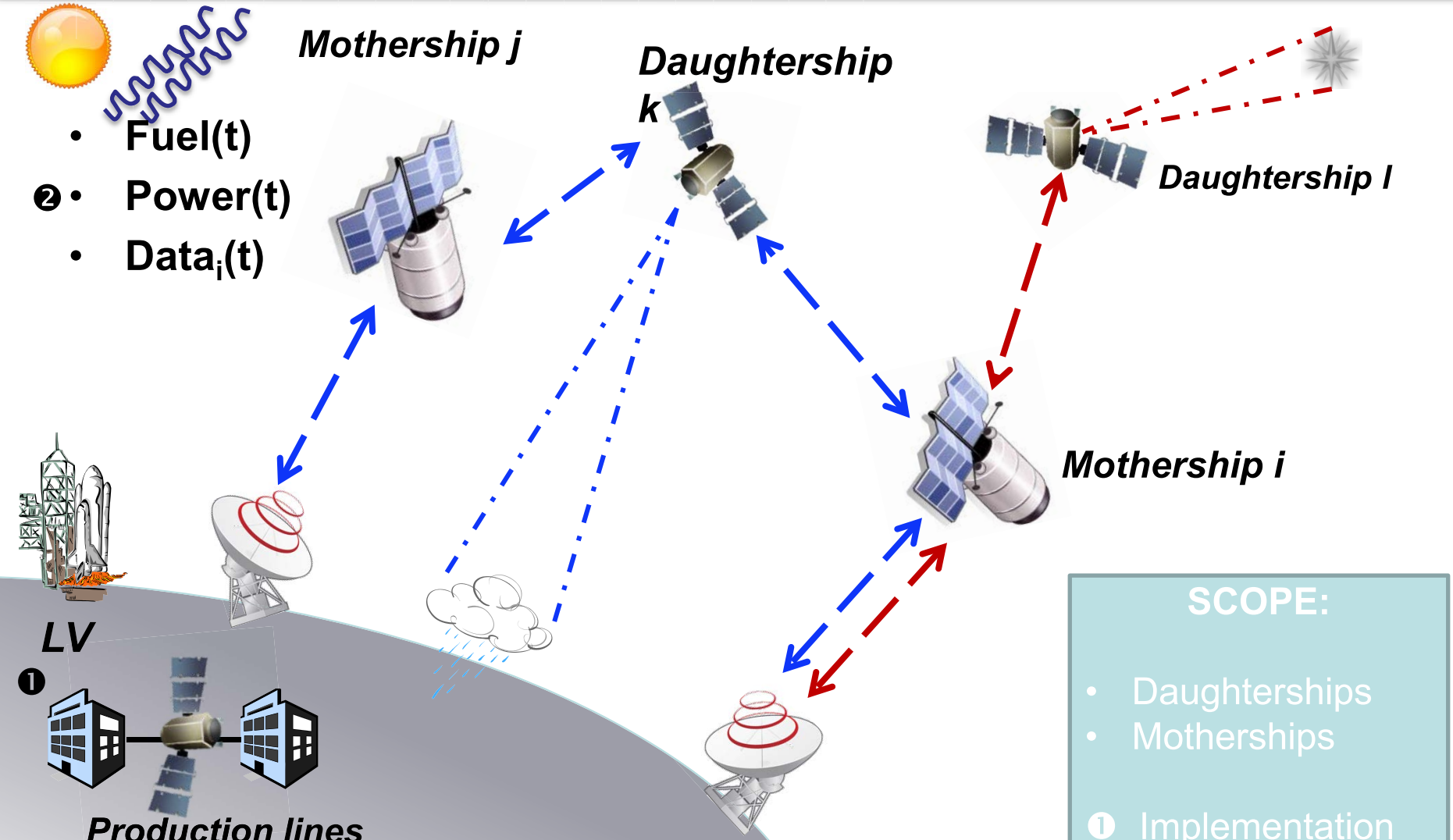
- Parametric variation is relatively easy
  - e.g. spacecraft bus mass and data link rate or time to build a given module
  - For example, software like Phoenix Model Center provides for multi-disciplinary parametric variation
- However, architectural variation ability is limited
  - For example: trade nuclear-powered flight systems vs. Electric Propulsion FS

The MBSE approach was chosen to facilitate exploration of a greater set of architectural variants.

- System model captures a rich set of rules & constraints that characterize a produceable architecture or set of architectural variants



ASDA Discrete Event Simulation Overview

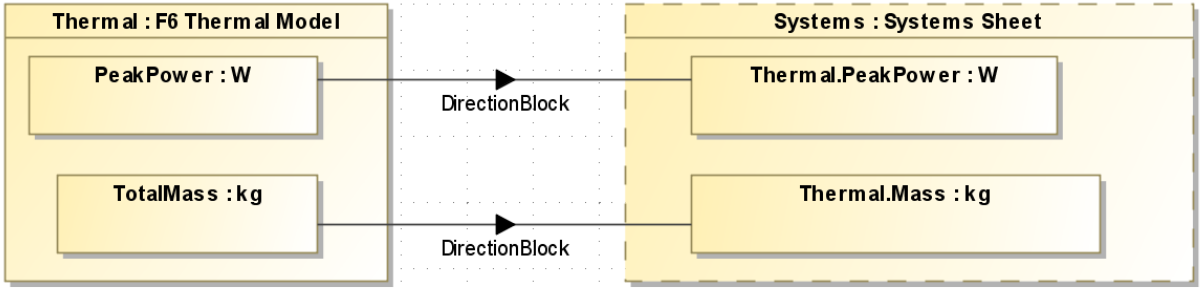


SCOPE:

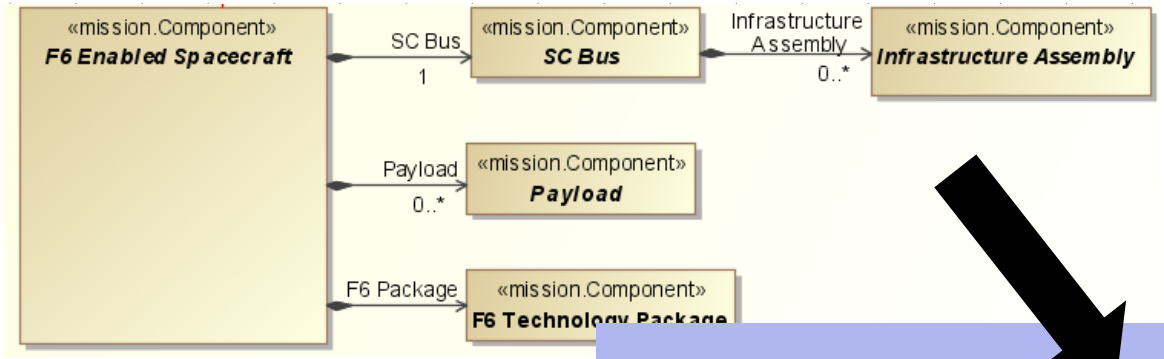
- Daughterships
- Motherships

❶ Implementation
❷ Operations

Parameter

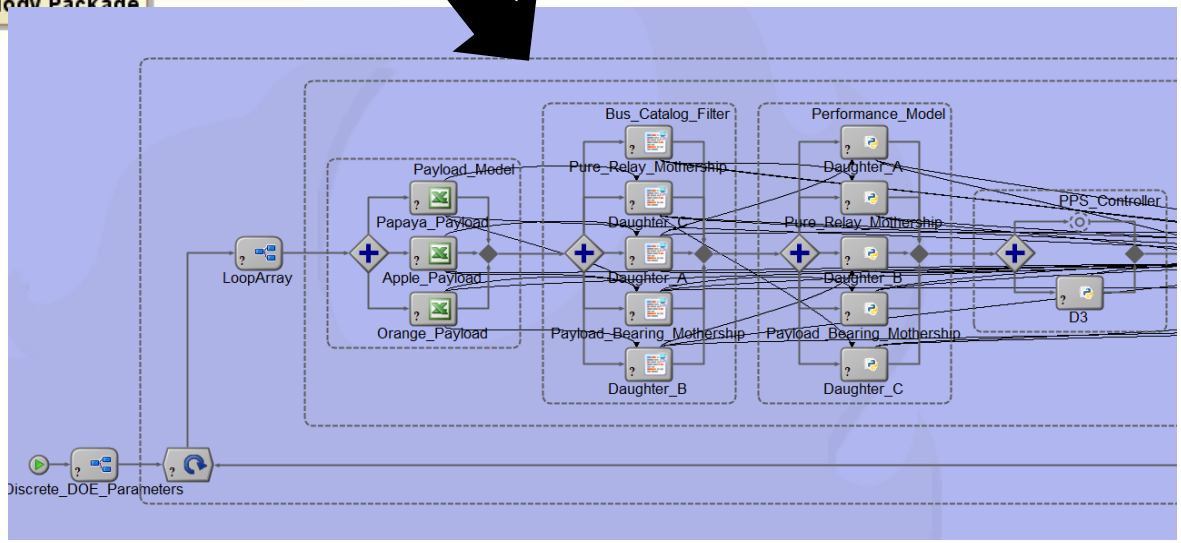


+ connection templates



Architectural Alternative

Architectural Analysis via Simulation

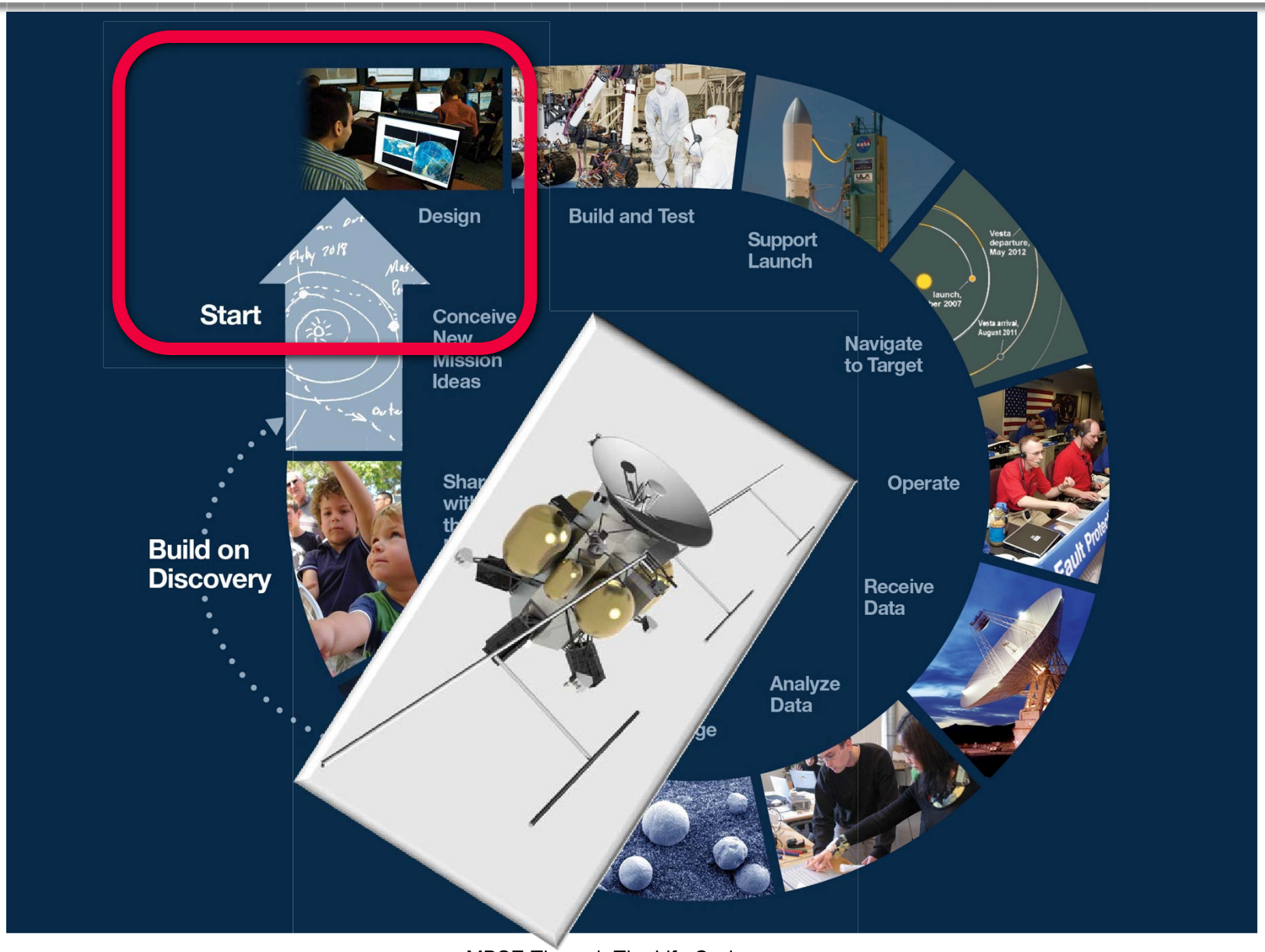


The Advanced Systems Design and Analysis Tool (ASDA)

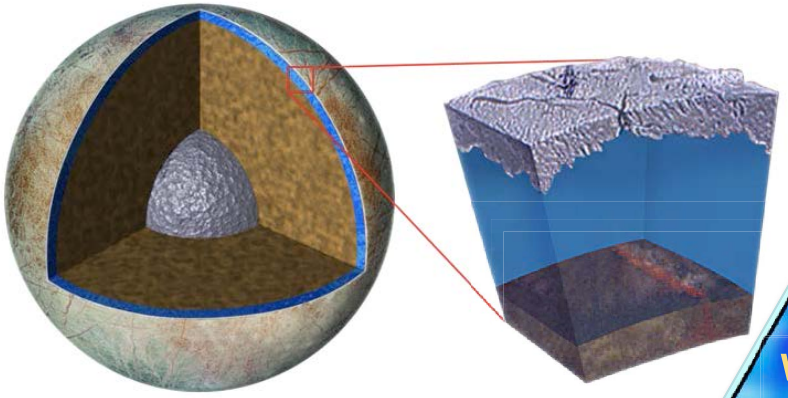
ASDA was designed to deal with a huge combinatorial space problem (architectural variation, nominal and off-nominal scenarios, and also design and economics)

- Managing variation and performing assessments of architectural options is much harder than coming up with simple design variants
- SysML templates have been instrumental in structuring analyses of architectural options
- MBSE has facilitated a fundamentally new capability that did not previously exist.

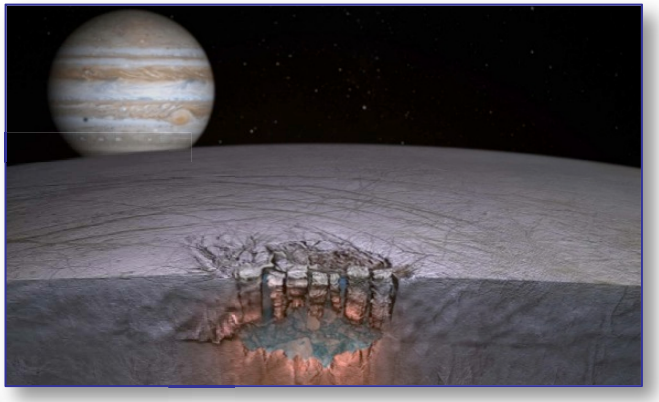
Mission Formulation: The Europa Clipper

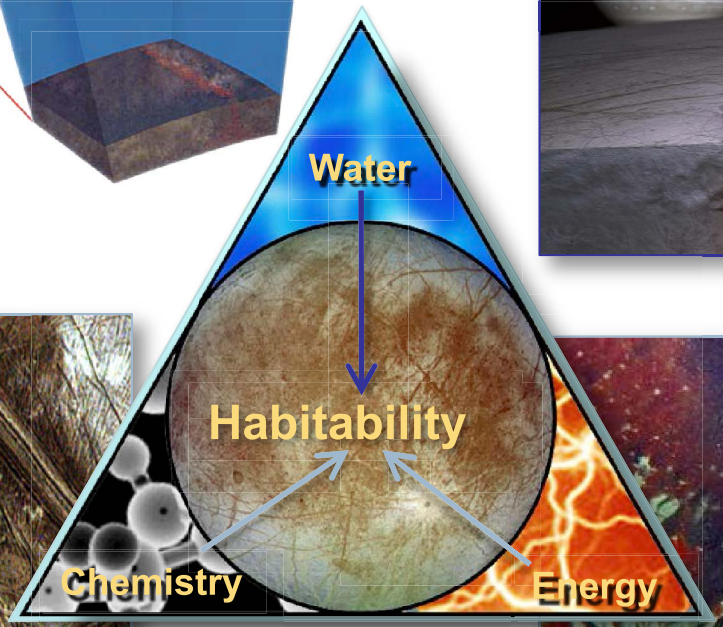


Europa Clipper: Looking for the Ingredients for Life?



Water: Are a global ocean and lakes hidden by Europa's shell of ice?





Chemistry: Do red surface deposits contain organics from below?

Energy: Can surface oxidants provide energy for metabolism?

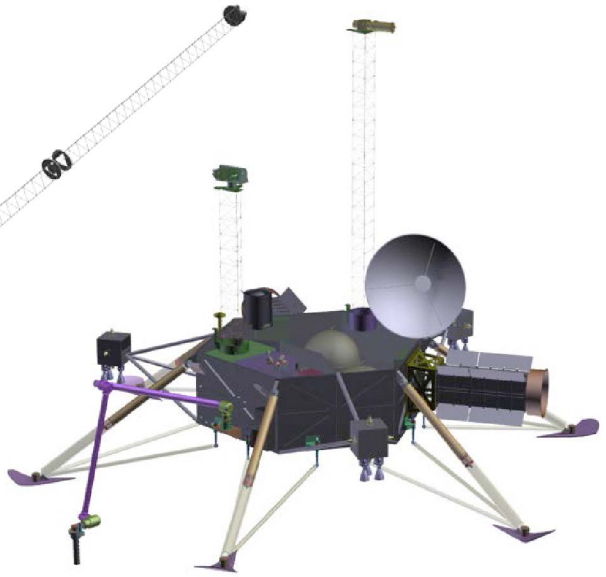
Background

The Jupiter Europa Orbiter (JEO) mission concept was deemed to be of extremely high science value, but un-affordable, by the NRC Decadal Survey, which requested a de-scoped option

- A one year study developed mission options (Orbiter, multiple flyby [Clipper], and Lander) that retain high science value at significantly reduced cost

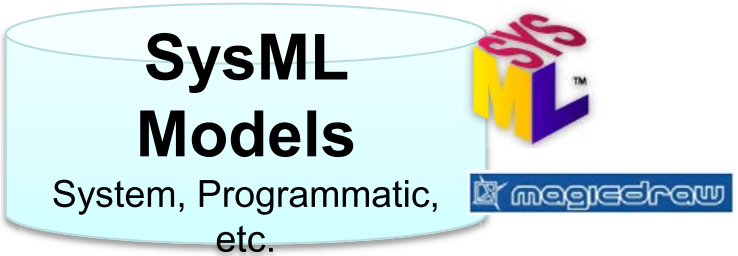
Multiple-Flyby in Jupiter Orbit
(The Europa Clipper)

Europa Orbiter

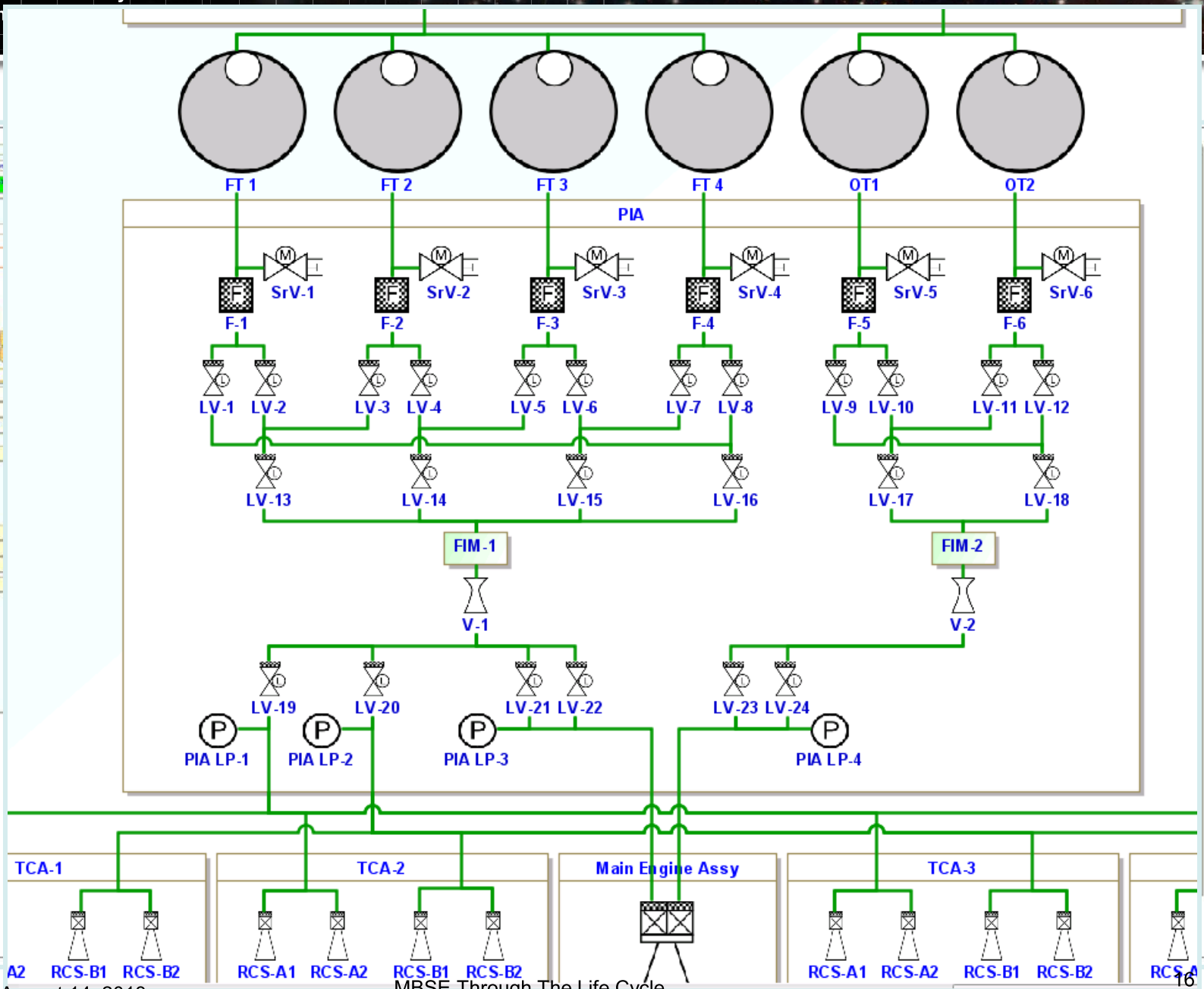


Europa Lander

The System Model as A Reusable Source



The System Model as A Reusable



2.1.1. MEL: Bill of Materials Table

Table 2.1. Bill of Materials Table of Clipper Flight System for Clipper WBS

	Workpackage	Deployments	Num of	Mass per Unit	Mass	Mass CBE + Contingency

2.1.2. MEL: Deployment Table

Table 2.2. Deployment Table of Clipper Flight System

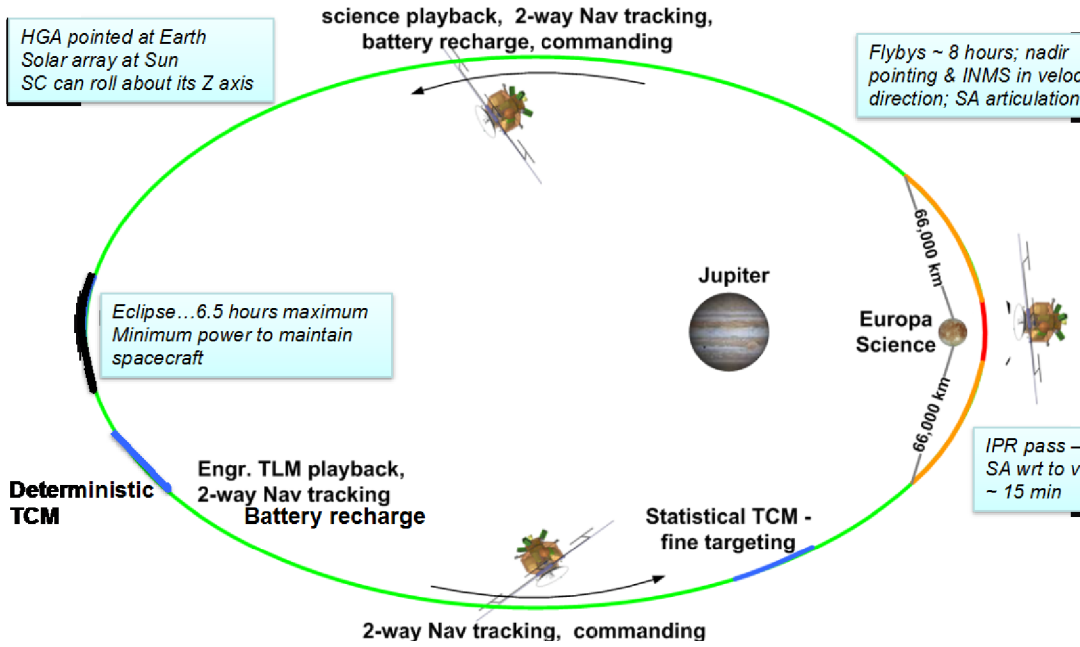
4. Power Mode List

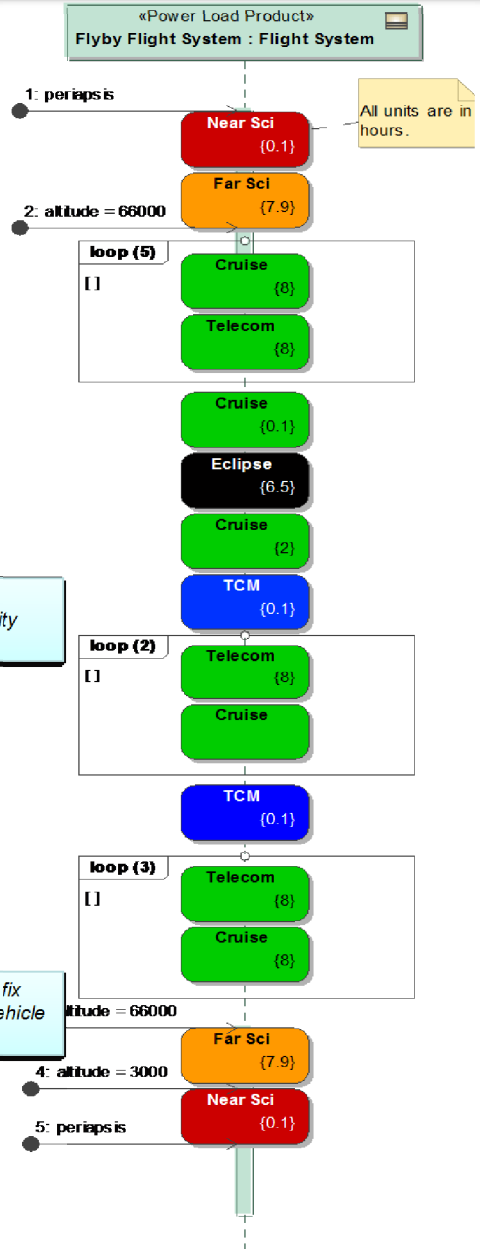
Table 4.1. PEL Table for Clipper WBS

	Workpackage	Product	Power Mode	Avg Pwr CBE[W]	Contingency	Avg Pwr MEV[W]
1	Clipper WBS					
2	05 Clipper Payload					
3	05.04 Neutral Mass Spectrometer					
4		NMS Capture/Timing Card	Off	0	0.5	0
5			On	0	0.5	0
6			Standby	0	0.5	0
7		NMS Processing/LVDS Card	Off	0	0.5	0
8			On	0	0.5	0
9			Standby	0	0.5	0
10		NMS Sensor	Off	0	0.5	0
11			On	12	0.5	18
12			Standby	6	0.5	9
13	05.05 Ice Penetrating Radar					
14		IPR Digital Processor Card	Off	0	0.5	0
15			On	3.75	0.5	5.62

Europa Clipper
Mission Scenario Modeling

- **Define each piece of a flyby petal as a system level power mode.**
- **Define the flyby scenario as a timeline in terms of the system level power modes.**

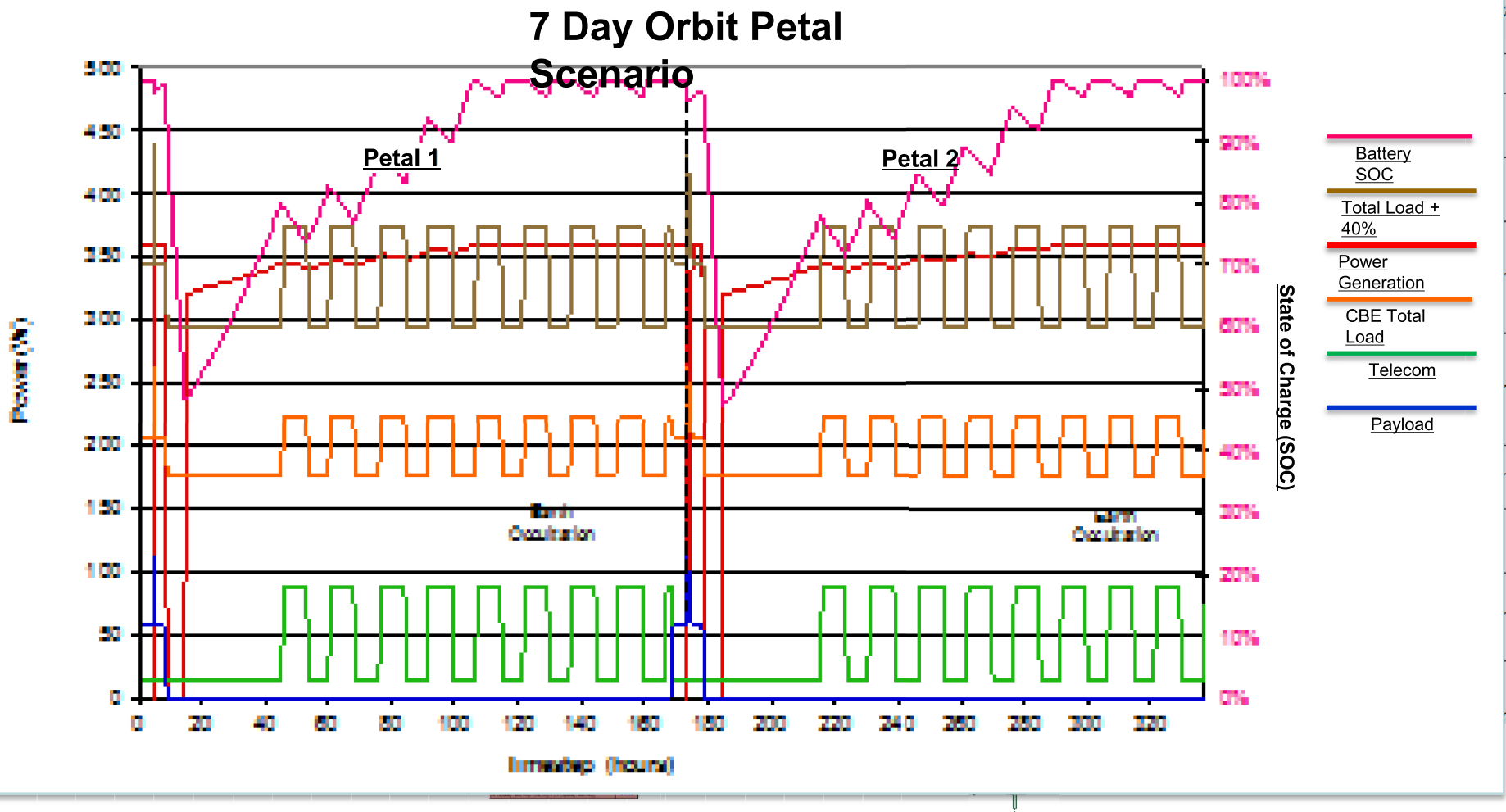




Analyzing Model-Generated Power Margin from Scenarios

Table 5.5. PEL Modes Simple for Clipper WBS

				Flyby	Flyby Prep (starts 24 hours before CA)	Flyb

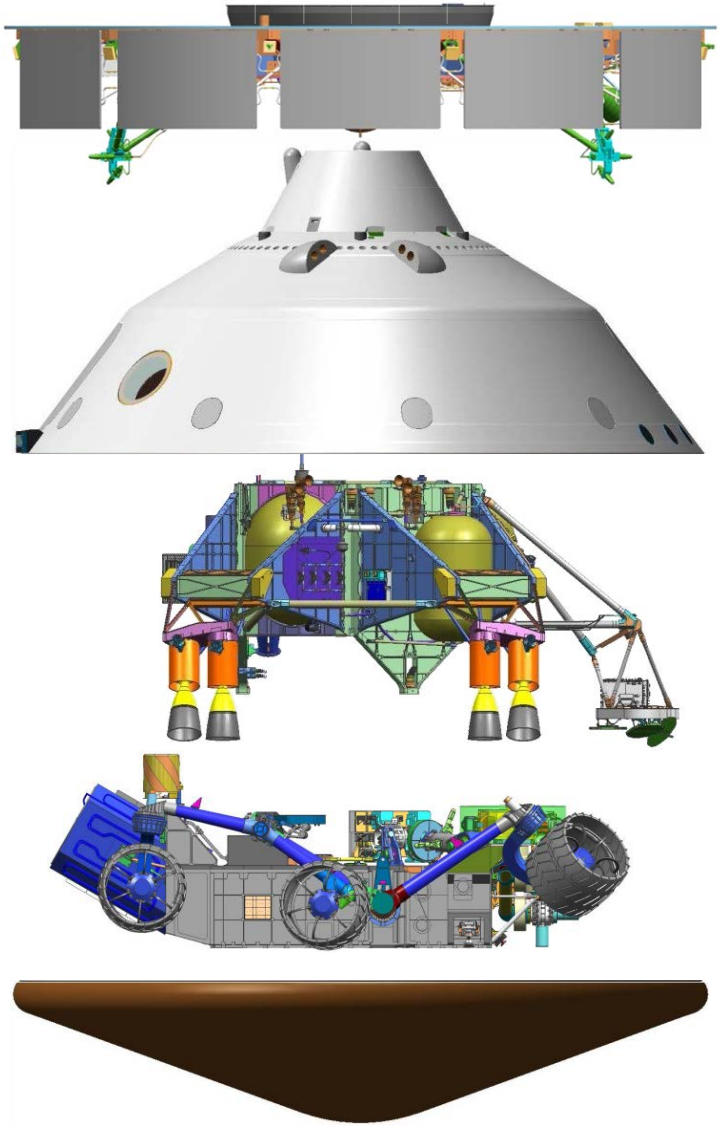


Europa Clipper: Benefits Realized Through MBSE

- Communication of technical information within project and among disciplines is more efficient and accurate
  - Not limited by foreseeable levels of increasing system complexity
  - Easily integrated with existing discipline tools (MBSE is the *keystone* for full Model Based Engineering)
- Re-use and evolution of alternate system design elements
  - 3 full mission studies in the time it usually takes for 1 or 2
  - 5 parallel configurations maintained
- Consistent, rapid generation of technical margins and normalization of risk assessment
  - Identical automated analyses are applied to all configurations and versions
- Efficient generation of project documentation
  - Ensuring consistency of documentation by drawing from same system model
- Bridges from college education to project best practices
  - Recent graduates are arriving with knowledge of and expectation of using MBSE methods
- Promotes capture of expert knowledge, lessons learned, principles
  - These things can be “baked in” to the system model

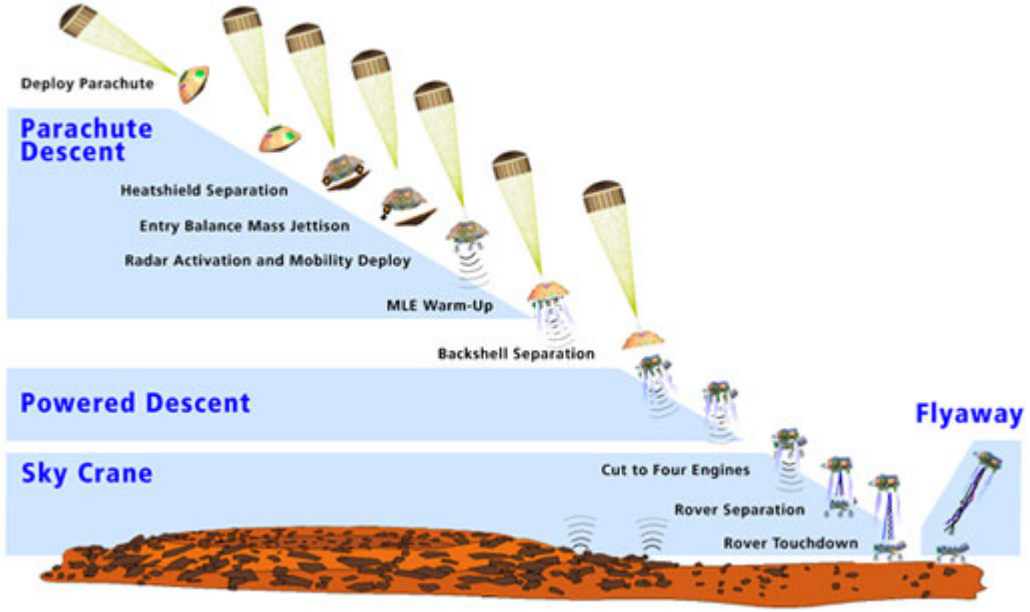
Mars 2020 – The Follow-On to Curiosity

MBSE Motivation and Background – Coping with Complexity



Mars 2020 challenge: Engineer an inherently complex mission and system with lower cost and changes to science and rover payloads

All we have to do is repeat the miracle (at even lower cost)…



Motivation and Background – MSL and the new challenges for Mars 2020

Mars 2020 is not a typical Pre-Phase A project

- Effectively in Phase C+ for much of the H/W and S/W design
- However, new mission, science objectives, and instruments
- Highly cost-constrained
- Leverage heritage via "build-to-print" philosophy

Need to modify the SE approach to address experiences on the MSL project

- Keep SE products updated with the ongoing design/developments/tests
- Sharing information across a diverse team avoiding information "silos"
- Improving the flow and traceability of design decisions and tests
- Managing cross-cutting complexity and understanding of scope
- Preempting the V&V "armageddon" at the end of the project – 3 test beds running 7 days a week
- Improving parameter tracking and test correspondence (and visibility by others on this)

Mars 2020 MBSE Objectives

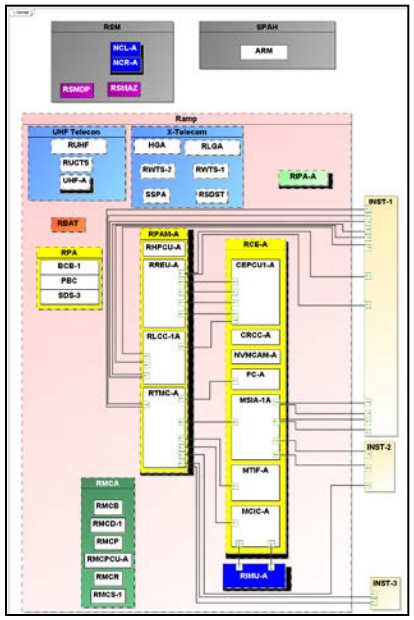
Focus on key flight system modeling products leading to the Mission Concept Review…

- **Initial focus on integration and consistency of views and products for**
  - Physical hardware and component decomposition (Reference Designators, physical hierarchy)
  - WBS and logical hierarchies
  - System block diagrams and interfaces
  - Resource tracking, e.g., with the Master Equipment List (MEL)
  - Key & driving requirements and top-level functions
- **Also improving team accessibility and usability of design information**
  - Generating web-accessible products to provide wider and immediate accessibility
  - Providing selected user-editable views online to ease usage/interaction with the model

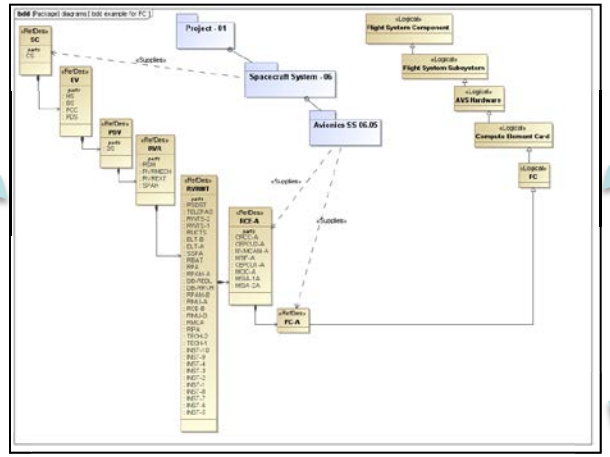
…and build a foundation for later support to the flight system PDR, CDR and instrument Announcement of Opportunity

Example System Modeling Products

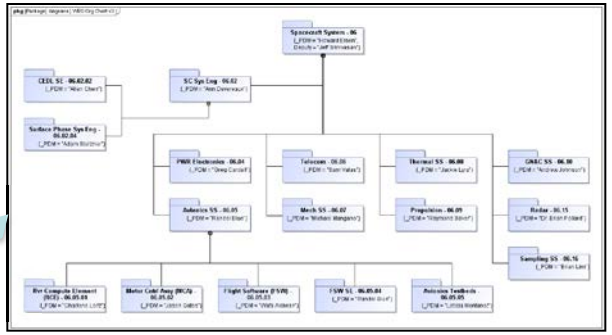
System Block Diagrams and Interfaces



Physical Decomposition, Logical Decomposition, and WBS



Org Chart



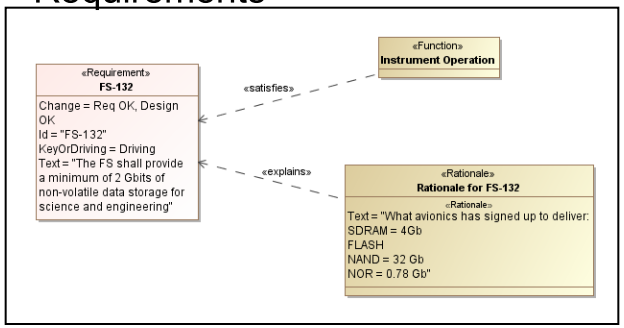
Linking information to core components (Reference Designators)

Resource Tracking (e.g., subset of web-accessible MEL)

Flight System	Flight Quantity	CBE (kg)	MEV (kg)	Contingency (Percent)	Contingency Level	CBE All Count (kg)	MEV All Count (kg)
Flight System	1	915.06	942.27	2.97	N/A	915.06	942.27
RPS	1	44.79	45.68	2.00	N/A	44.79	45.68
RTG	1	44.79	45.68	2.00	N/A	44.79	45.68
_PAYLOAD	1	72.25	73.73	2.04	N/A	72.25	73.73
Thermal	1	41.14	41.96	2.00	N/A	41.14	41.96
RVRTSTAT	12	0.01	0.01	2.00	N/A	0.16	0.16
RIPA	1	14.58	14.87	2.00	N/A	14.58	14.87
RVRTHRM	1	17.28	17.63	2.00	N/A	17.28	17.63
CHRSFL	1	0.90	0.91	2.00	N/A	0.90	0.91
RVRPRT	192	0.00	0.00	2.00	N/A	0.28	0.29

Subset of patterns are extended from institutionally-and Europa derived patterns

Assessment of Key & Driving Requirements



System model provides integrated, consistent, and broadly-accessible design information and change assessment

Early Assessment of Value & Benefits for Mars 2020

The team is seeing value already, particularly in generating artifacts like the MEL, heritage tables, and interface block diagrams and making them broadly accessible to the team

- Providing mutually-consistent products that are readily updated (e.g., a change to an item in one place immediately propagates that update to all affected views/products).
- Going through this process is also helping to identify areas of inconsistencies in separately generated and maintained historical documents, spreadsheets, etc. inherited from MSL. Getting these into the model is helping us to reconcile these discrepancies.
- Products are being created that are quickly and broadly accessible (e.g., via web interface) by the wider team (e.g., not having to track down the latest version of an Excel spreadsheet on an individual's computer).
- This is also helping with increasing the visibility and understanding of the design by the team.

Looking ahead, it is evident how the model will help us with another important aspect – using the model to help with knowledge transfer and continuity as personnel come in and out of the project over the coming years

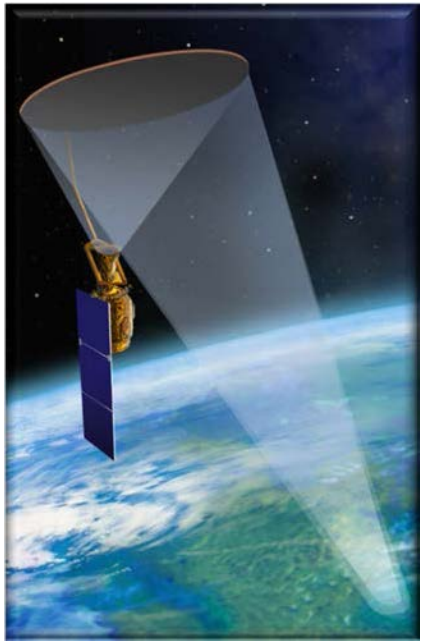
The Soil Moisture Active Passive (SMAP) Mission V&V

SMAP Pilots: Using MBSE for V&V

Motivation:

- The complexity (number of states) of flight and ground systems is increasing yet time for V&V is decreasing.
- The complexity of the test environment is increasing

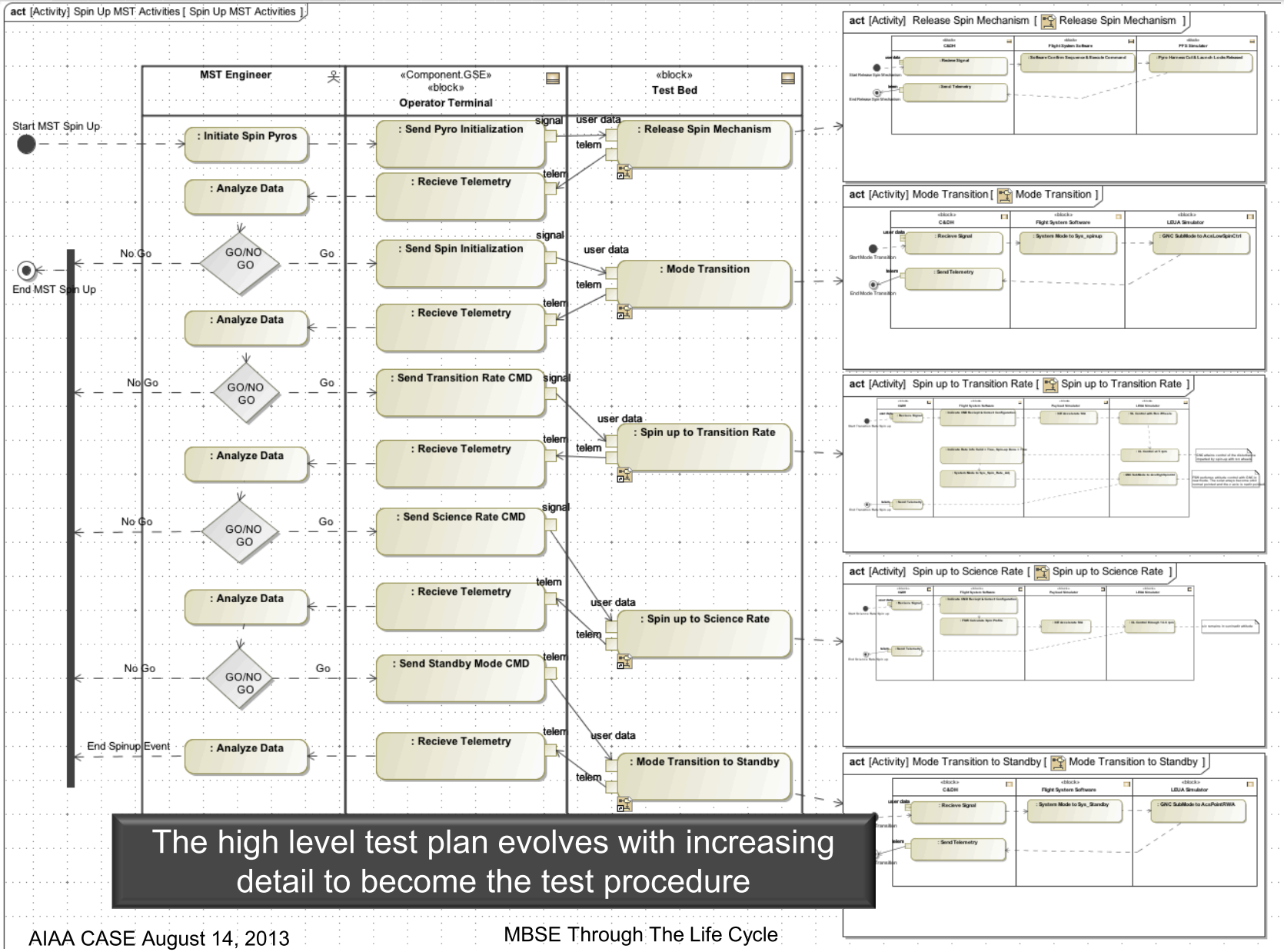
Desired Value: Explore a greater state space in less time



1. **Generate V&V products such as test plans and procedures, using the SMAP antenna spin-up event as a reference case.**

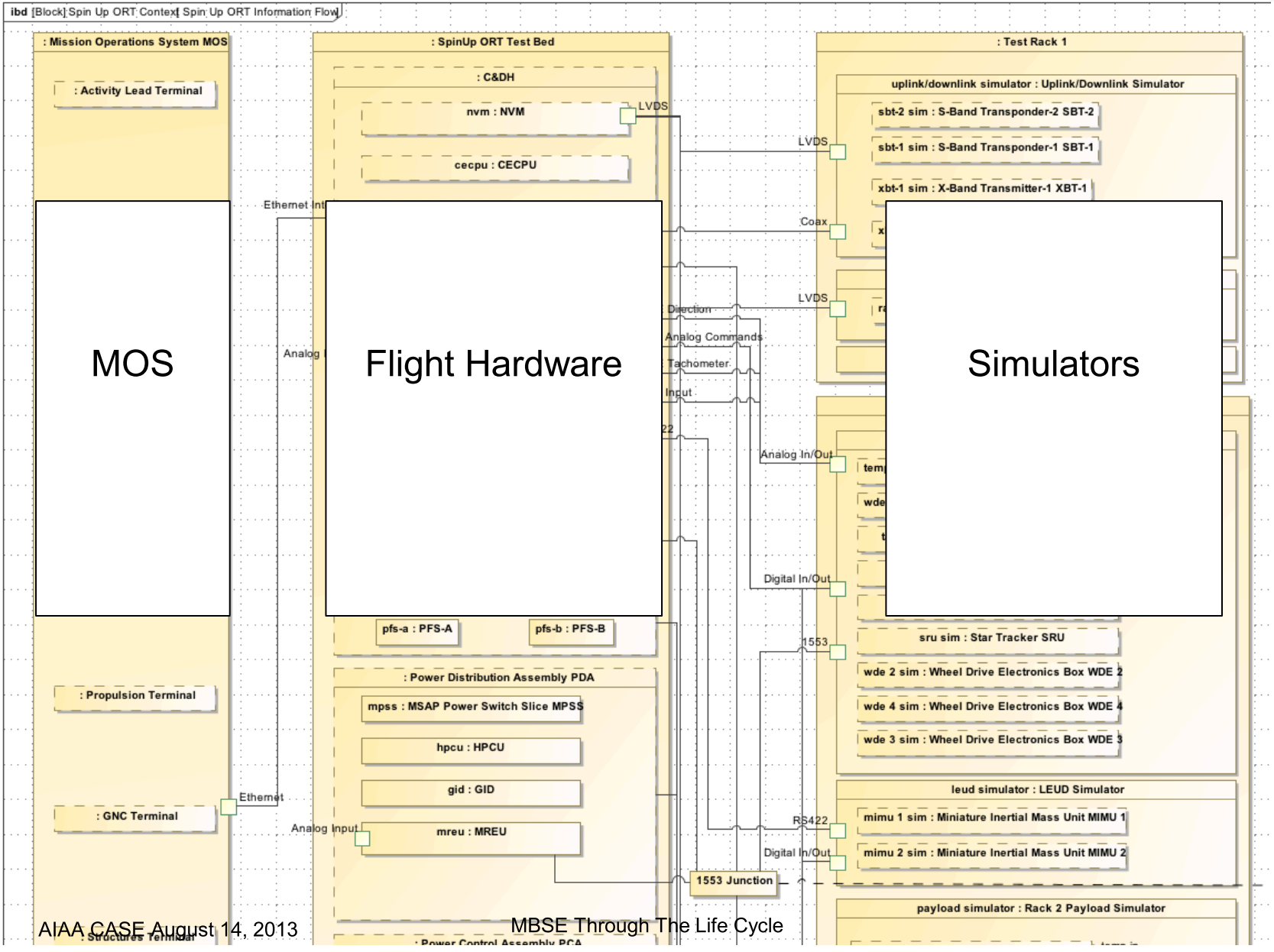
2. **Validate the Fault Protection System algorithms for SMAP by creating a model in SysML that can be formally verified.**

Products: Spin-up Mission Scenario Test Planning

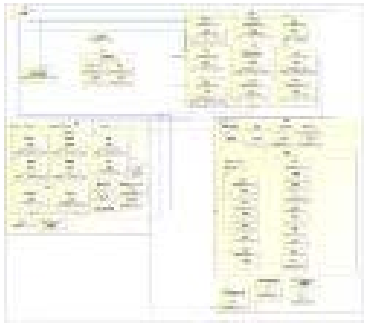


The high level test plan evolves with increasing detail to become the test procedure

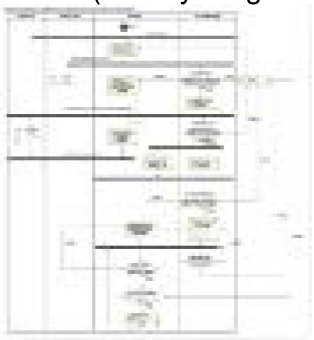
Products: SMAP Spin-Up Test Hardware & Software Configuration



I&T Product Development



Test Procedures
(Activity Diagrams)



Supporting Tools and Infrastructure:
MagicDraw
DocWeb
IMCE
Autoscript tool
…

Equipment and configuration

Sequence of Tests

System Model Procedure

Test Plan

Add detail

SW Testbed Procedure

Autoscripting

Script

Flat-Sat Procedure

Autoscripting

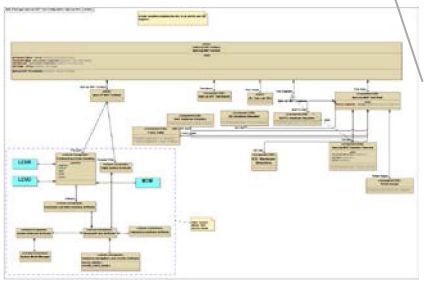
Script

Flight Vehicle Procedure

Autoscripting

Script

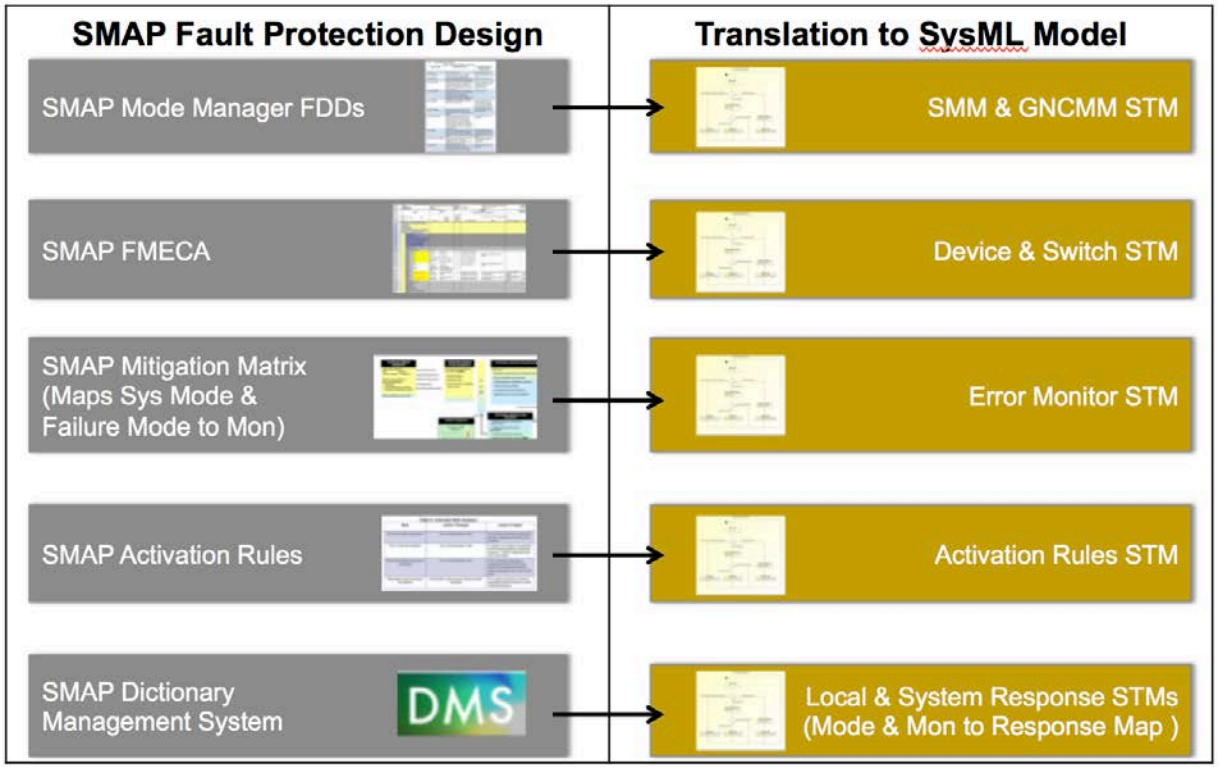
Operational Procedure



Requirements and test objectives linked to tests, results, and certification

SMAP Fault Protection Design Verification

- **Translate SMAP FP logical design into SysML state charts**
  - Explicitly model behavior as a network of collaborating state charts
  - Provide basis for checking Fault Protection Design vs. Defined Failure Space

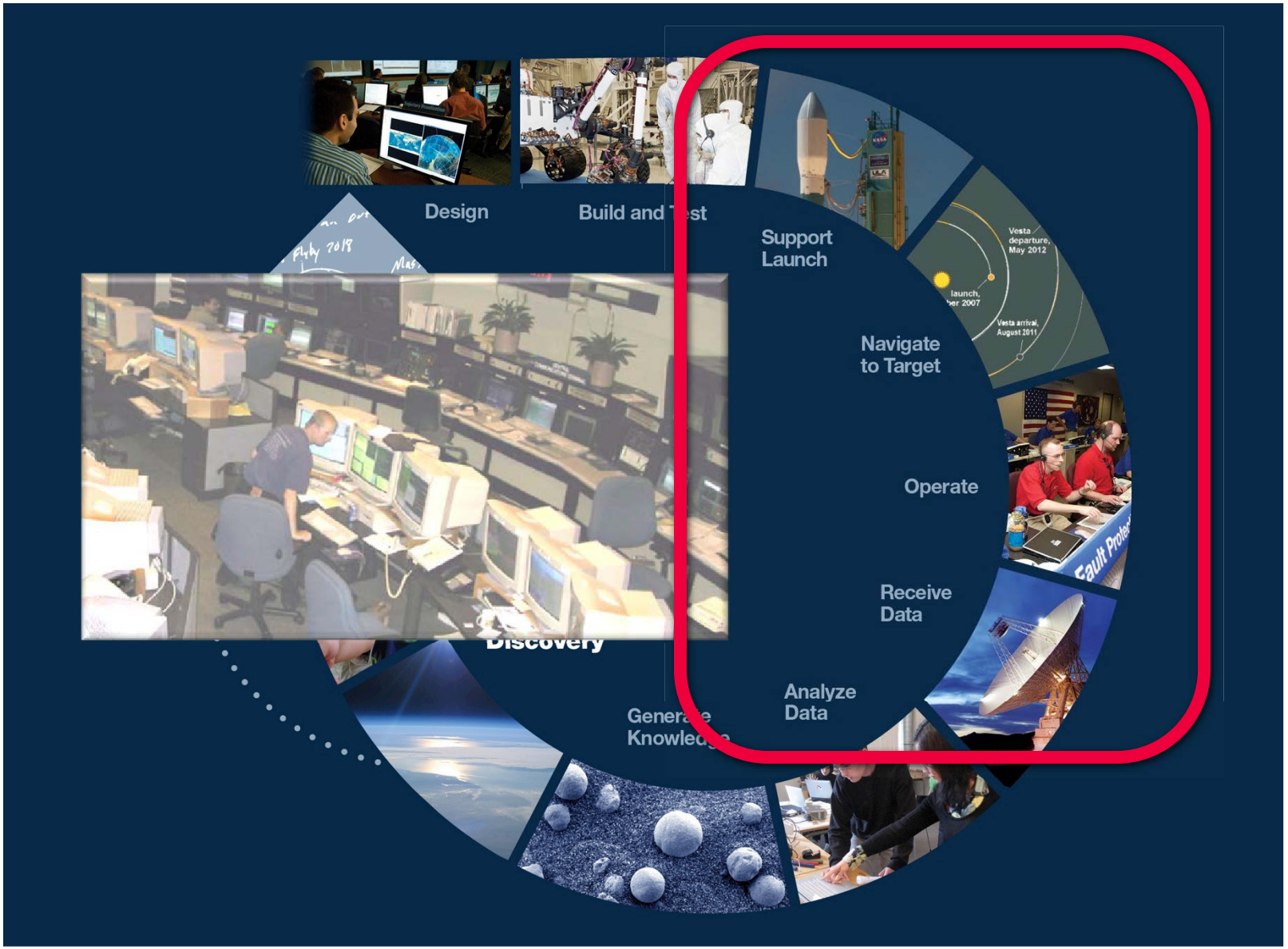


- **Executable state charts**
  - Fault injection testing
  - Create scenarios of Fault Protection behaviors
- **Model Checking**
  - Validate the design of fault protection system against domain specific constraints
    - Example: During ascent, want receiver on, transmitter off

V&V Demonstrated Value

- **Simulations derived directly from models enable us to validate operations concepts and validate scenarios early in the project lifecycle, reducing the cost of later remediation**
  - Validate the model itself
  - Validate the design
- **V&V products developed as views developed from an integrated model**
  - take advantage of precursor models developed by designers by using existing design material
  - provide greater inheritance from plans, to testbed procedures, through integration procedures, to operational procedures than existing products
  - are more intuitive to modify and execute than text based procedures
  - The procedure can become the script for configuring and running the unit under test
- **All of the above save time and money during the development cycle and reduce defects**

Mission Operations: Ops Revitalization



Re-Architecting The Advanced Multi-Mission Operations System (AMMOS)

AMMOS - Adaptable tools and services for operating NASA's robotic missions

Motivation for Re-architecting Effort

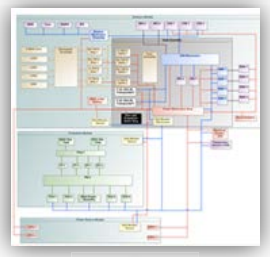
- Ground system and operations design has evolved over the past 30 years
- Need to refactor the system to address "pain points", enhance operations personnel efficiency, and gain higher levels of re-use from mission to mission.

Motivation for applying MBSE

- Promote architectural integrity
- Provide single source of design reference
- Provide rigorous, non-ambiguous description of system design
  - Requirements
  - Interfaces
  - Operations processes

MOS System Engineering Products

MagicDraw



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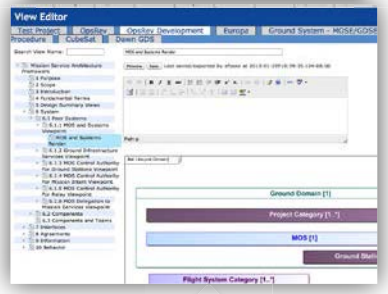
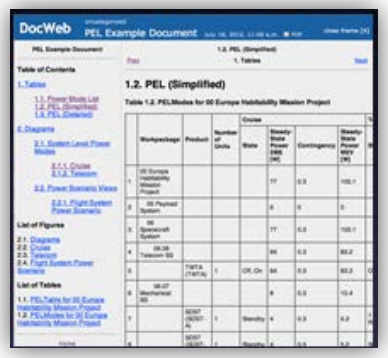


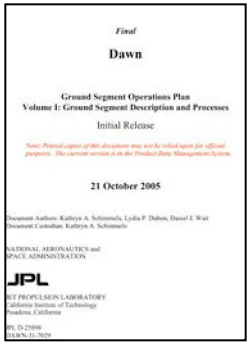
Modeling the MOS

Model Repository

- Use Cases
- System Composition
- Capabilities
- Interfaces
- Scenarios
- Processes

DocGen → DocWeb





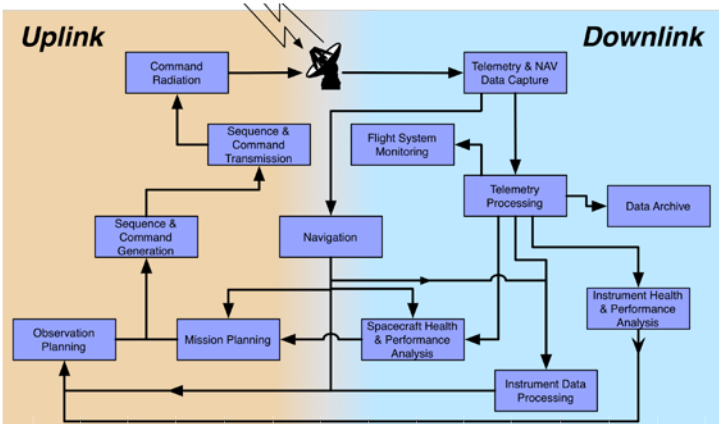
Reports, Documents, and Project-specific Gate Products

The Value of Using MBSE for the MOS

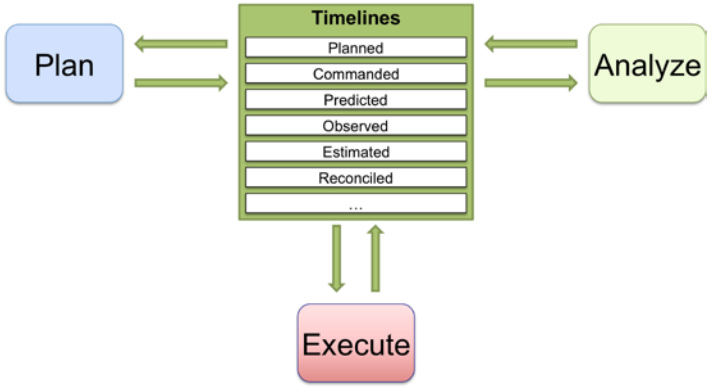
MBSE Facilitates:

- The ability to understand and analyze very complex systems
- The ability to accurately depict relationships between capabilities, processes, and the exchange of information that supports those relationships.
- The ability for operations personnel to better define the system functionality they need
- Understanding of how changes impact each part of the system
- Exposure of the connection between engineering products (artifacts) and system elements, many of which have been implicit.

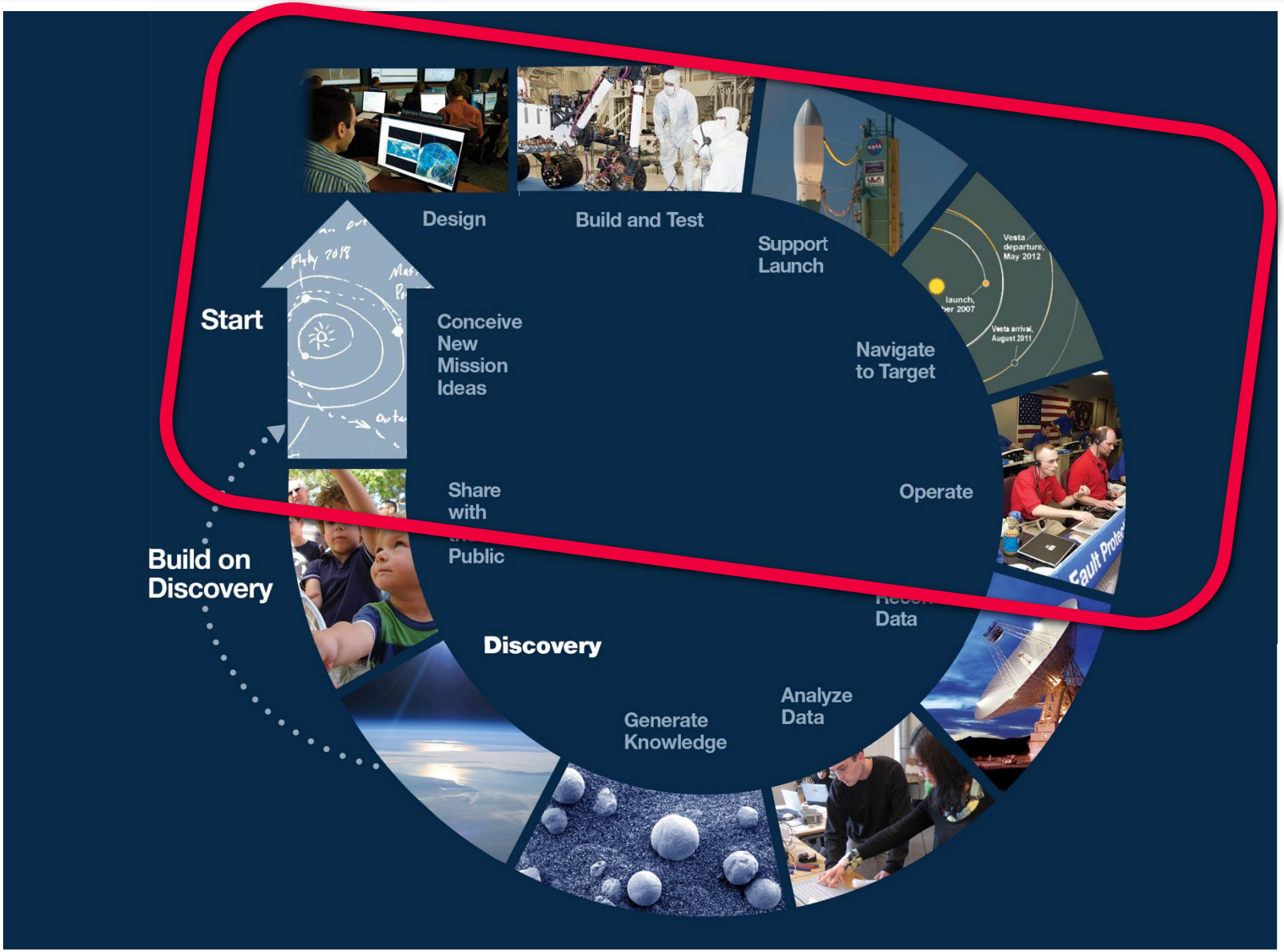
Control System As-Is



To-Be: A Timeline Based Control System



In Summary…


Start
Conceive New Mission Ideas
Design
Build and Test
Support Launch
Navigate to Target
Operate
Data
Analyze Data
Generate Knowledge
Discovery
Share with Public
Build on Discovery

What JPL MBSE Practitioners Say (1 of 3)

- **It Enhances Communication**
  - A single, authoritative source of information keeps team on same page
  - Promotes accurate, efficient, consistent communication within a project
  - More complete transmission of concepts & rationale from proposal to implementation
  - Based on my task and MBSE experience with the task "My first move would be to develop a system model."
- **It Improves Productivity**
  - "Europa team was able to study 3 distinct mission concepts for the resources usually sufficient to study only 1 or 2, and the high quality of all 3 studies was lauded by the Hubbard Review Board and by NASA HQ."
  - "Development of the initial system model … took a fraction of the time it would otherwise have, by reusing modeling patterns and analyses learned earlier on EHM."
  - Time-consuming project documents/reports become trivial to generate

What JPL MBSE Practitioners Say (2 of 3)

- **It Improves Quality**
  - Earlier detection of inconsistencies due to clearer semantics
    - Example: 35 inconsistencies identified in Exploration Missions E-E Test
  - "One thing that I've found is that the process of modeling leads to 'escape discovery'. …capturing the details leads to a greater understanding of the system and makes errors or potential problem areas 'pop out'."
  - Promotes early/on-going requirements validation and design verification
  - Standard documents are kept consistent and up-to-date
- **It Supports Integration**
  - Provides consistent definition of system to integrate with discipline models, including cost models and science margin models

What JPL MBSE Practitioners Say (3 of 3)

- **It Helps Manage Complexity**
  - "We are able to evaluate 100s-1000s of consistent, structured, and transparent design options and explicitly compare cost/benefit in a fraction of the time and cost of conventional methods."
  - Different views address the concerns of different stakeholders
- **It Enables Reuse of Institutional Knowledge**
  - MBSE enhances reuse of intellectual property (model elements embody hard-earned technical expertise)
- **It Attracts Early Career Talent**
  - MBSE forms a bridge from college education to JPL best practices
  - MBSE methods are beginning to be taught in universities to engineering students
  - Early adopters are dominated by the early career hires

Necessary Infrastructure Elements

Enable development of SysML (and other) project models

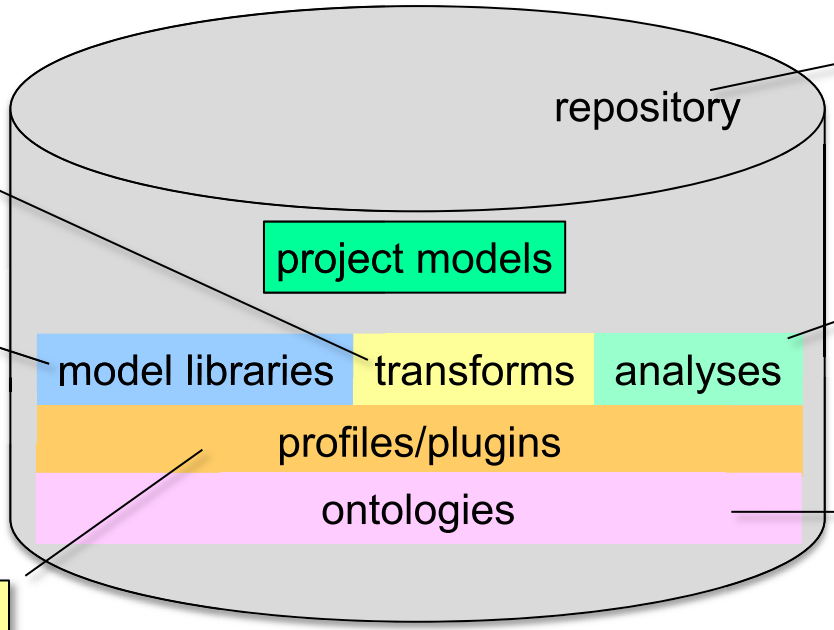
Tools
(e.g., Magic Draw)

Guidance
(e.g., SysML modeling Guide; MBSE based life-cycle methodology)

Explain proper use and benefits of institutional standards and infrastructure

Construct or translate models from one form to another

Provide reusable model elements



Secure storage of project models and reusable assets

Analyze models for well-formedness, completeness, consistency, V&V

- Customize SysML tools with ontologies
- Add user interface helpers

- Establish common concepts for flight project engineering
- Establish consensus rules for expressing design
- Enable information exchange

….Thank You!