Integrated Model-Centric Engineering:

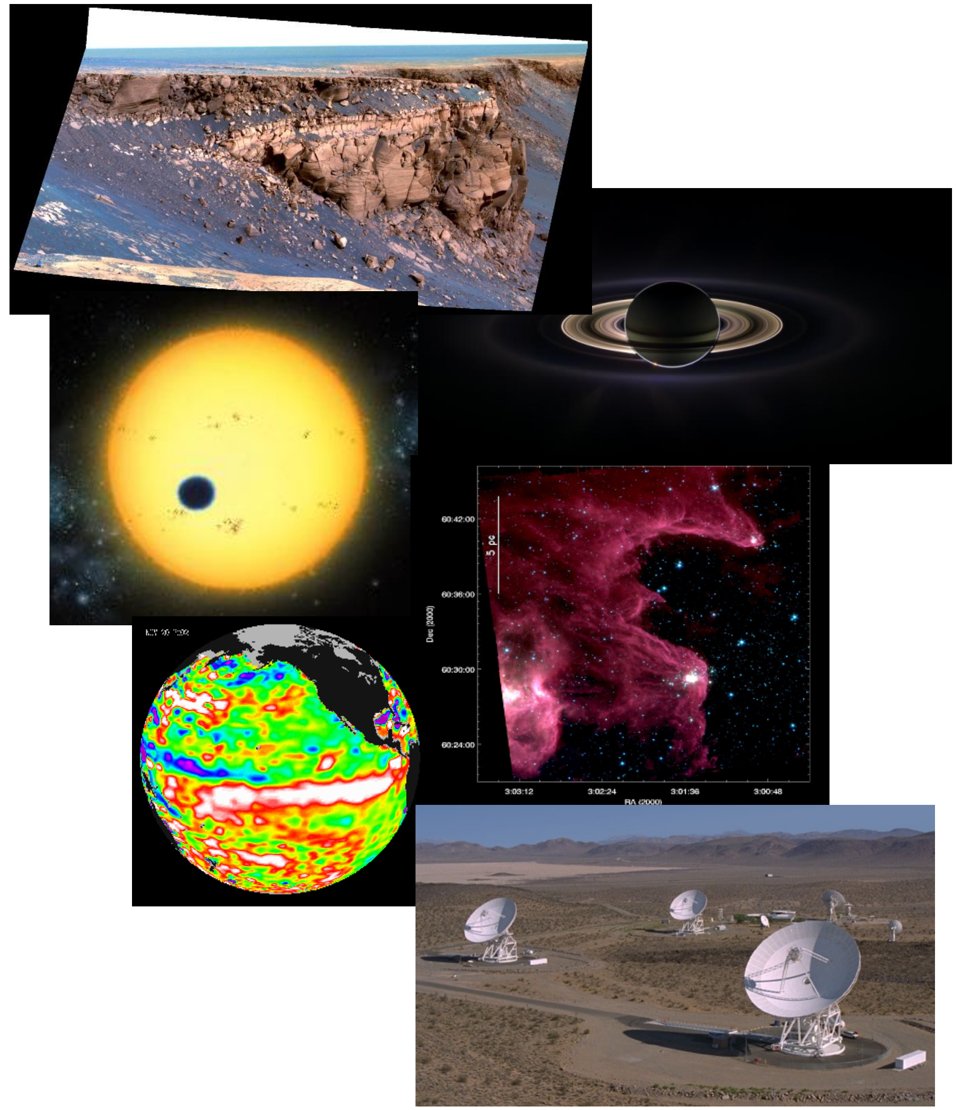
The Application of MBSE at JPL Through the Life Cycle

Dave Nichols
Chi Lin

INCOSE International Workshop
MBSE Workshop
January 26, 2014

JPL's Mission for NASA is *Robotic* Space Exploration

- **Mars**
- **Solar system**
- **Exoplanets**
- **Astrophysics**
- **Earth Science**
- **Interplanetary network**



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…

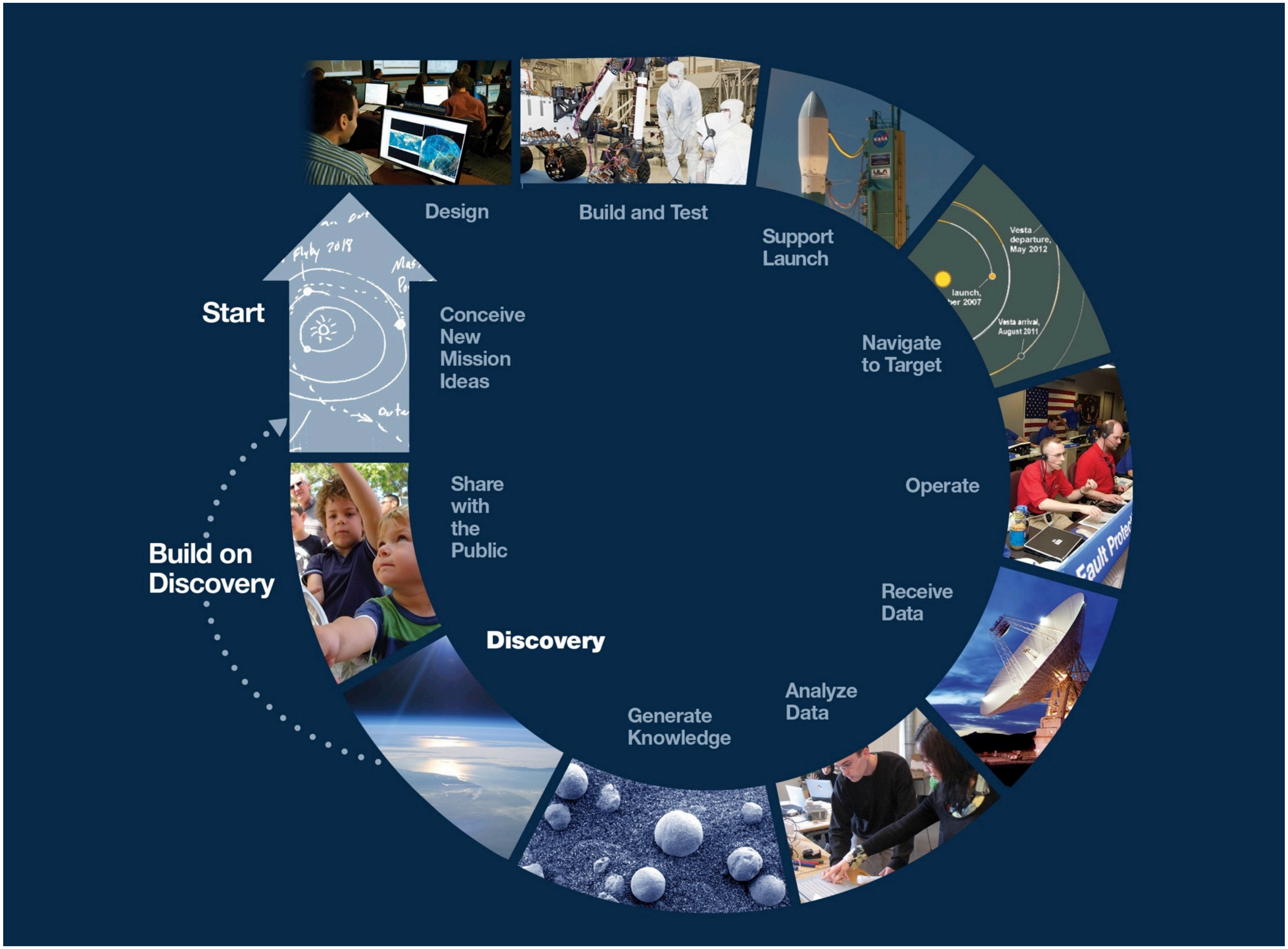
- **Reduce the number of product and mission defects in the face of growing complexity**
- **And increase productivity/reduce costs**

Status of MBSE at JPL

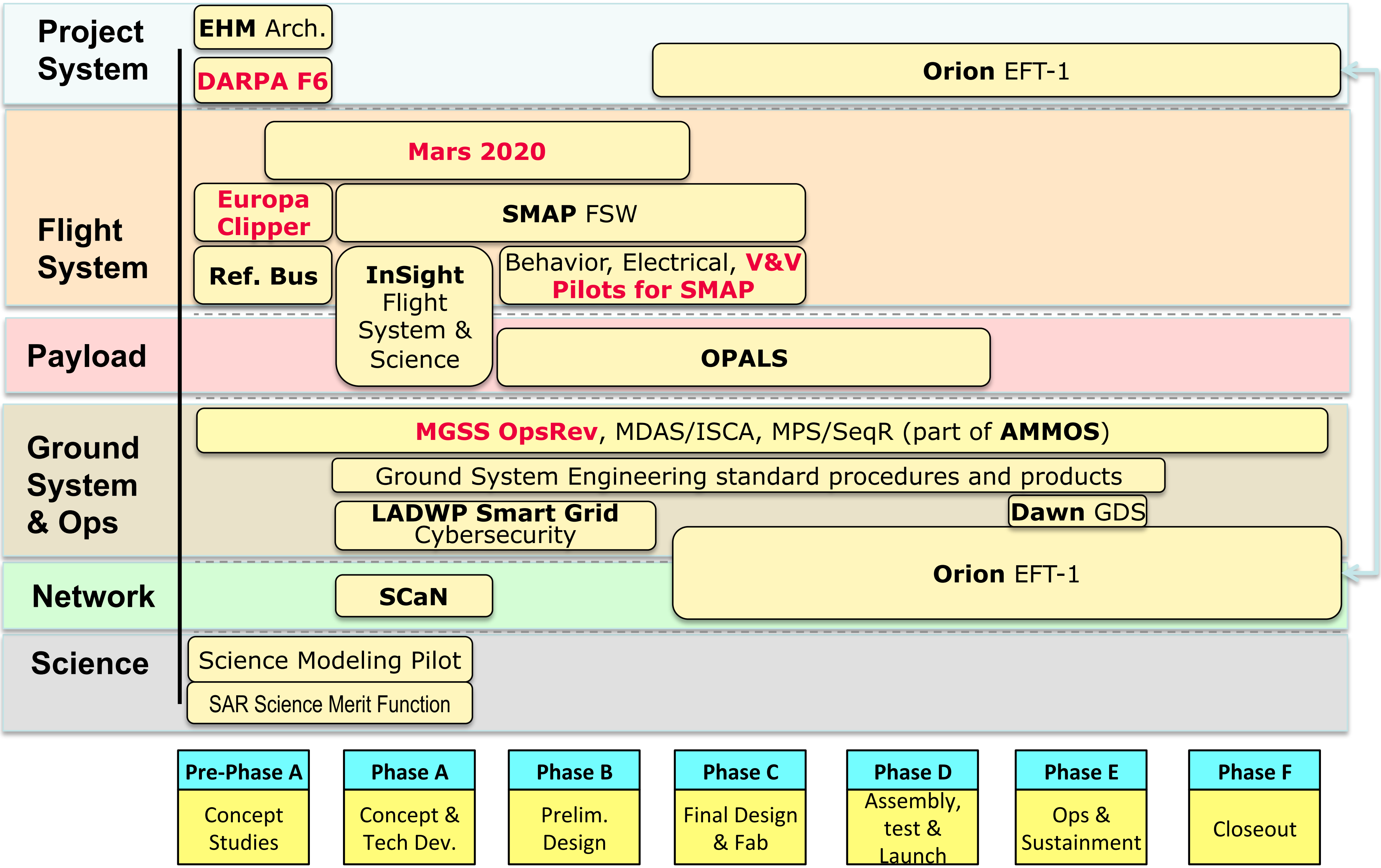
JPL has been:

- 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

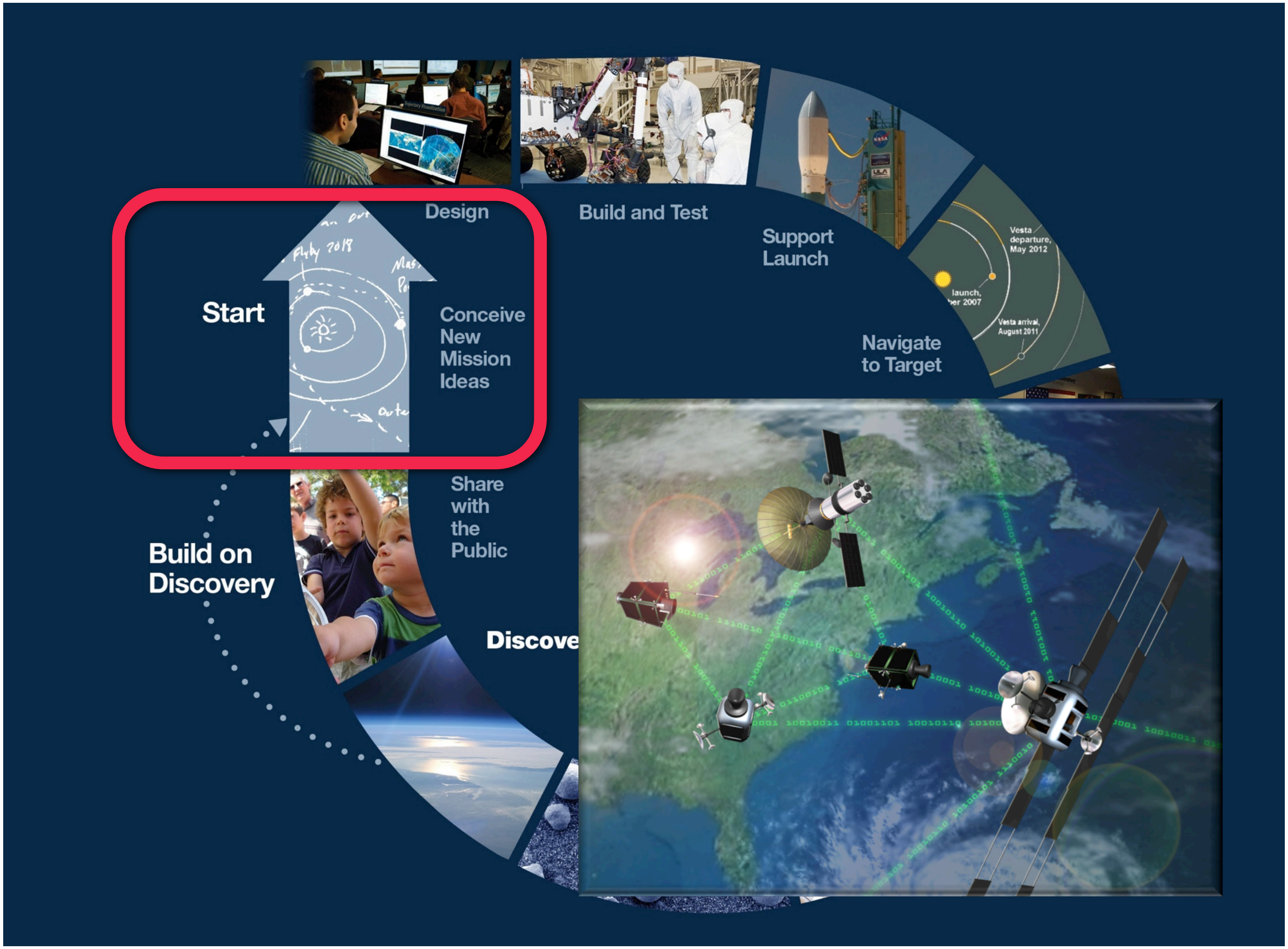
The JPL Product Life Cycle



Landscape of MBSE Applications at JPL

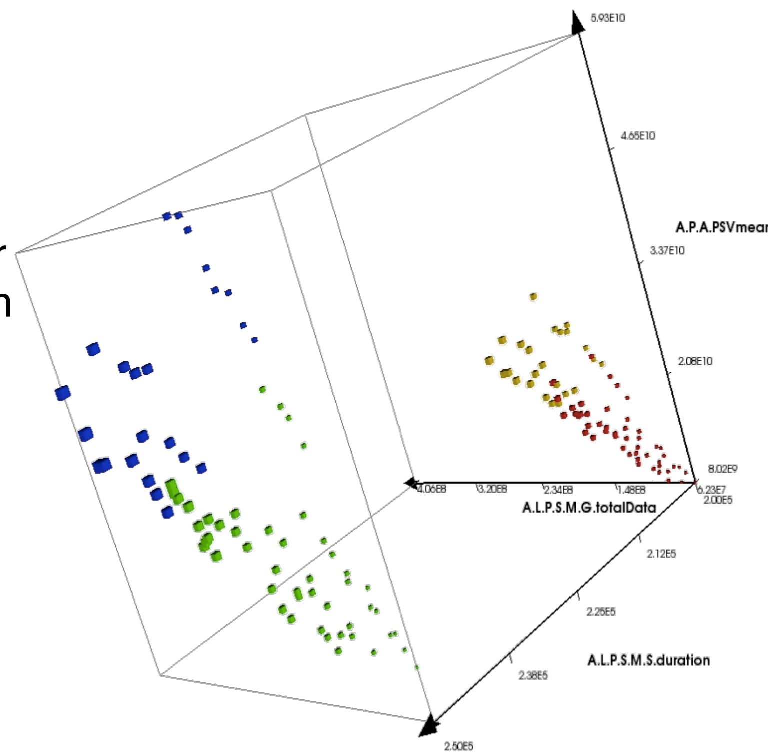


Mission Formulation: Trade Space Exploration



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
- Limited <u>architecture</u> variation ability
  - For example: trade nuclear-powered flight systems vs. Electric Propulsion FS

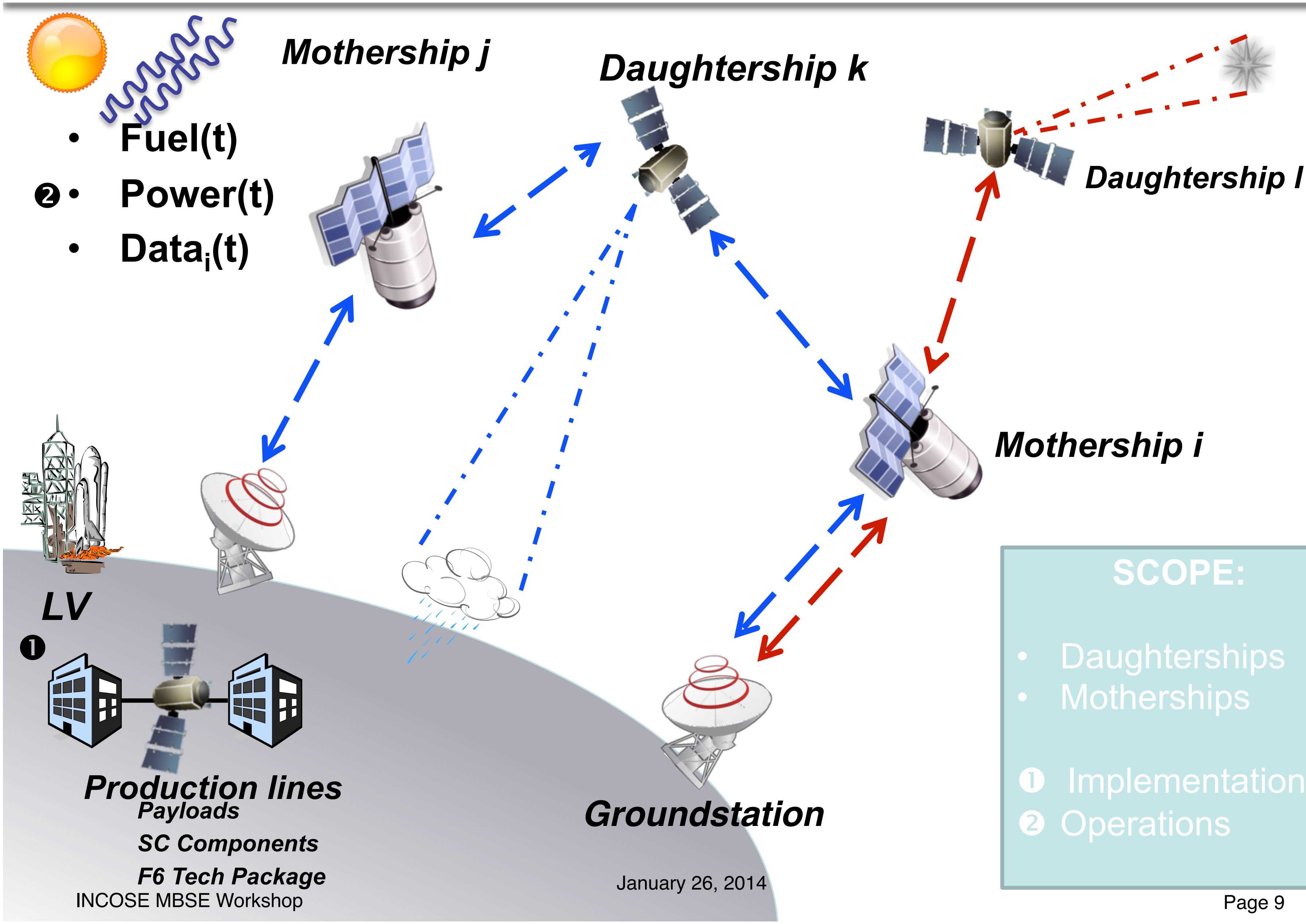


The MBSE approach was chosen to facilitate exploration of a greater set of architectural variants.

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

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

ASDA Discrete Event Simulation Overview

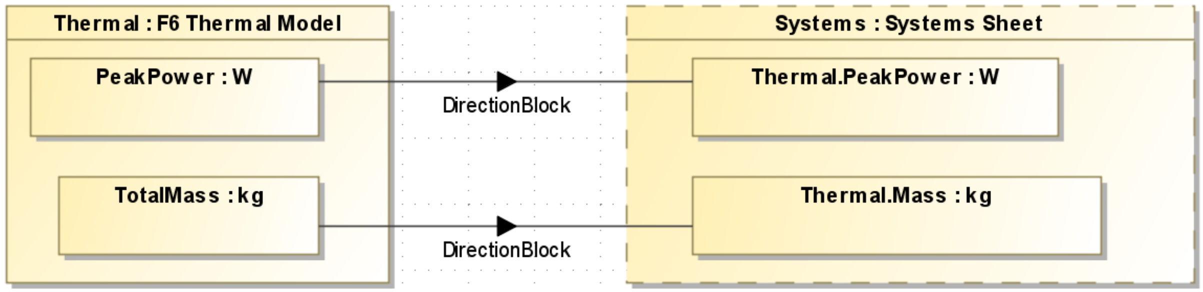


SCOPE:

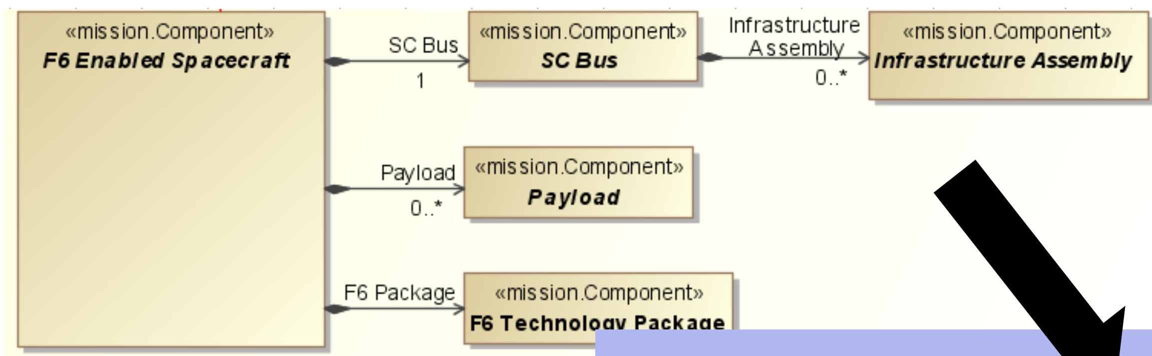
- Daughterships
- Motherships

❶ Implementation
❷ Operations

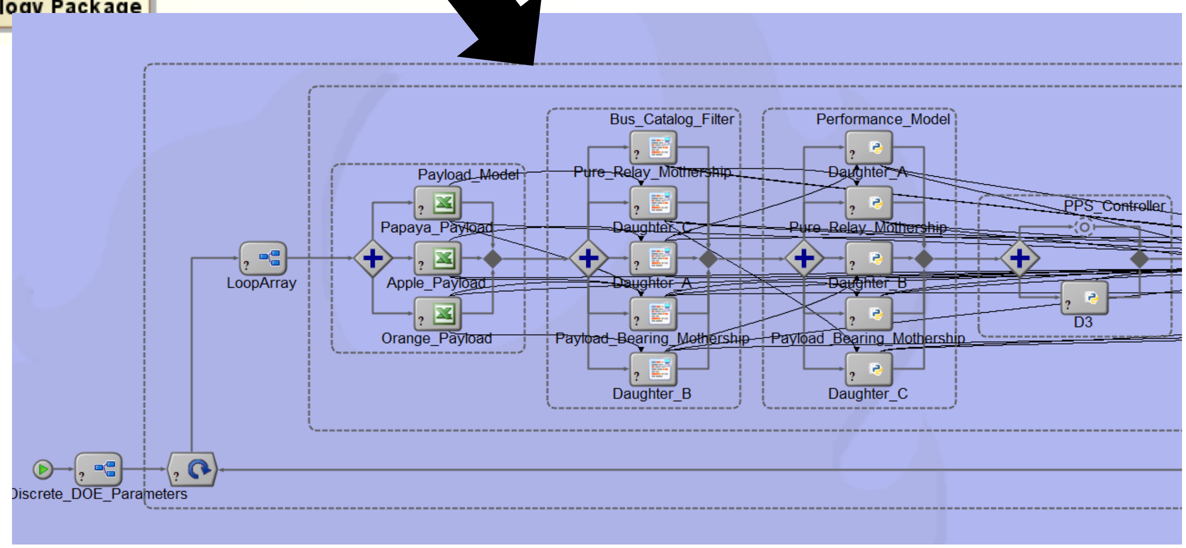
Parameter connection templates



Architectural Alternative



Architectural Analysis via Simulation

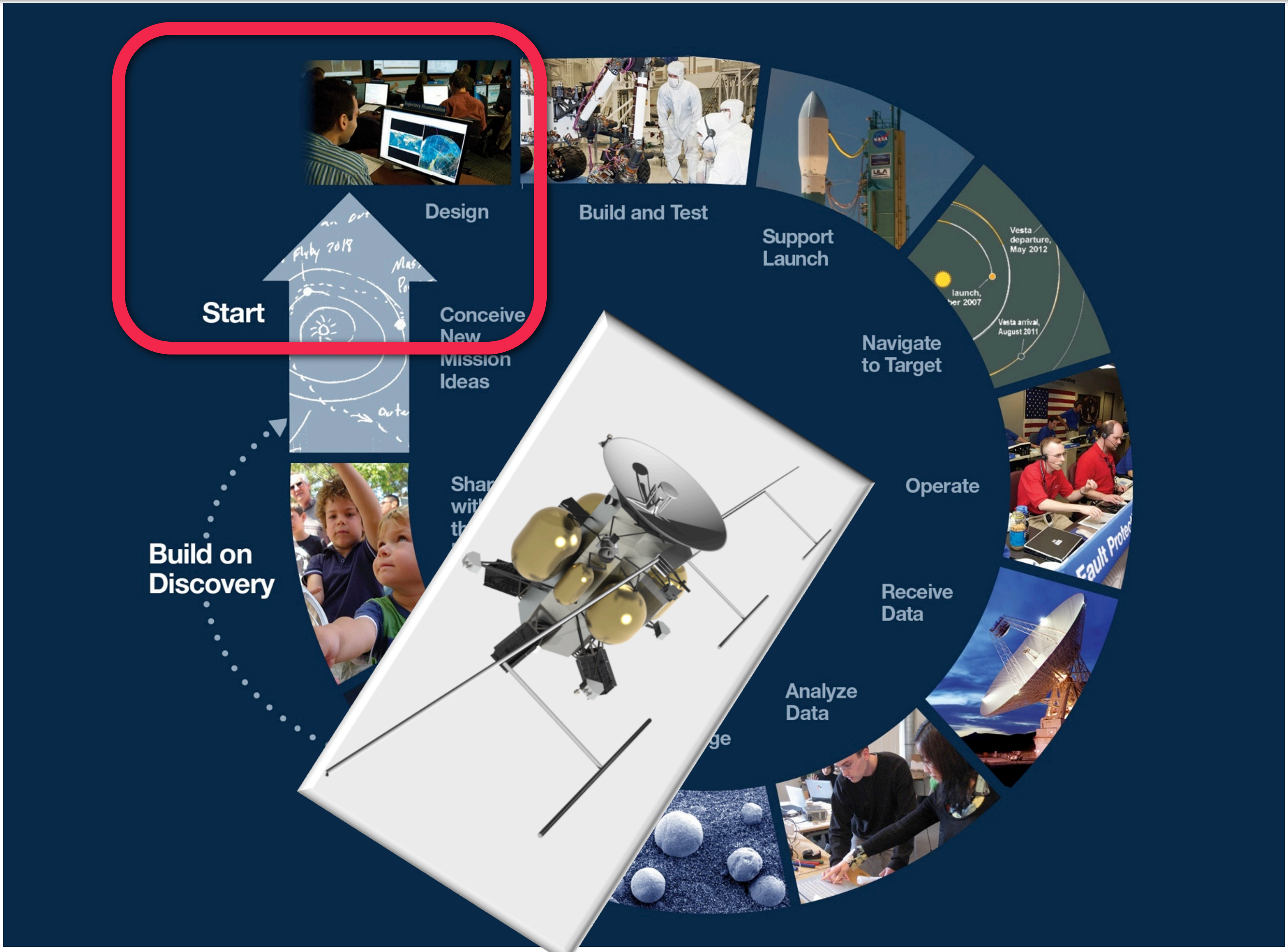


The Advanced Systems Design and Analysis Tool (ASDA)

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

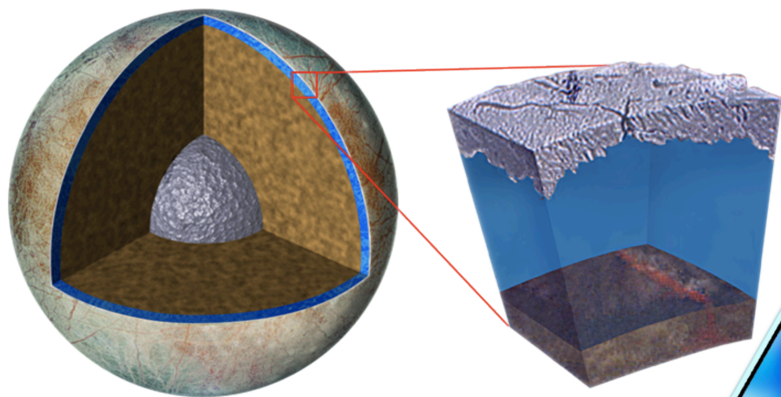
- SysML templates have been instrumental in structuring analyses of architectural options
- MBSE has facilitated a fundamentally new capability that did not previously exist.

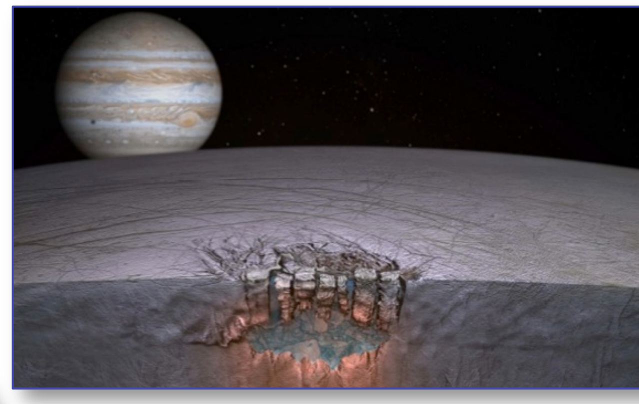
Mission Formulation: The Europa Clipper

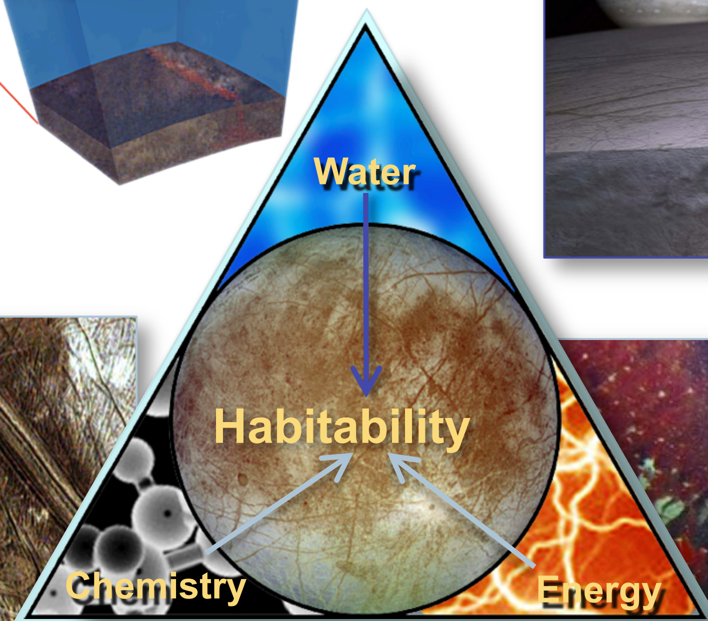


Europa: Looking for the Ingredients for Life?

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?

Systems Engineering Challenges During Formulation Phase

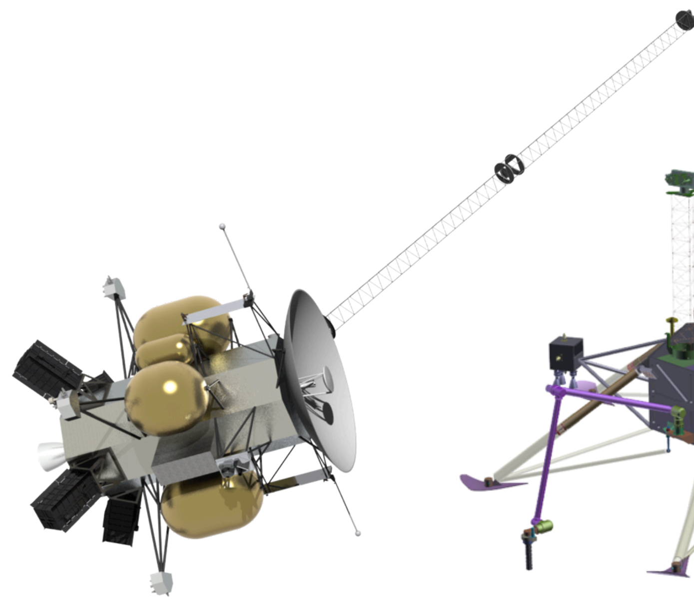
- **Managing multiple architectural alternatives**
- **Reliably determining whether design concepts "close" on key technical resources**
- **Ensuring correctness and consistency of multiple, disconnected engineering reports**
- **Managing design changes before a full design exists**

Background

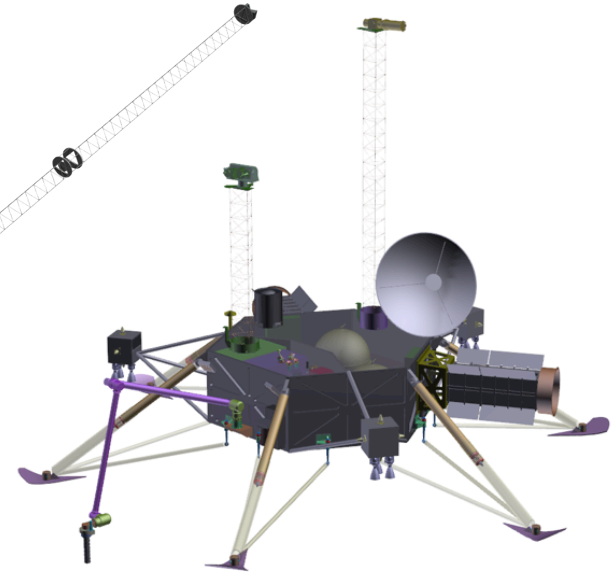
The Jupiter Europa Orbiter (JEO) mission concept was deemed to be of extremely high science value, but un-affordable, by the NRC Decadal Survey, which requested a de-scoped option

- 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)



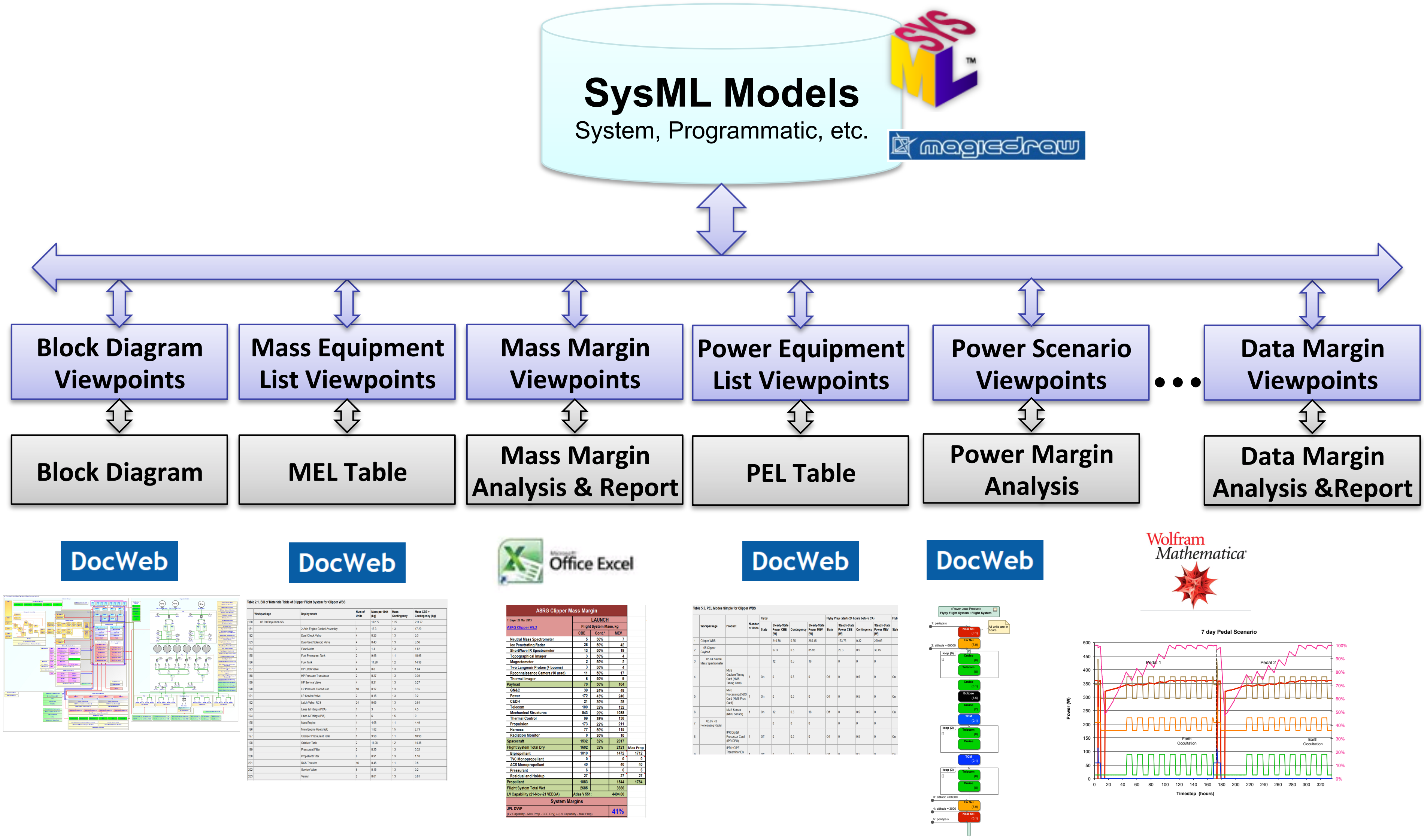
Europa Orbiter



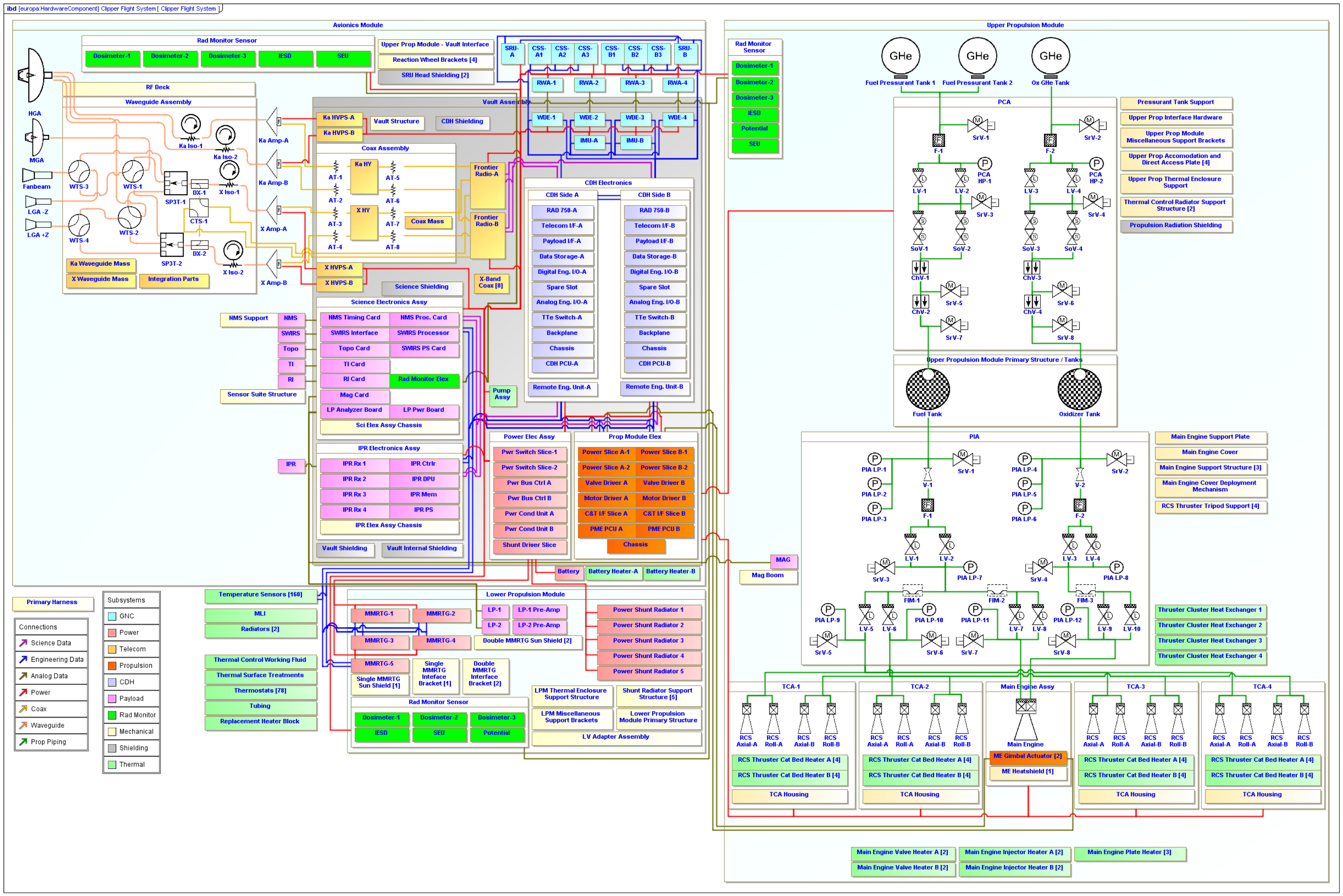
Europa Lander

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Europa System Model Framework



More Meaningful System Diagrams



Automated Mass Accounting

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

	Workpackage
1	Clipper WBS
2	05 Clipper Pay
3	05.04 Neutra Spectrometer
4	
5	
6	
7	05.05 Ice Pe Radar
8	
9	
10	
11	
12	
13	
14	
15	05.06 Short \ Infrared Spectrom
16	
17	
18	
19	
20	05.07 Topogı Imager
21	

Table 2.14. Deployment Table of Clipper Flight System

	Deployment	Num of Units	Mass CBE per Unit (kg)	Total Mass CBE (kg)	Mass Contingency	Mass MEV per Unit (kg)	Total Mass MEV (kg)	Workpackage
1	Clipper Flight System	1	1439.91	1439.91	0.27	1835.26	1835.26	Clipper WBS
2	Multi-layer Insulation	1	16.5	16.50	0.3	21.45	21.45	06.08 Thermal SS
3	Radiators	2	4.29	8.58	0.3	5.58	11.15	06.08 Thermal SS
4	Temperature sensors	160	0.01	1.60	0.3	0.01	2.08	06.08 Thermal SS
5	Thermostats	78	0.02	1.56	0.3	0.03	2.03	06.08 Thermal SS
6	Thermal Surface Treatments	1	1.4	1.40	0.3	1.82	1.82	06.08 Thermal SS
7	Thermal Control Working Fluid	1	6.7	6.70	0.5	10.05	10.05	06.08 Thermal SS
8	Tubing	1	5.3	5.30	0.5	7.95	7.95	06.08 Thermal SS
9	Replacement Heater Block	1	2	2.00	0.3	2.6	2.60	06.08 Thermal SS
10	Primary Harness	1	100.46	100.46	0.5	150.69	150.69	06.11 Harness SS
11	Avionics Module	1	561.96	561.96	0.32	739.61	739.61	Clipper WBS
12	Neutral Mass Spectrograph	1	4.98	4.98	0.5	7.47	7.47	05.04 Neutral Mass Spectrometer
13	NMS Sensor	1	2.94	2.94	0.5	4.41	4.41	05.04 Neutral Mass Spectrometer
14	NMS Detector Shielding	1	2.04	2.04	0.5	3.06	3.06	06.07B Payload Radiation Shielding
15	Ice Penetrating Radar	1	25.2	25.20	0.5	37.8	37.80	05.05 Ice Penetrating Radar
16	IPR Antenna and Cable Assembly	1	12.2	12.20	0.5	18.3	18.30	05.05 Ice Penetrating Radar
17	IPR HCIPE Transmitter Elx	1	8	8.00	0.5	12	12.00	05.05 Ice Penetrating Radar
18	IPR Shielding	1	5	5.00	0.5	7.5	7.50	06.07B Payload Radiation Shielding
19	Short Wave IR Spectrograph	1	16	16.00	0.5	24	24.00	05.06 Short Wave Infrared Spectrometer
20	SWIRS Sensor	1	10.1	10.10	0.5	15.15	15.15	05.06 Short Wave Infrared Spectrometer
21	SWIRS Shielding	1	5.9	5.90	0.5	8.85	8.85	06.07B Payload Radiation Shielding

Integrated Power/Energy Analysis

System Model:
- Equipment List
- Demand vs Mode
- Scenario Definitions

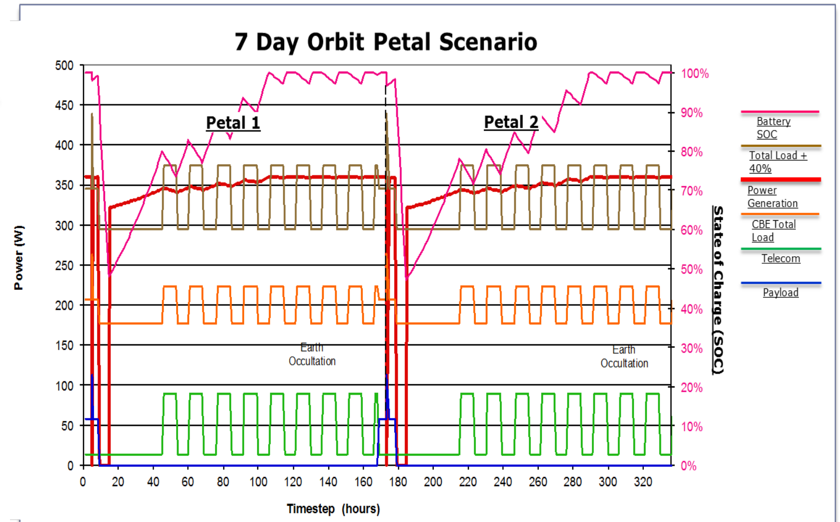
Subsystem Power Models
- Power Source Models
- Battery Models
- Load Profile Simulation

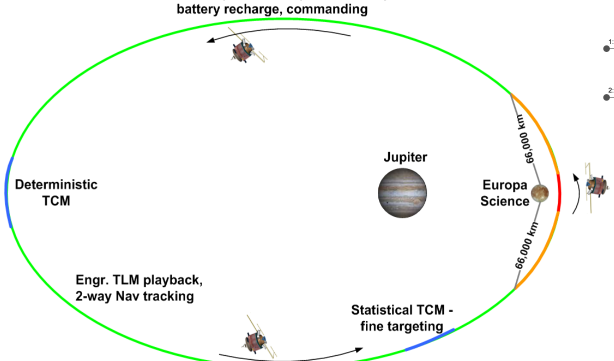
Integrated Power/Energy Analysis

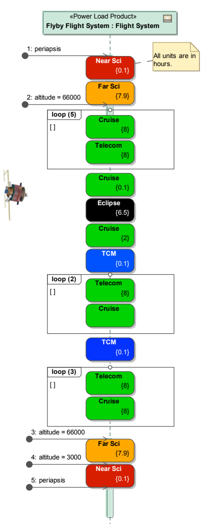
Table 4.11. PEL Table for 06.06 Telecommunications SS

	Work Package	Product	Power Mode	Avg Pwr CBE per Unit [W]	Contingency	Avg Pwr MEV per Unit [W]	Notes
1	06.06 Telecommunications SS						
2		Frontier Radio	Ka-Band Transmit	9.5	0.3	12.35	Transponder is powered and transmitting at Ka-band frequencies. It is capable of receiving X-band signals in this state.
3			Off	0	0.3	0	
4			X + Ka-Band Transmit	13.5	0.3	17.55	Transponder is powered and transmitting at both X and Ka-Band frequencies. It is capable of receiving X-band signals in this state.
5			X-Band Receive	5.5	0.3	7.15	Transponder is powered in an X-Band receive state, No transmission capability in this state.
6			X-Band Transmit	9.5	0.3	12.35	Transponder is powered and transmitting at X-band frequencies. It is capable of receiving X-band signals in this state.
7		Ka-Band Amplifier Tube and Electron Gun	High Power Drive Off	35	0.3	45.5	
8			High Power Drive On	74	0.3	96.2	
9			Off	0	0.3	0	
10			Standby	10	0.3	13	
11		X Band Amplifier Tube and Electron Gun	High Power Drive Off	20	0.3	26	
12			High Power Drive On	45	0.3	58.5	
13			Off	0	0.3	0	
14			Standby	10	0.3	13	

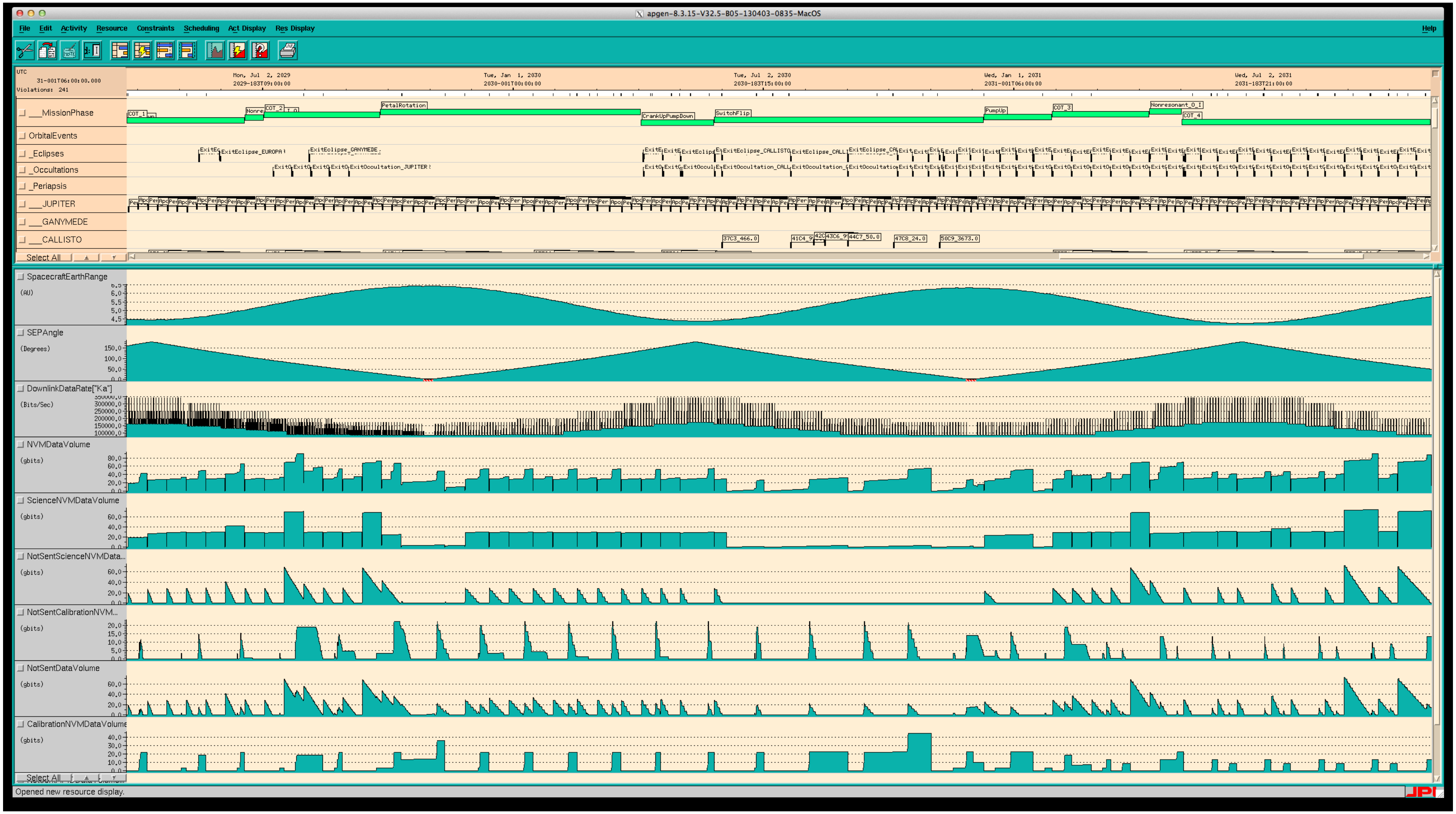
Power Profile Analysis







Integrated Data Throughput Analysis



Configuration-Managed, Web-Based Reporting

DocWeb Clipper MMRTG

Clipper MMRTG Nov. 19, 2013, 2:22 p.m. PDF close frame [X

The technical data in this document is controlled under the U.S. Export Regulations, release to foreign persons may require an export authorization.

Clipper MMRTG

Table of Contents

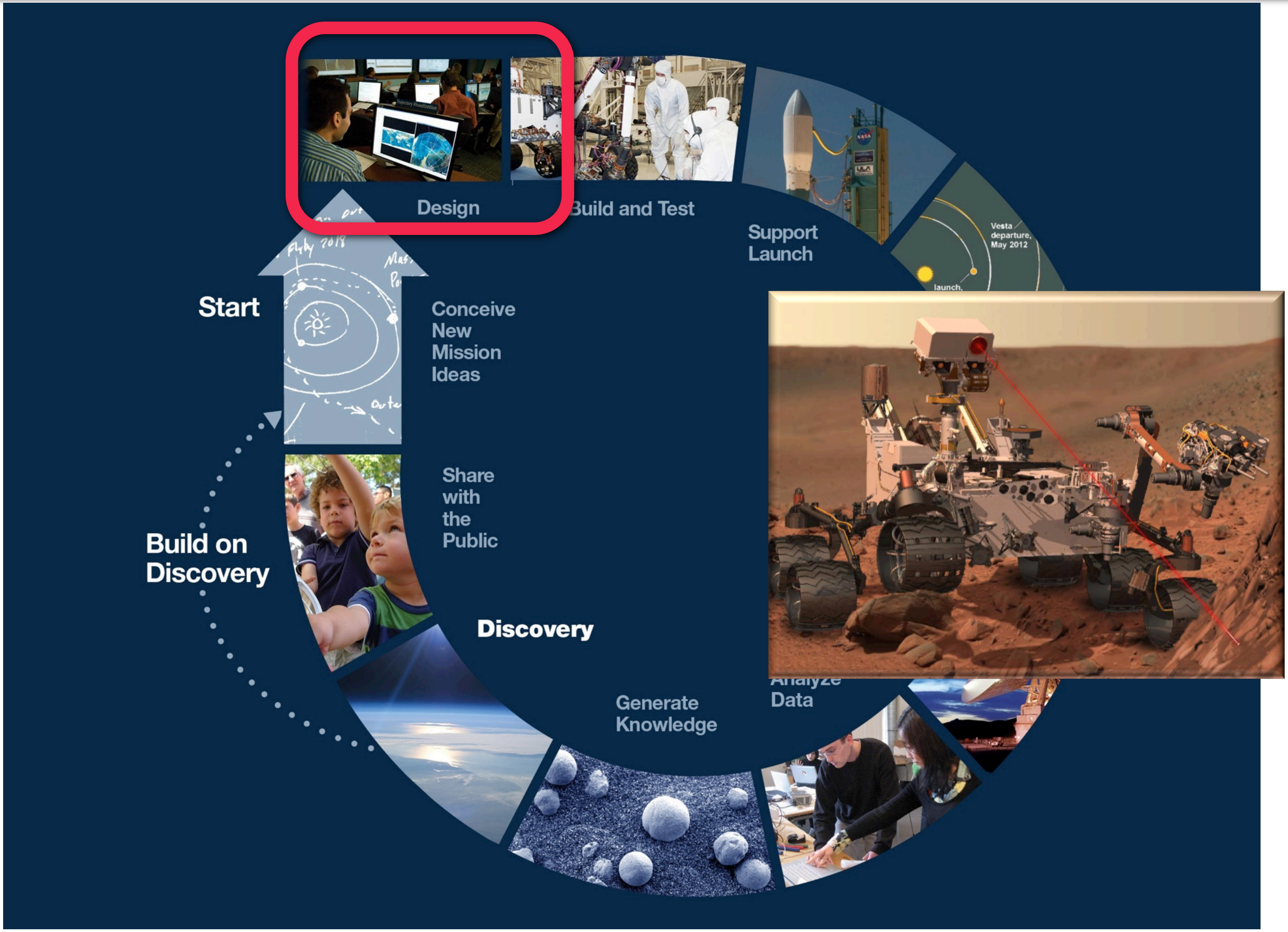
Table 1.1. Change log

Version	Release Date	Changes
7.2	11/22/2013	This version incorporates the following Model Change Requests (MCRs): • EMOD-423 (Add Propellant & Pressurant Tank Capacity in MEL Notes Field) • EMOD-428 (Update MMRTG Battery Capacity & Mass) • EMOD-445 (Implement ECR 539 Prop Module Electronics Change in MMRTG Clipper Model) • EMOD-450 (Connector from SRU to CDH is wrong, not carrying science data) This version also incorporates the following items that were not associated with a JIRA: • [TBD] The following are known issues with this version: • In the Telecom block diagrams, some attenuators are connected directly to other attenuators. This seems incorrect.
7.1	11/13/2013	This version incorporates the following Model Change Requests (MCRs): • EMOD-337 (Need Legends for line & block colors on all Flight System Block Diagrams) ○ Subtask: EMOD-341 (Add Legends to DocWeb Figures) • EMOD-351 (Add New Power Mode Scenario to MMRTG Model) • EMOD-406 (Remove Gravity Science Antennas from MMRTG Model) • EMOD-407 (Replace SDST with Frontier Radio in MMRTG Model) • EMOD-415 (Update MMRTG Telecom Workpackage per ECR-534) • EMOD-427 (Update Flyby 6 Mode Scenario Text) • EMOD-434 (CDH subsystem MEL, PEL, and Block Diagram updates as per ECR-527) • EMOD-447 (IPR component name change) • EMOD-449 (Change to Change Log format) This version also incorporates the following items that were not associated with a JIRA: • An error in the Inner Cruise mode scenarios was corrected: the Magnetometer and Langmuir Probes were incorrectly set to be on. This resulted in a 4.5W savings in all Inner Cruise mode scenarios. The following are known issues with this version:

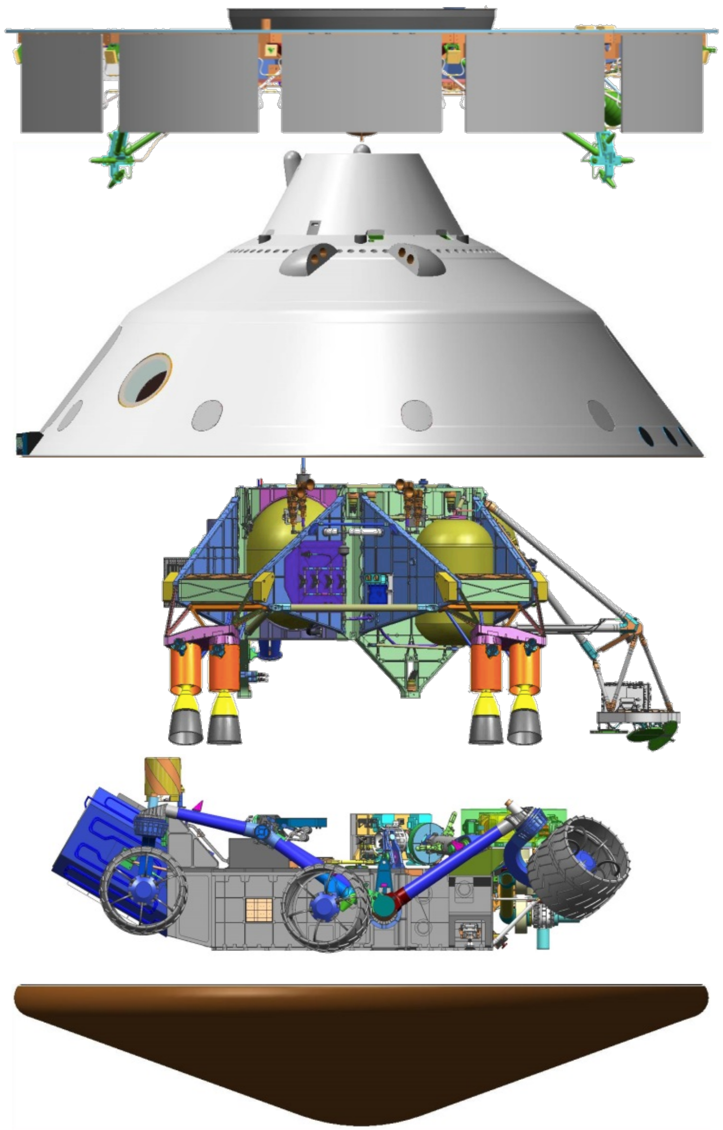
Europa Clipper: Benefits Realized Through MBSE

- 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
- Improved control over the evolution of system designs
- 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

Mars 2020 – The Follow-On to Curiosity

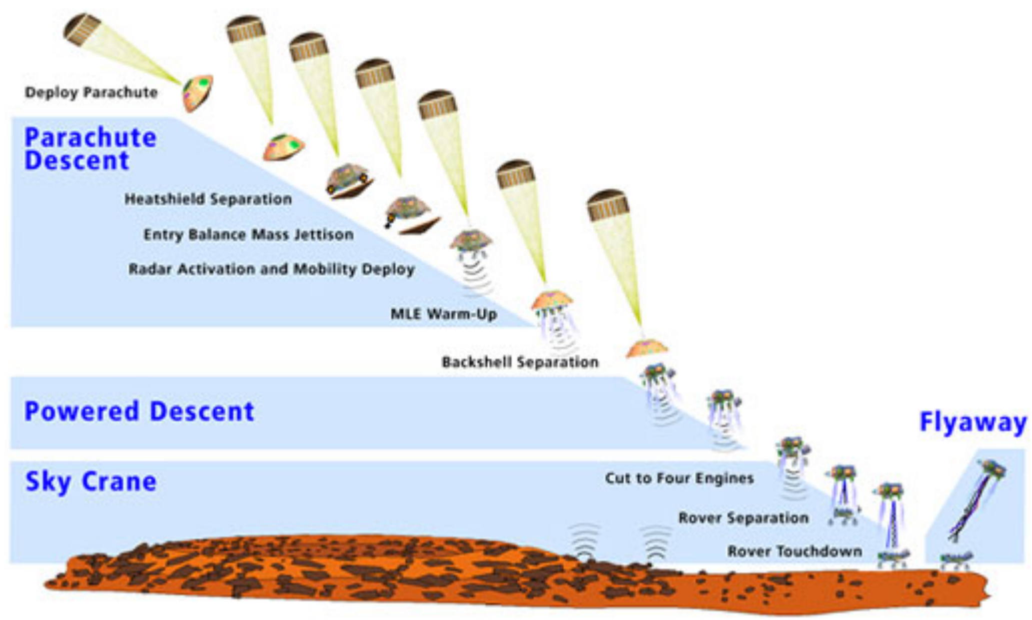


MBSE Motivation and Background – Coping with Complexity



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

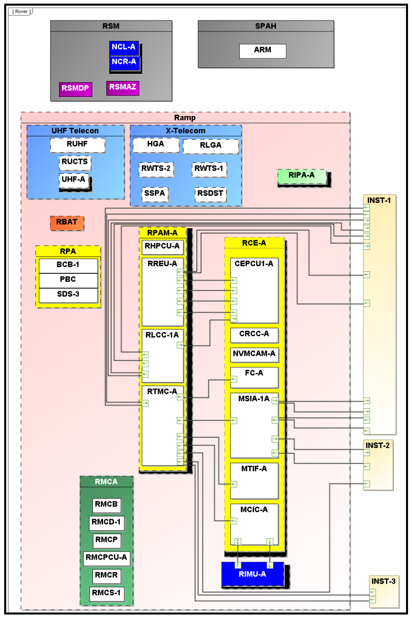
- Effectively in Phase C+ for much of the H/W and S/W design
- However, new mission, science objectives, and instruments
- Highly cost-constrained
- Leverage heritage via "build-to-print" philosophy

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

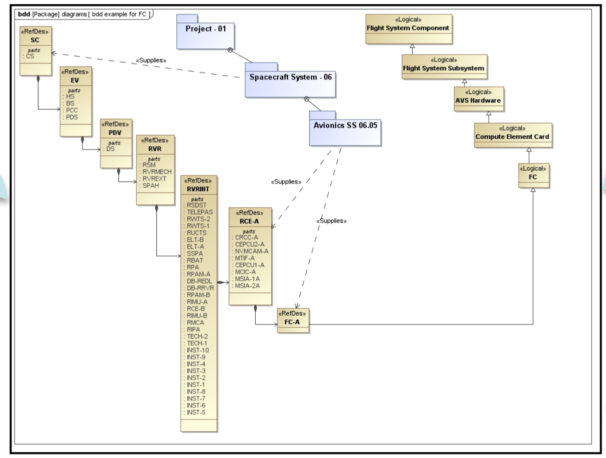
- Keep SE products updated with the ongoing design/developments/tests
- Sharing information across a diverse team avoiding information "silos"
- Improving the flow and traceability of design decisions and tests
- Managing cross-cutting complexity and understanding of scope
- Preempting the V&V "armageddon" 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)

Example System Modeling Products

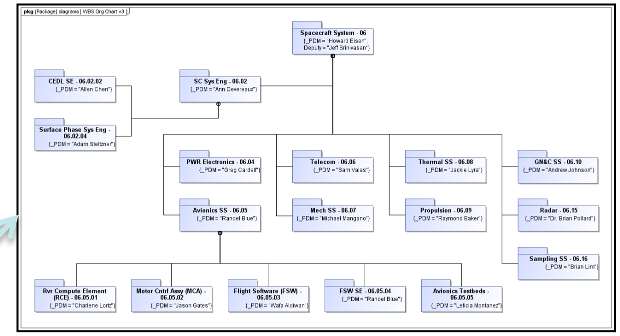
System Block Diagrams and Interfaces



Physical Decomposition, Logical Decomposition, and WBS

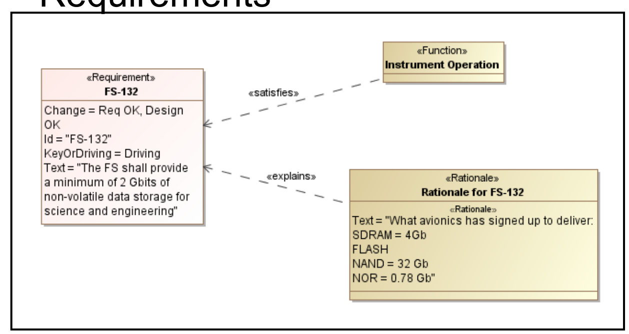


Org Chart



Linking information to core components (Reference Designators)

Assessment of Key & Driving Requirements



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

Flight System	Flight Quantity	CBE (kg)	MEV (kg)	Contin-gency (Percent)	Contin-gency Lev-el	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

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

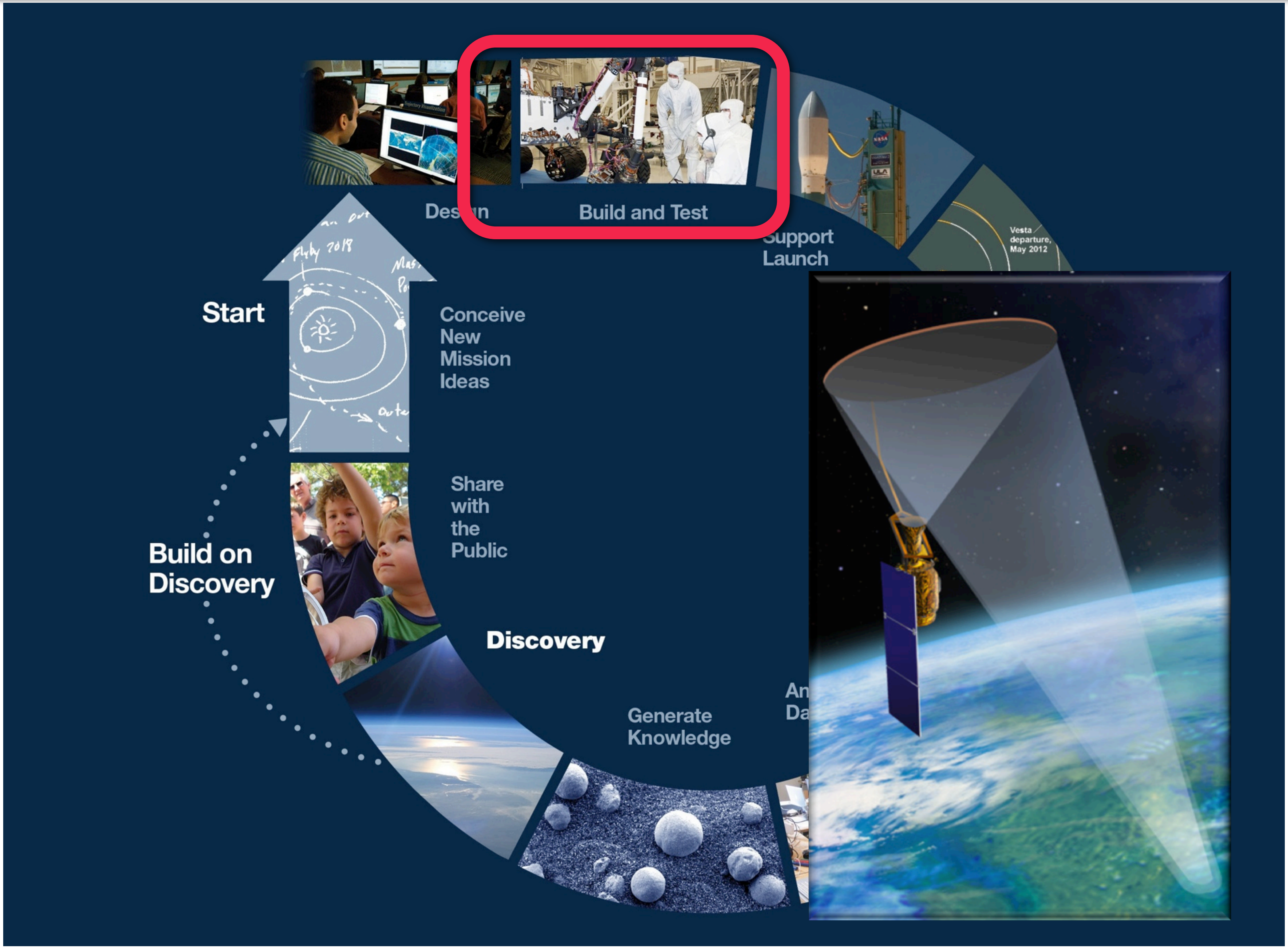
Early Assessment of Value & Benefits for Mars 2020

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.

"The model will help us with knowledge transfer and continuity as personnel come in and out of the project over the coming years."

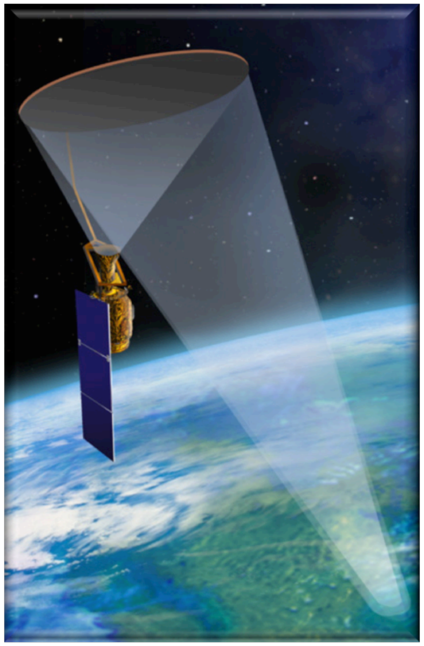
The Soil Moisture Active Passive (SMAP) Mission V&V



SMAP Pilots: Using MBSE for V&V

Motivation:

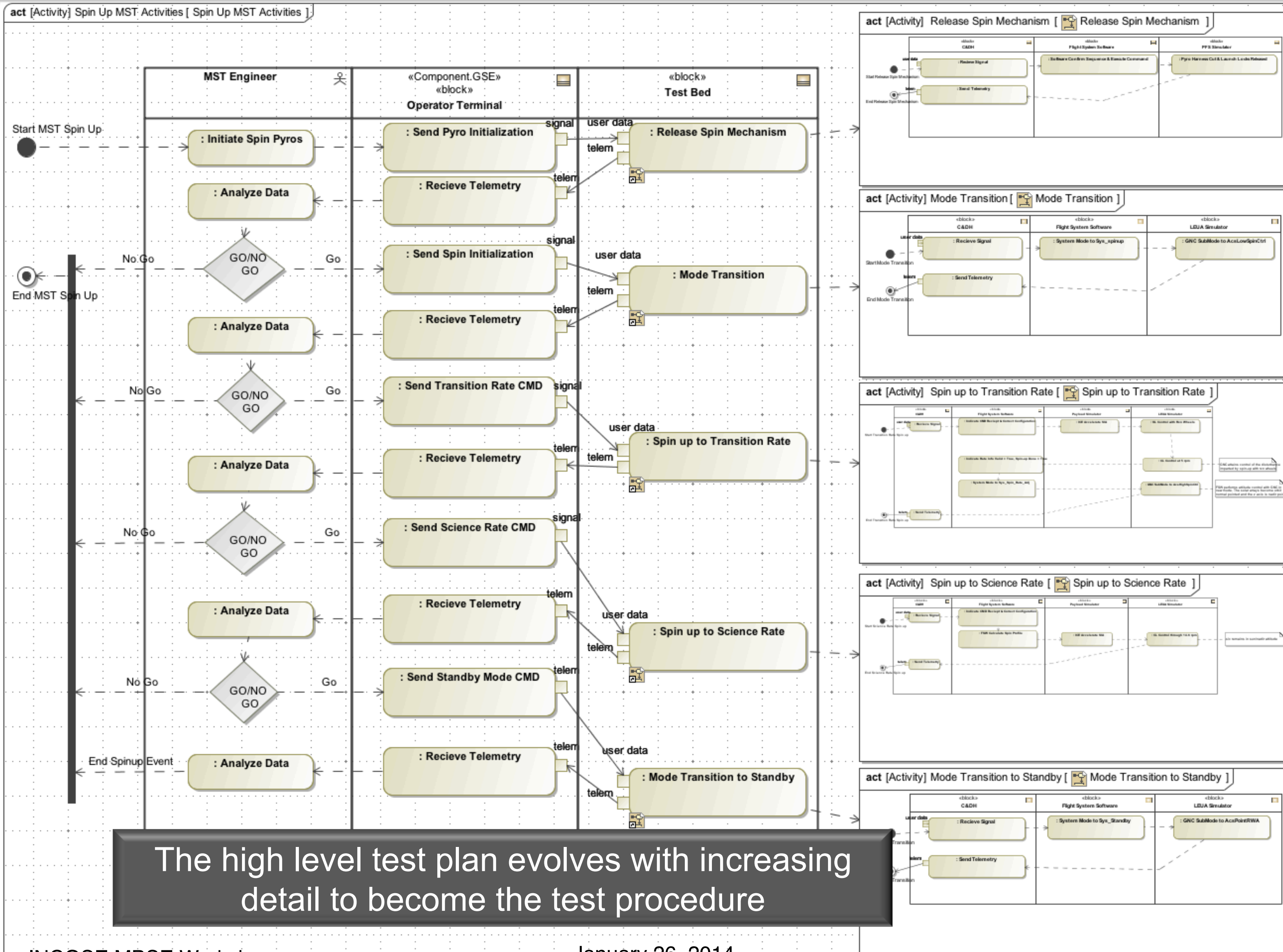
- The complexity (number of states) of flight and ground systems is increasing yet time for V&V is decreasing.
- The complexity of the test environment is increasing



Desired Value: Explore a greater state space in less time

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

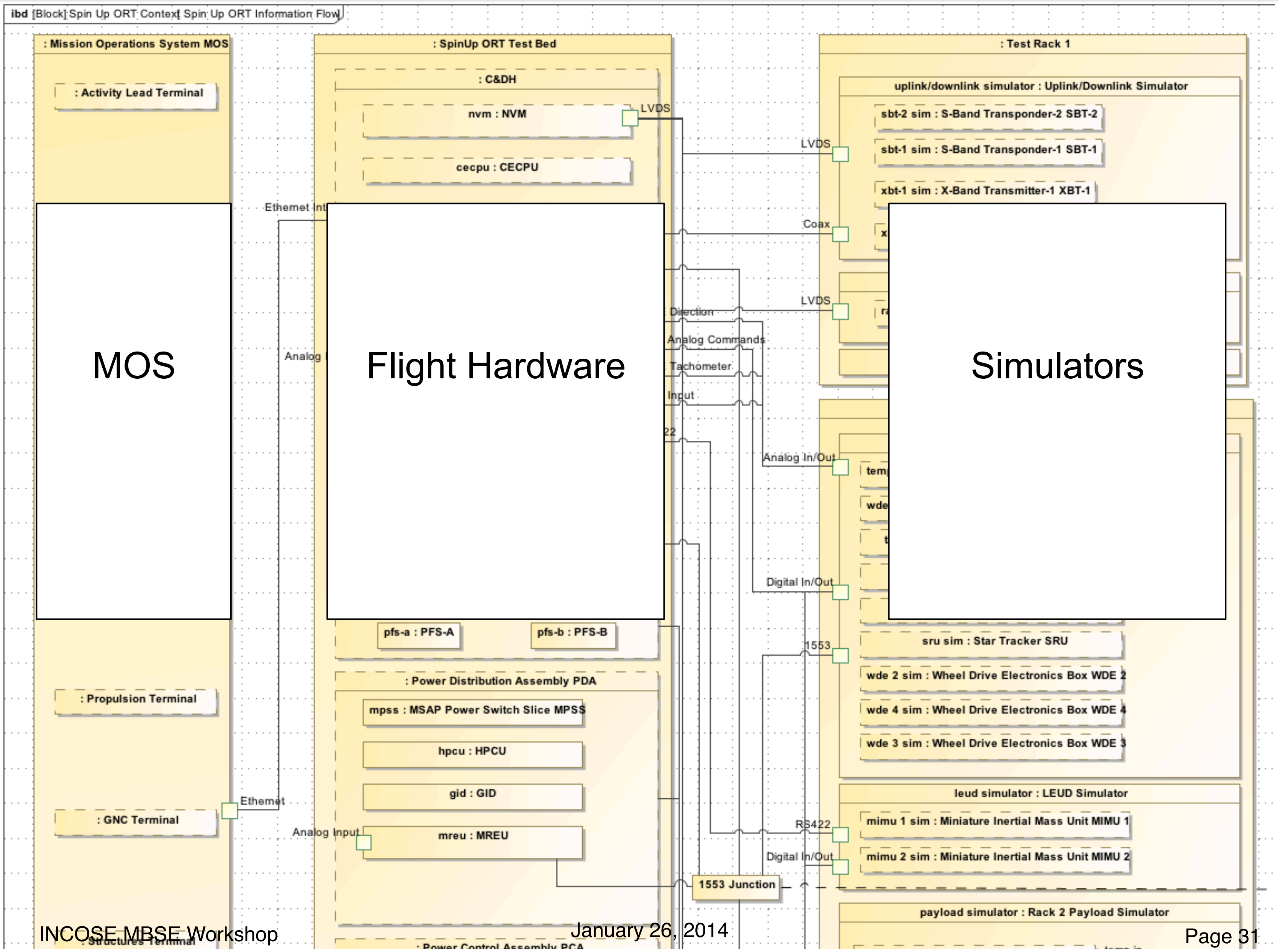
Products: Spin-up Mission Scenario Test Planning



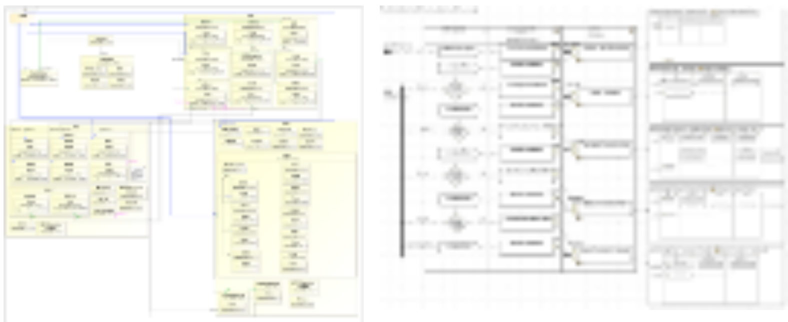
The high level test plan evolves with increasing detail to become the test procedure

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Products: SMAP Spin-Up Test Hardware & Software Configuration



I&T Product Development

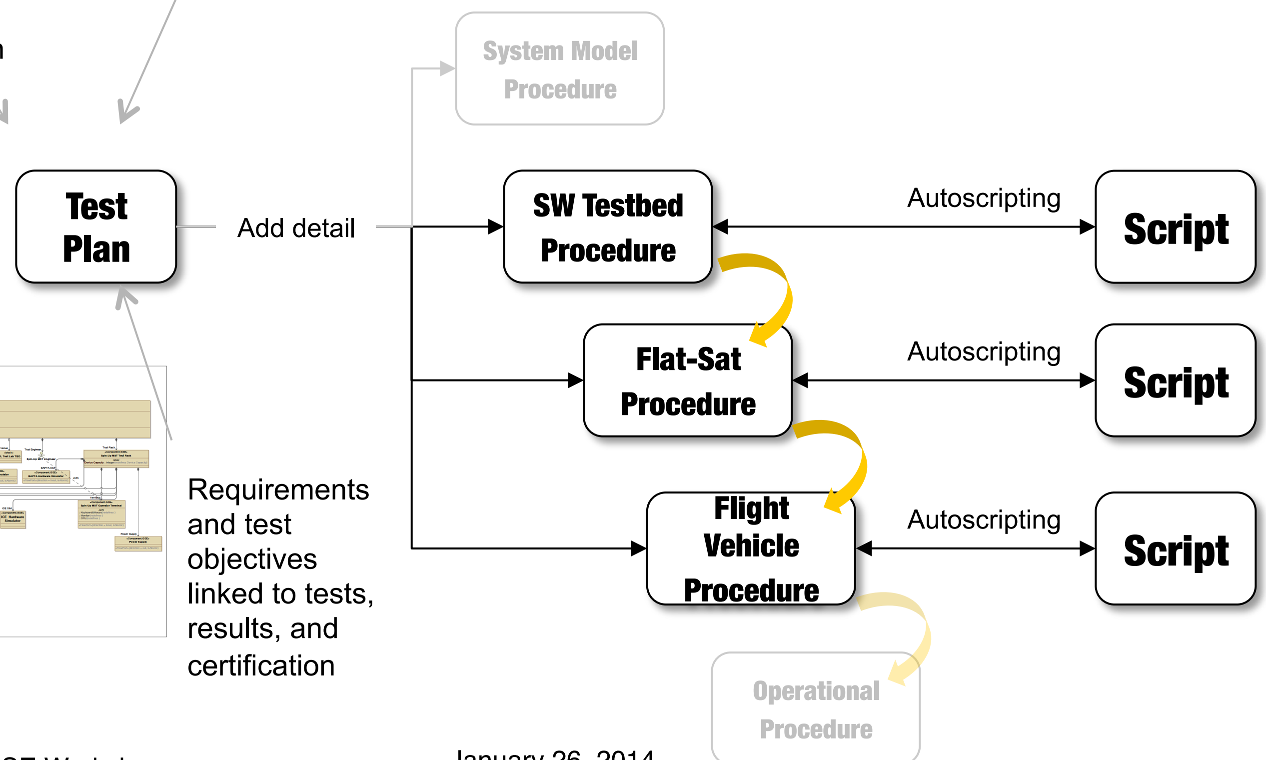


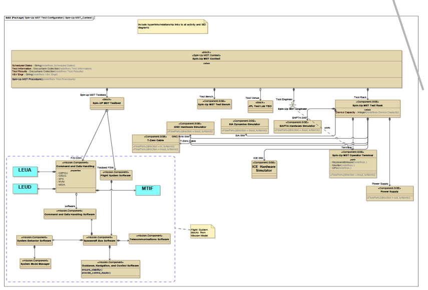
Test Procedures
(Activity Diagrams)

Supporting Tools and Infrastructure:
MagicDraw
DocWeb
IMCE
Autoscript tool
…

Sequence of Tests

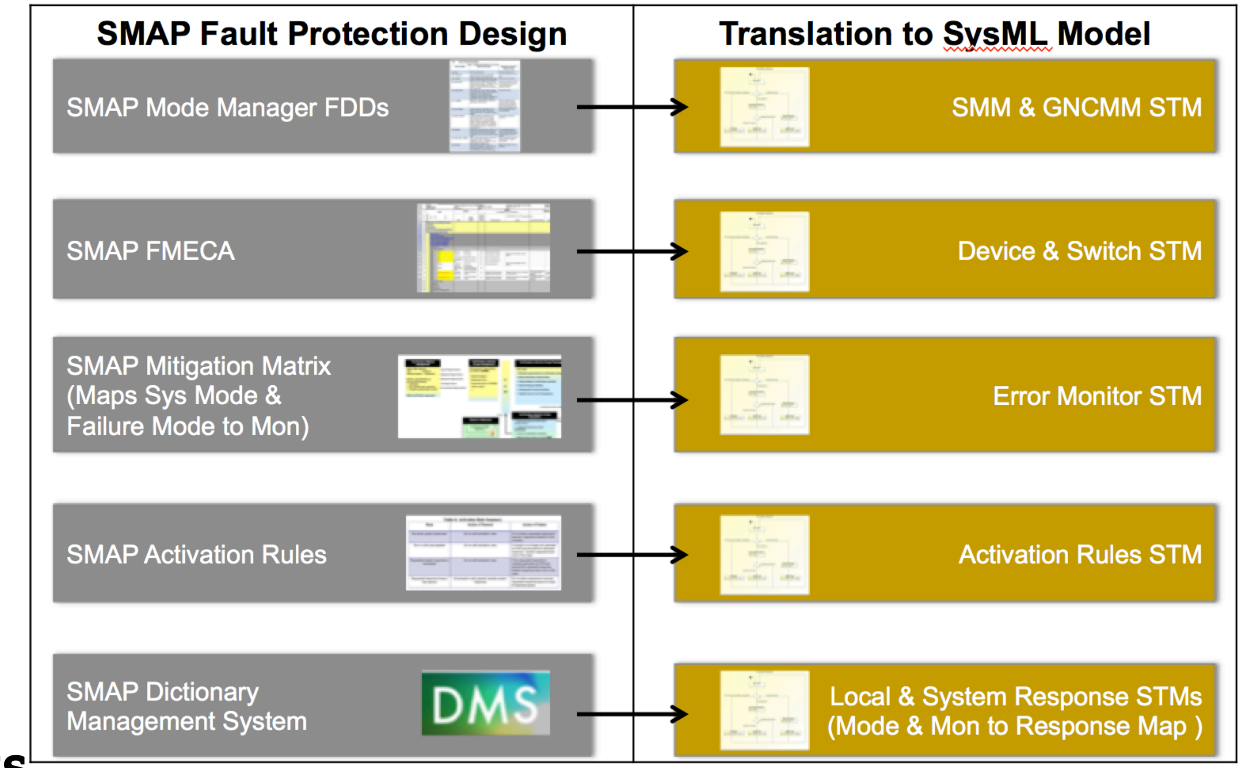
Equipment and configuration





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

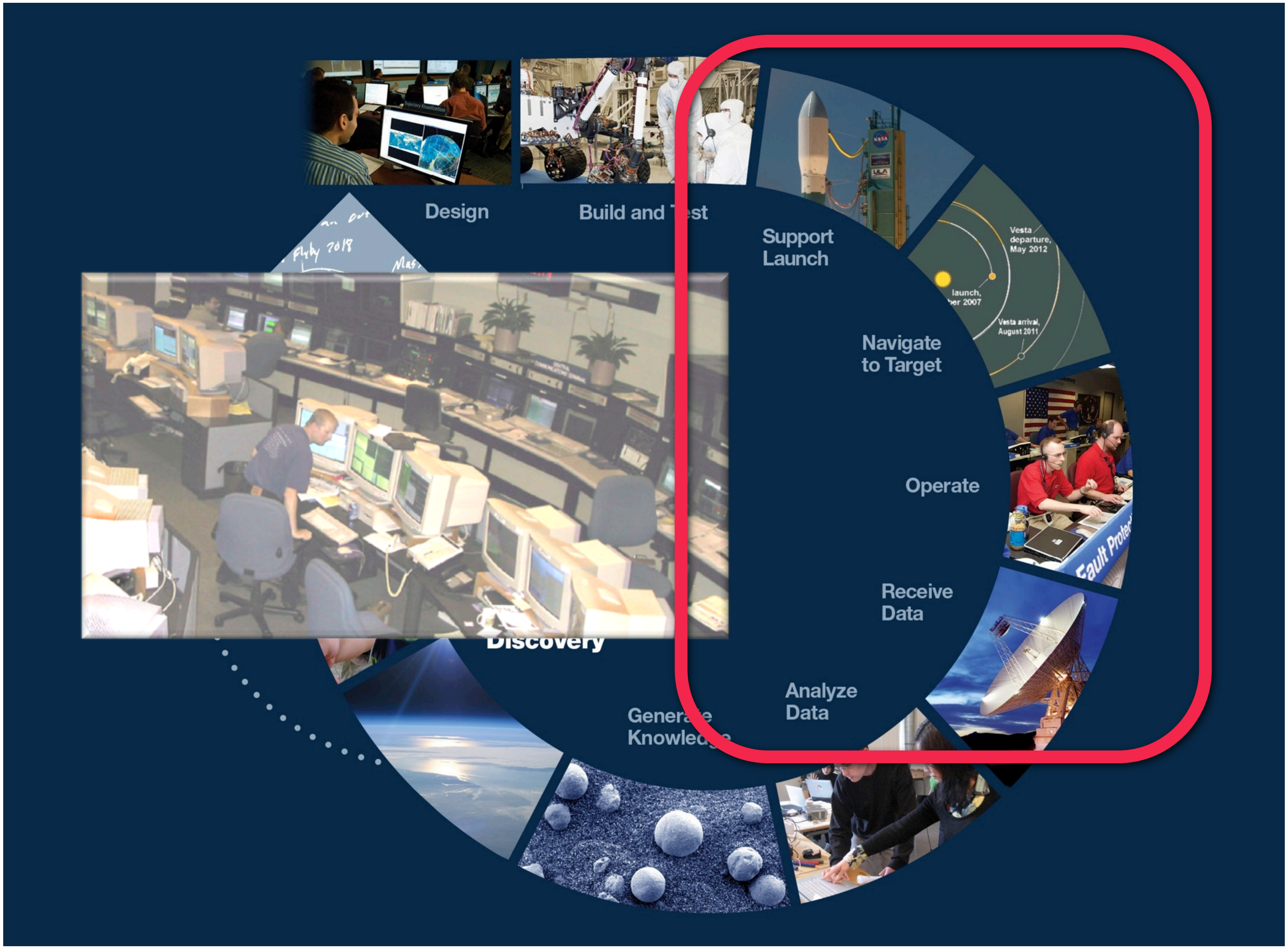
V&V Demonstrated Value

- **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**
  - 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

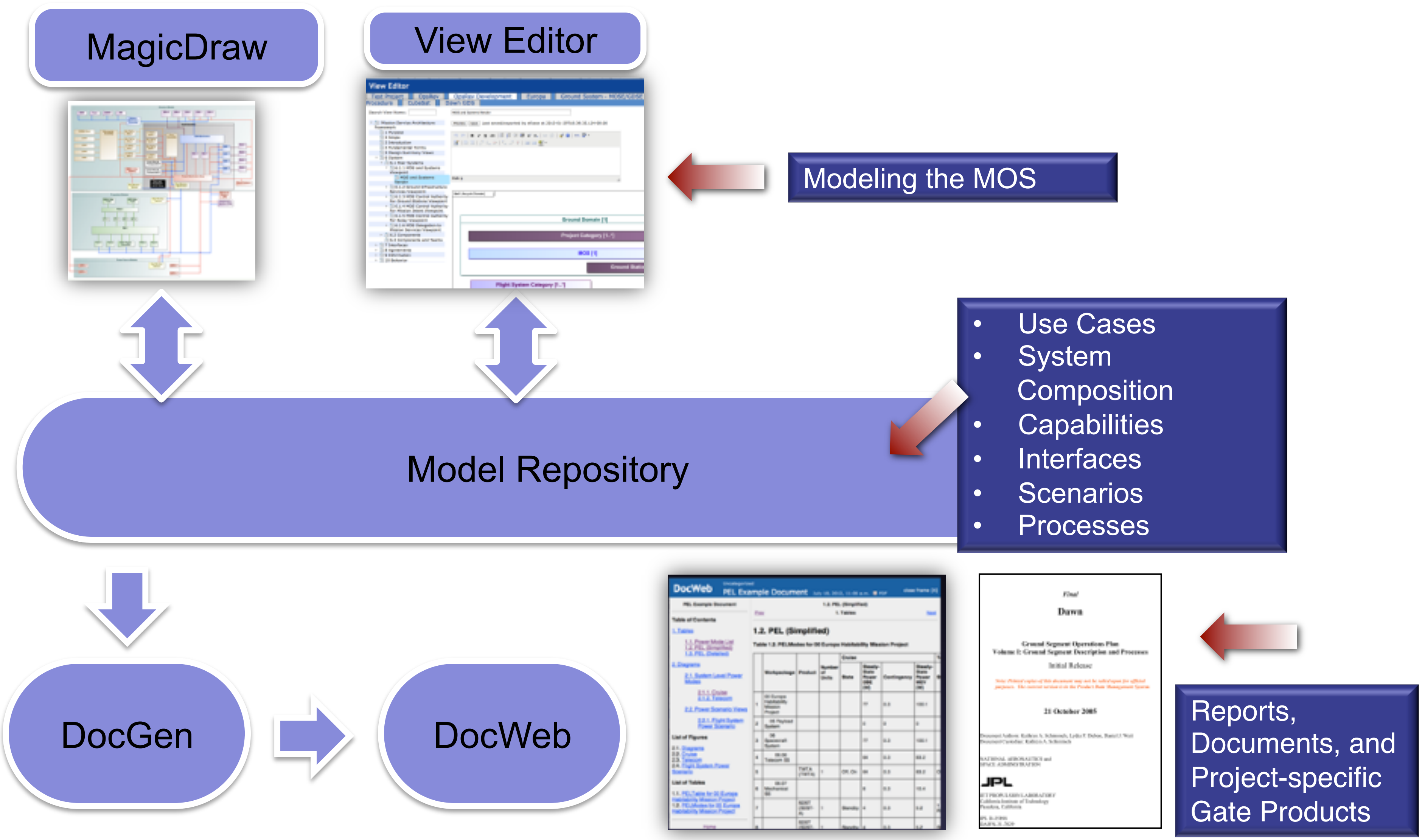
Motivation for Re-architecting Effort

– 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

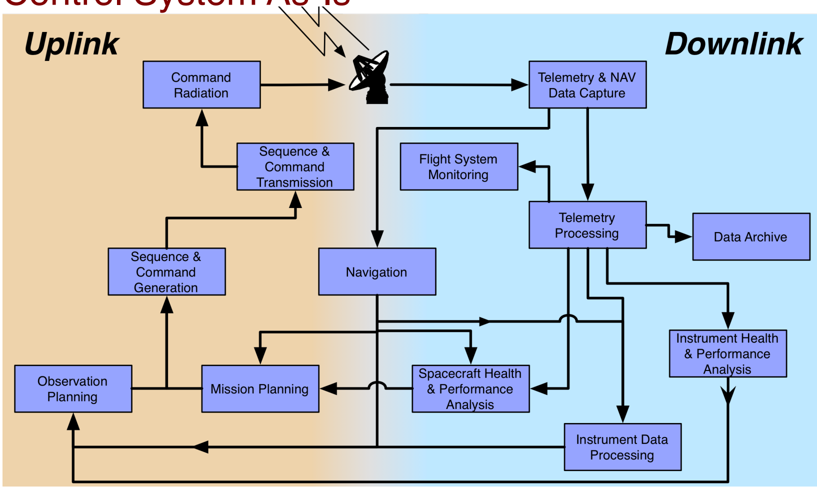


The Value of Using MBSE for the MOS

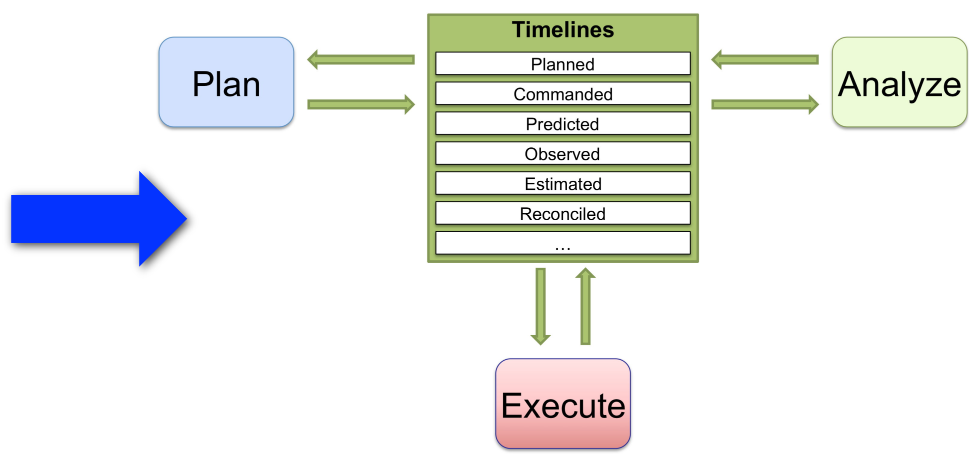
For Operations, MBSE Facilitates:

- 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.

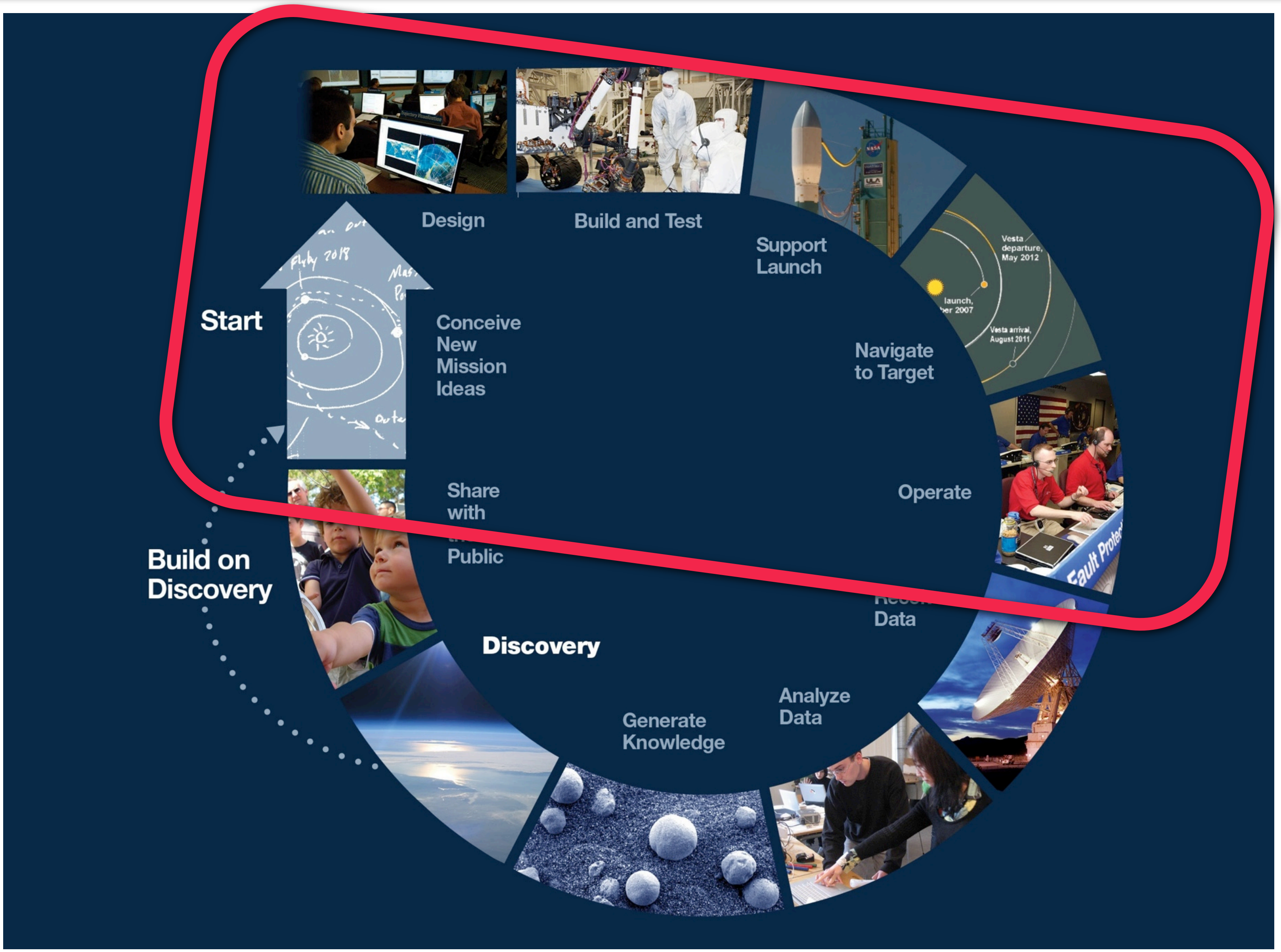
Control System As-Is



To-Be: A Timeline Based Control System



...but the Challenge is Infusion



How Did We Start?

- **Prior to FY'09**
  - MBSE started as a grass-roots effort
  - It was supported and championed by a few senior managers
- **FY'09-FY'12**
  - The concept of MBSE was introduced to Executive Management
  - Integrated Model Centric Engineering (**IMCE**) initiative was established with a moderate investment, but many were skeptical about the value and readiness of MBSE for prime time.
- **FY'13 – Present**
  - IMCE has gradually being accepted as an institutional strategic initiative
  - Some wait and see sentiment still exists
  - It is being sought out and used by previously skeptical engineering leadership because of its demonstrated value.

Multi-Year Strategy: Capabilities

Degree of Maturity

Phase 1: Building

Key Capabilities:

1. Cadre of trained MBSE modelers
2. Modeling infrastructure that facilitates collaborative modeling activities
3. Initial modeling standard
4. Modeling user's guide
5. Initial CM-controlled model repository framework w/ examples

Phase II: Maturing

Key Capabilities:

1. MBSE methodology that supports systems & software development
2. Modeling framework that enables model/tools integration
3. Standard design views and viewpoints that support:
   - capturing technical designs in formal models
   - performing reviews based on formal models
4. Standard set of modeling tools are established and supported
5. CM-controlled repository populated with validated reusable models created from formulation to implementation

Phase III: Integrating

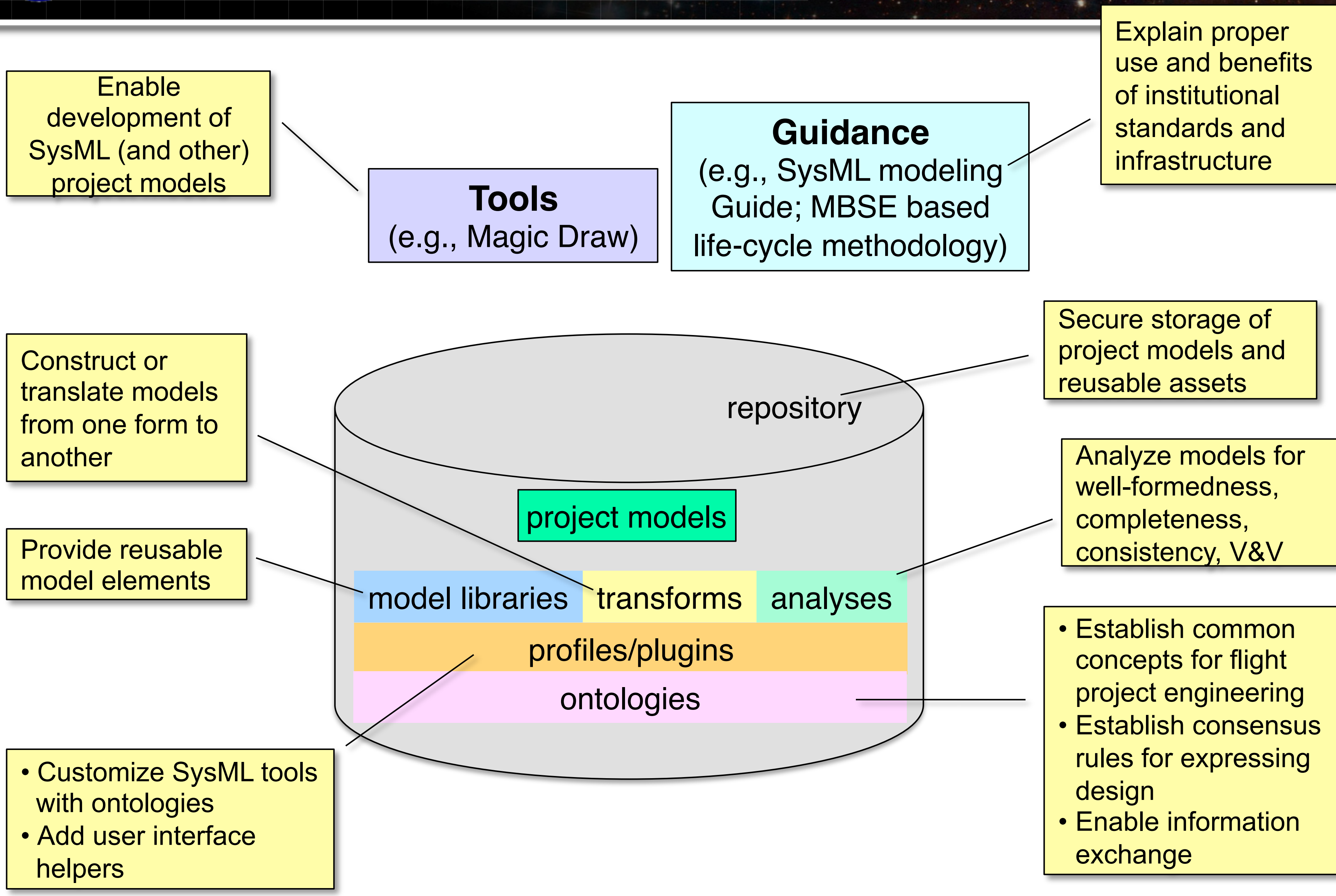
Key Capabilities:

1. A fully operational modeling Infrastructure that enables integration of system models with domain discipline analytical models, simulation/visualization models to support:
   - Design to cost
   - Reviews
   - Trade study…
2. A matured model-based development methodology with training support
3. A fully CM controlled operational model repositories that collaboratively managed by projects, lines and Institution

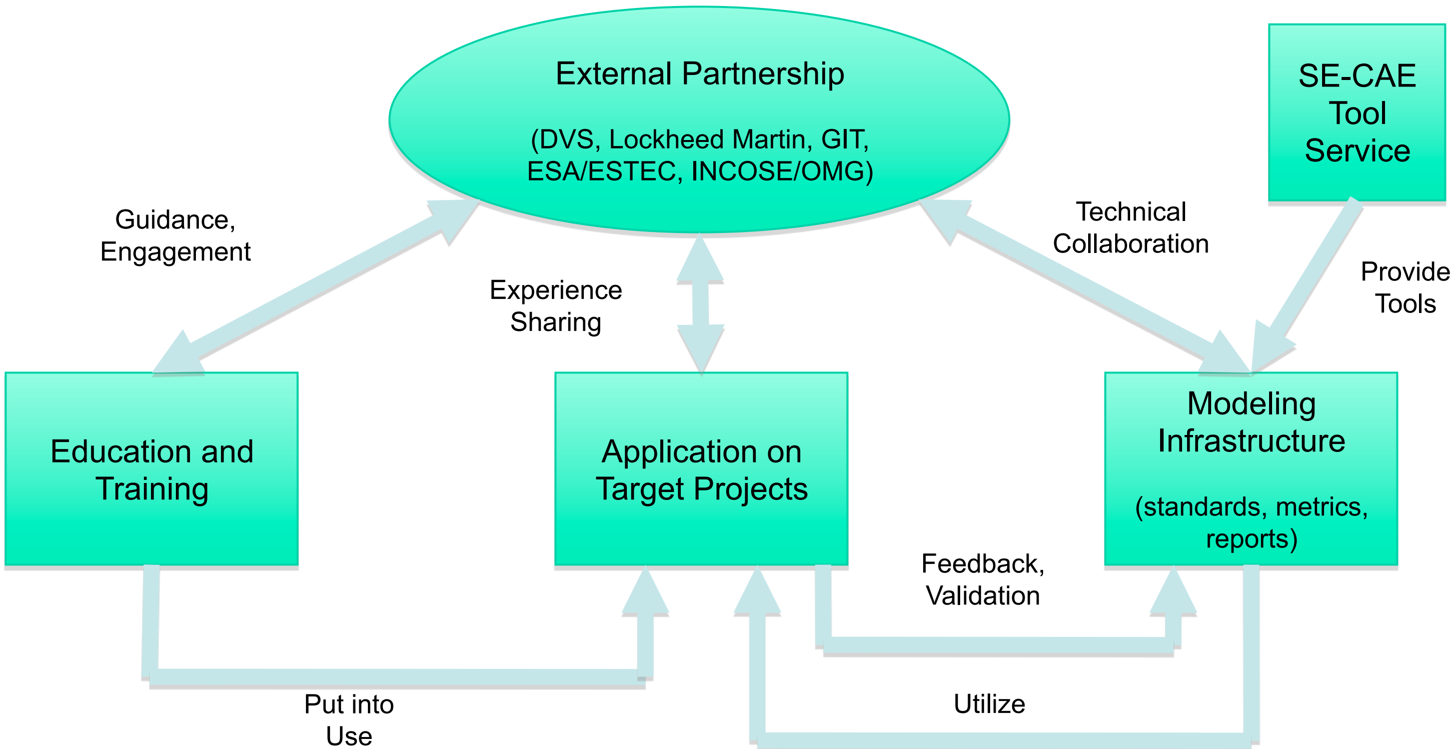
Continuous Practice

FY09 → FY16

Modeling Infrastructure Elements



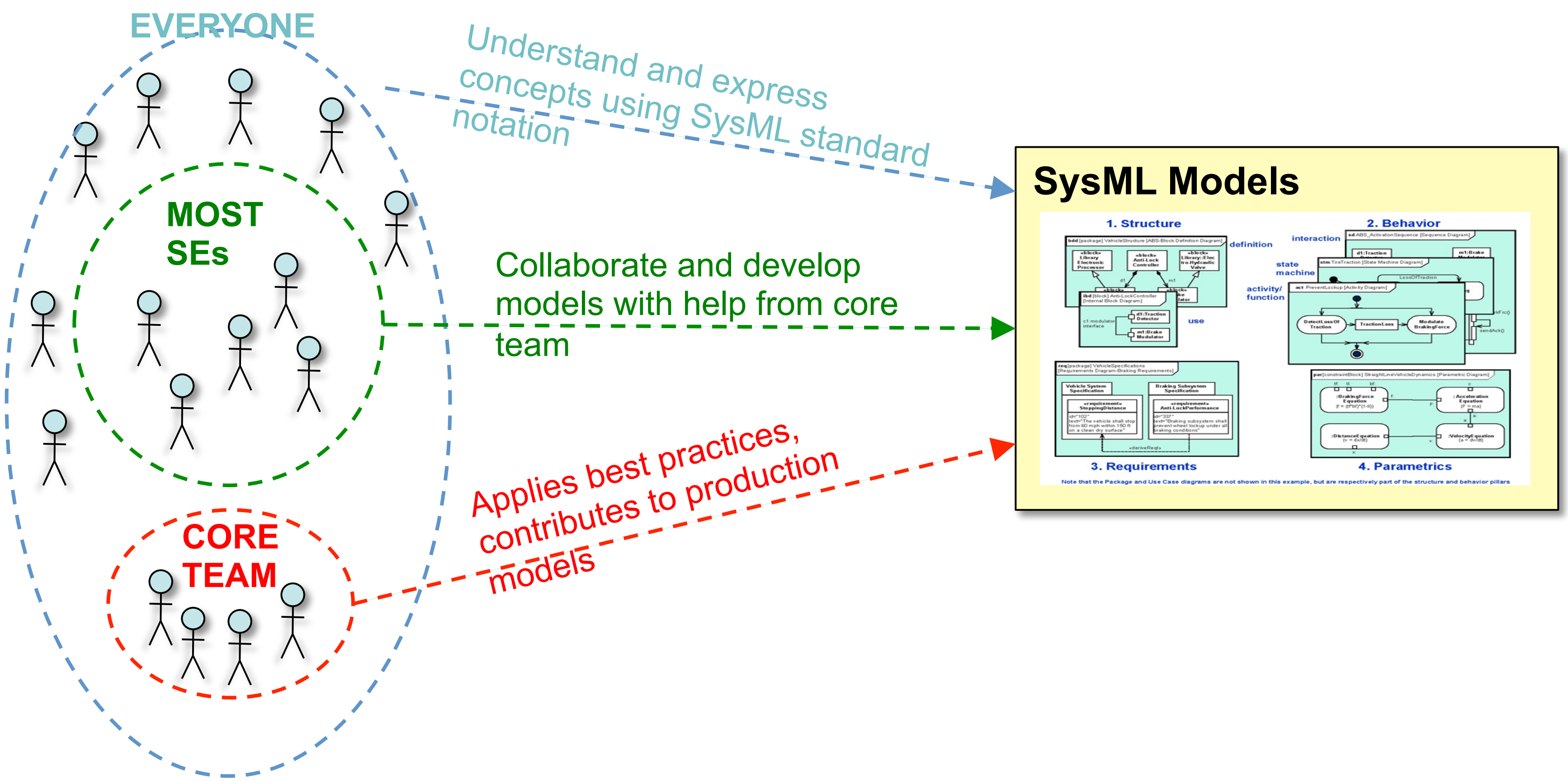
Key Infusion Elements and their Relationships



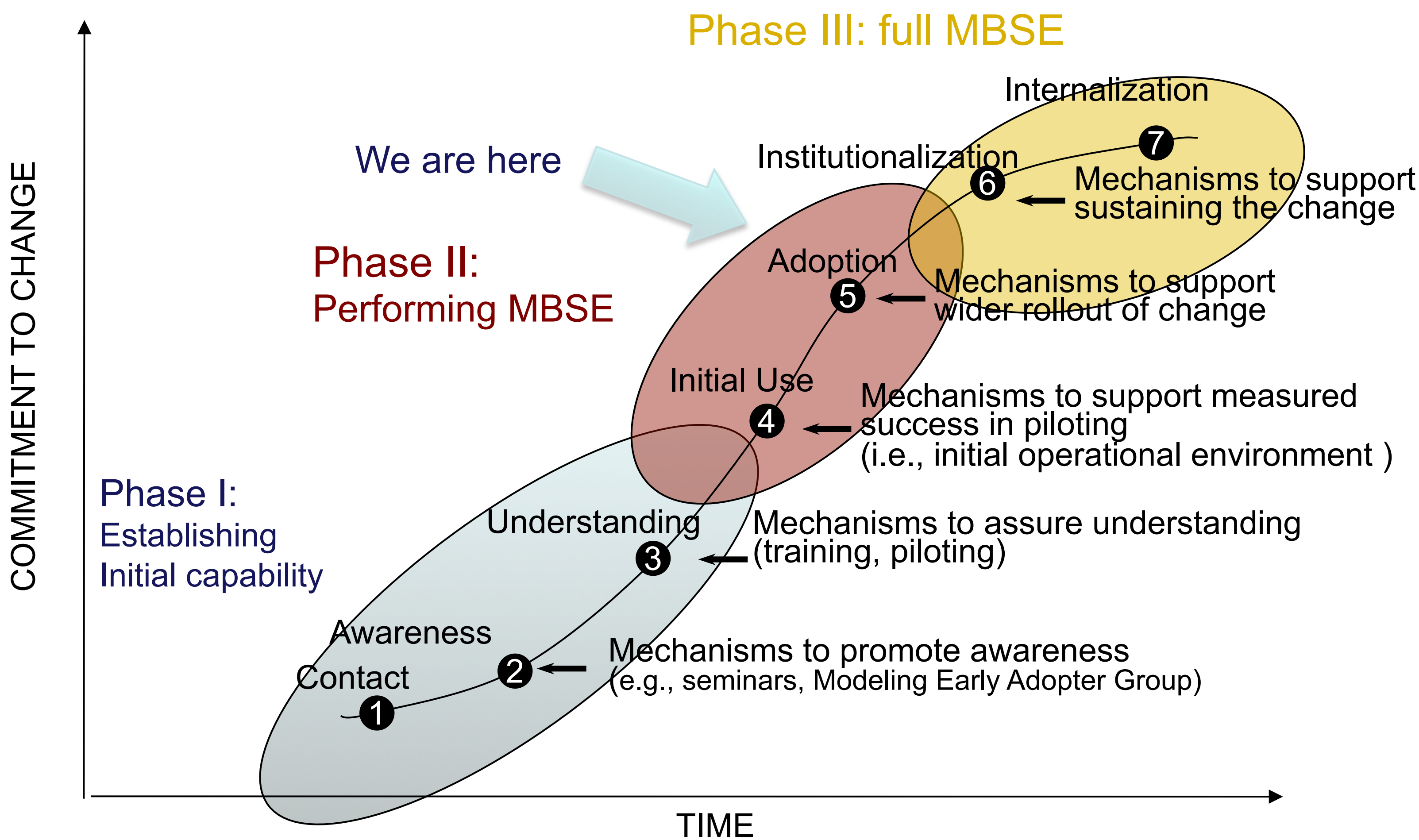
Multi-pronged approach

- **Educate and train an initial cadre of modelers**
  - Pair domain experts with early career hires
- **Build on grass-roots efforts**
- **Work with strong advocates and advisors consisting of international and national experts**
- **Establish an institutionally-supported modeling environment**
  - Define modeling standards, enable collaborative modeling effort, build a reusable model repository; provide support to system model developers
  - Address usability issues with SysML and modeling tools
- **Identify and build applications**
  - Develop system models that have immediate benefits to project's needs
  - Put training into practice
  - Modelers partner with project's system engineers to get early buy in
  - Use the initial application to validate the reusable modeling environment
- **Partner with industry, INCOSE, academia and OMG to learn, contribute and stay current**

The New SE Team Composition

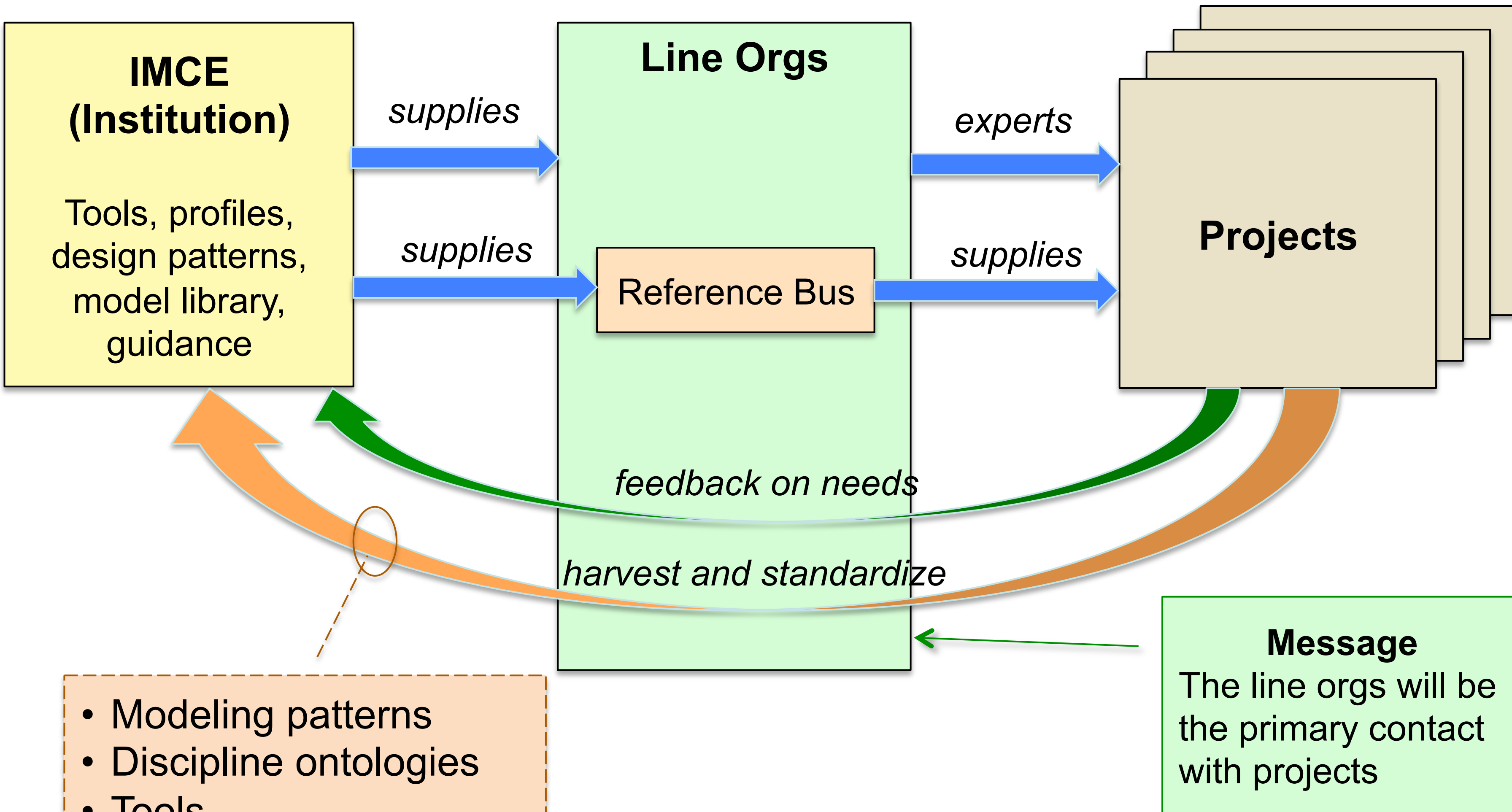


MBSE Infusion Model and Where We Are



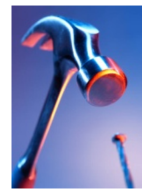
Adapted from Out from Dependency: Thriving as an Insurgent in a Sometimes Hostile Environment, SuZ Garcia and Chuck Myers, SEPG Conference, 2001

Infusion and Institutionalization Framework
Steady state scenario



Supporting Change

- **Carrot**
  - Rewards and recognition



- **Stick**
  - Integrate into standard practices

- **Evangelism**
  - A persistent and consistent message from management
  - Provides awareness and distinctions

- **The X-Team* approach**
  - Go “outside” – make external outreach a *modus operandi* from day 1

* *X-Teams: How To Build Teams that Lead, Innovate, and Succeed* (Harvard Business School Press, 2007)

Summary

Infusion Success

It's the results

It's the support

It's the people

….Thank You!

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