Jet Propulsion Laboratory
California Institute of Technology

Requirements Analysis and Verification for the Thirty Meter Telescope with OpenMBEE and the OpenSE Cookbook

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Outline

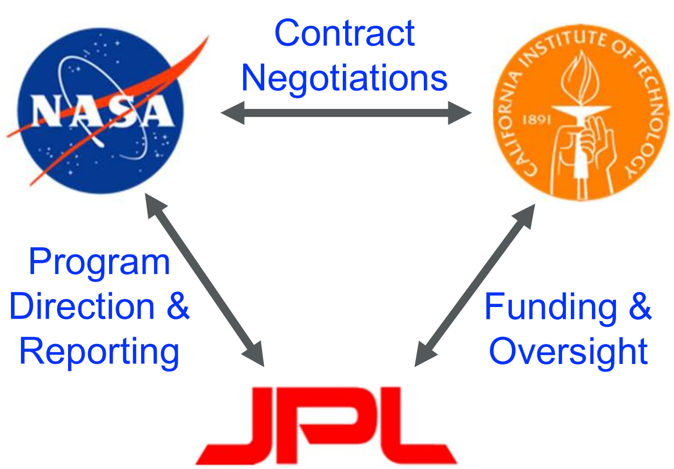
- Introduction
- Thirty Meter Telescope Project (TMT) and MBSE
- OpenSE Cookbook
- TMT Requirements Verification
- JPL Systems Environment
- Summary & Conclusions

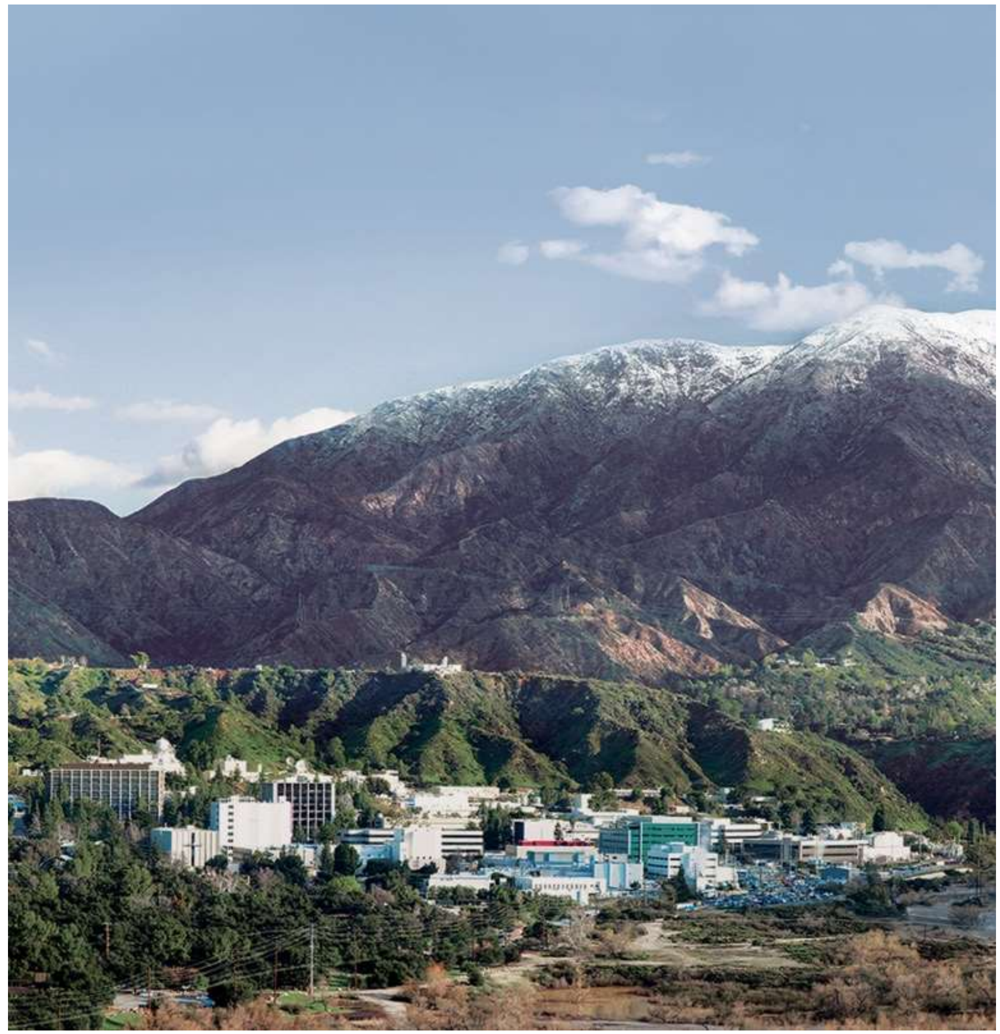
Who is Robert?

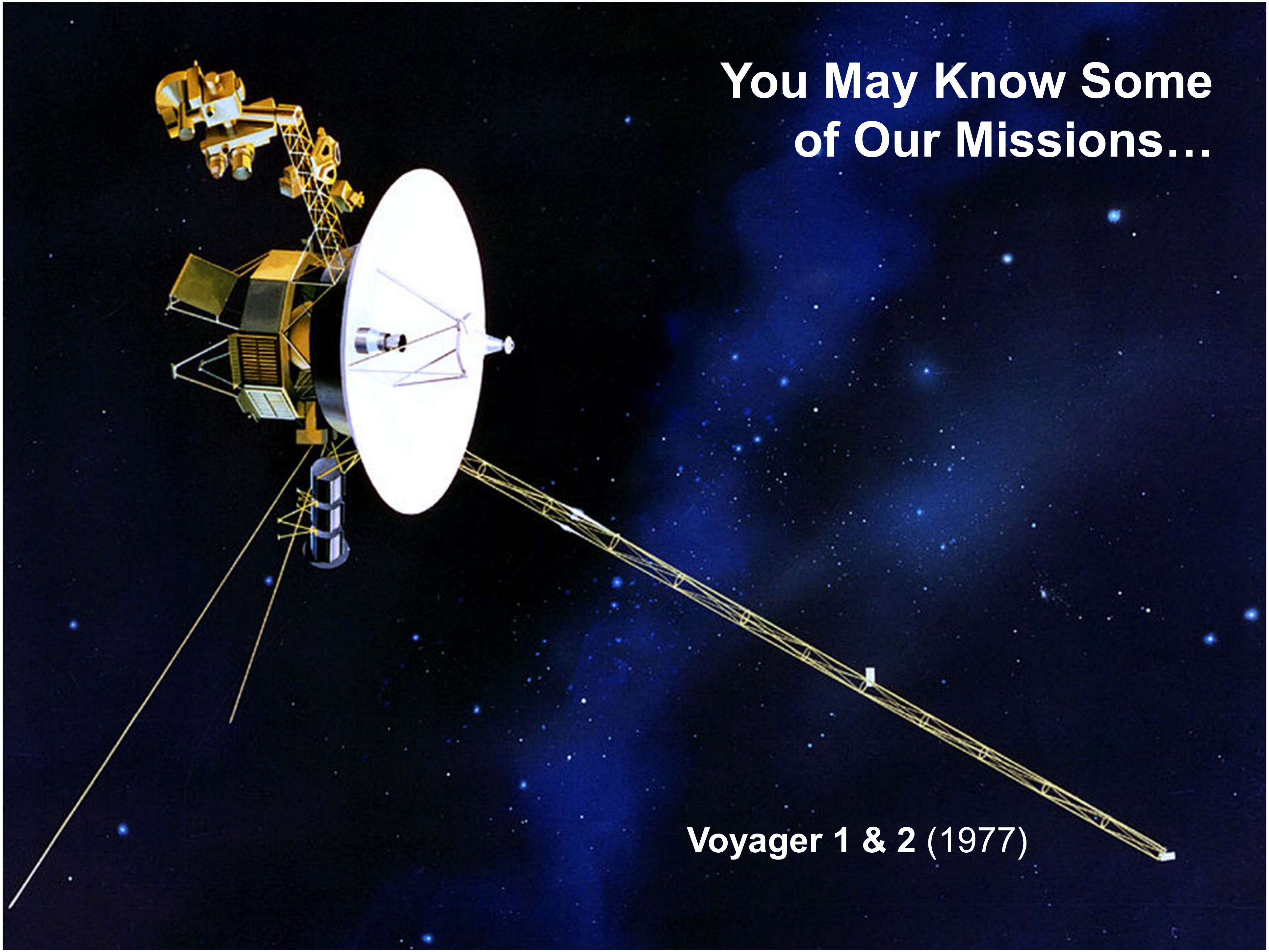
- CAE Project Systems Engineer
  at NASA's JPL - USA
- Member of INCOSE
- Formerly Control System/Software Engineer and Architect at:
  - European Southern Observatory – Germany, Chile
  - CERN – Switzerland/France
  - Siemens Healthcare - Austria
- M.Sc. Computer Science (Austria)

NASA Jet Propulsion Laboratory (JPL)

- Located in Pasadena, CA
- NASA-owned *"Federally-Funded Research and Development Center"*
- University-operated
- ~5,000 employees






You May Know Some of Our Missions…
Voyager 1 & 2 (1977)

JPL's Mission is Robotic Exploration

Mars Science Laboratory (2012)

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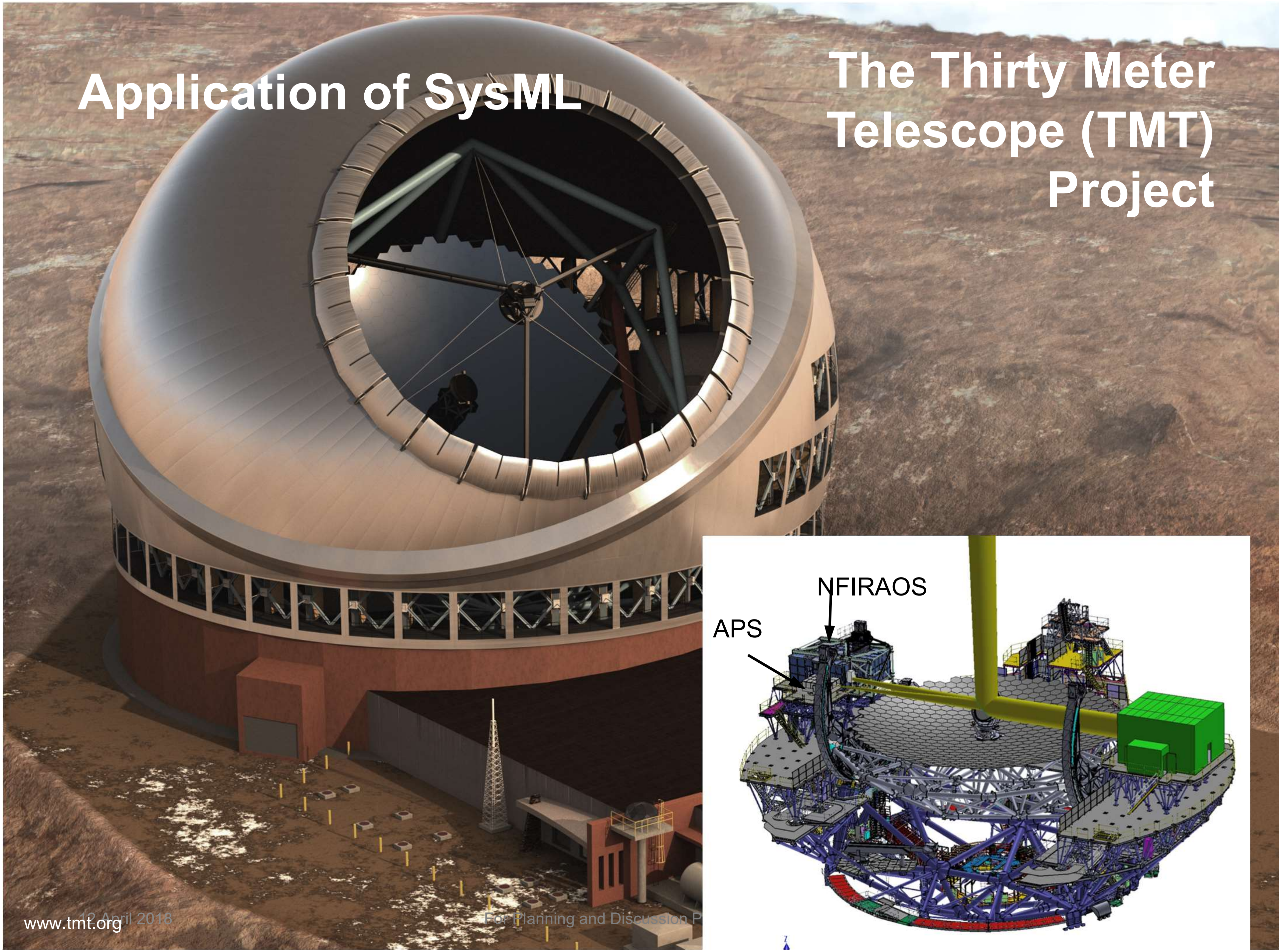
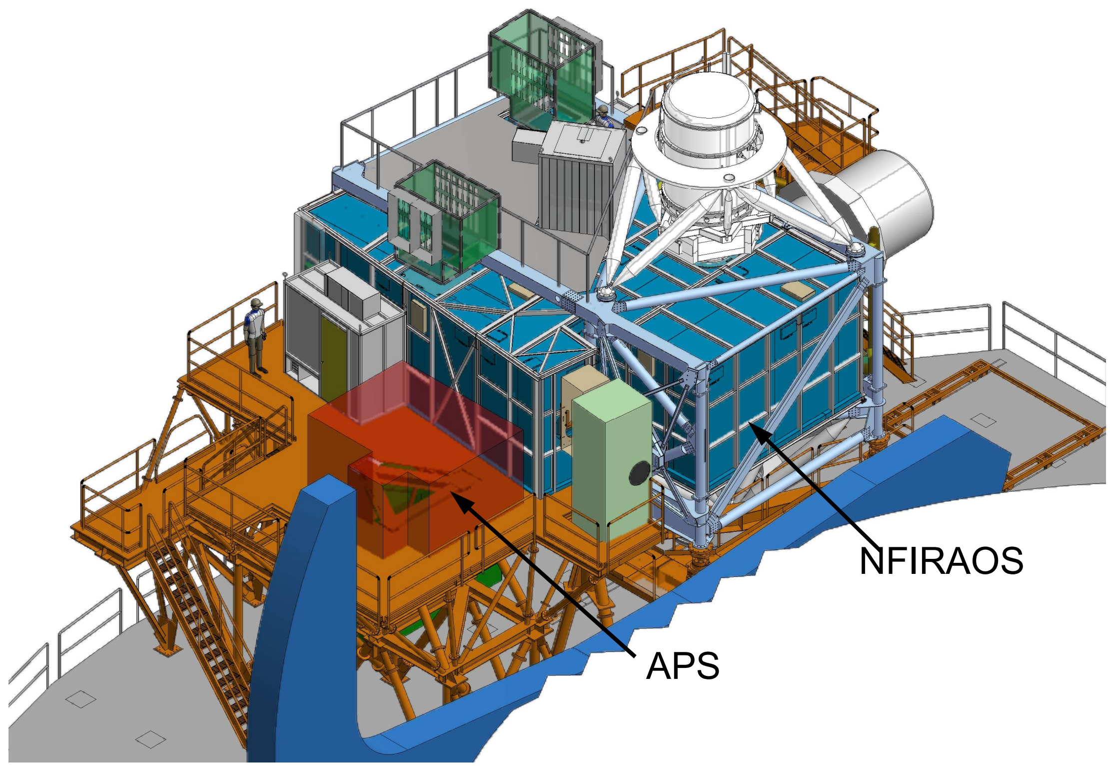
Application of SysML

The Thirty Meter Telescope (TMT) Project



Alignment and Phasing System (APS)

- Alignment and diagnostic instrument located on a Nasmyth platform
- Modified Shack-Hartmann wavefront sensor
- Responsible for pre-adaptive optics wavefront quality
- Uses starlight to measure wavefront errors and determine commands to send for aligning optics



TMT applies "Hybrid" Systems Engineering Approach

Traditional SE

- Clear, defined deliverables
- Easily accessible
- Shallow learning curve
- Simple traceability

MBSE

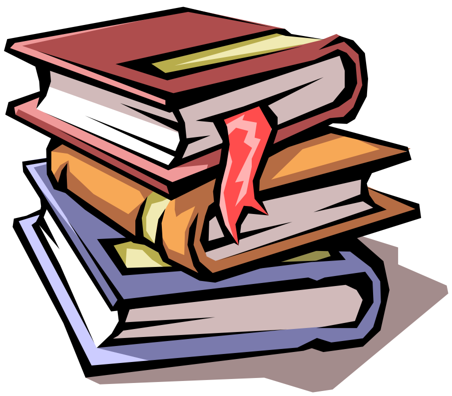
- Understanding behaviors of a system
- "Rich" capability to represent complex systems

Exploit the advantages of each approach

Model Based Systems Engineering

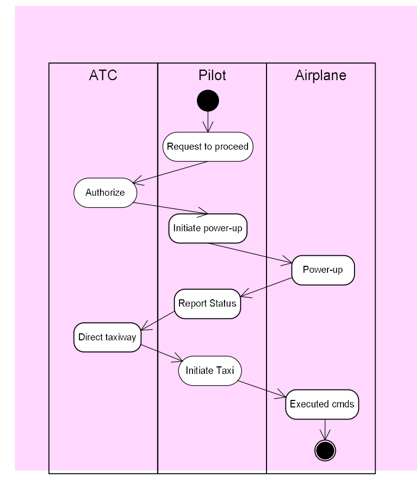
- MBSE is the formalized application of modeling techniques to support system requirements, design, analysis, verification, validation and documentation activities
- MBSE expresses a system using a Systems Modeling Language (SysML), a profile of UML
- MBSE is often applied with a method like Object Oriented System Engineering Method (OOSEM)
- OOSEM maps onto the ISO systems engineering process and integrates top-down (**functional decomposition**) approach with **model-based** approach

Present



- **Specifications**
- **Interface requirements**
- **System design**
- **Analysis & Trade-off**
- **Test plans**

Future



Moving from Document centric to Model centric

TMT MBSE Objectives

- Define an **executable SysML model**
- Use the model to **analyze the system design and verify requirements** on power consumption, mass, duration, pointing errors, …
- Produce **engineering documents**
  - Requirement Flow Down Document
  - Operational Scenario Document
  - Design Description Document
  - Interface Control Documents
- Use **standard languages and techniques, and COTS tools where practical** to avoid custom software development

Applications of MBSE with SysML at JPL

- JPL is already applying MBSE practice in a wide variety of projects, across a number of lifecycle phases
  - Planned mission to Europa / Europa Clipper
  - Mars 2020 (next Mars Rover)
  - InSight
  - Thirty Meter Telescope
  - Ground system development
  - Mars Sample Return
  - Cyber security
  - ...

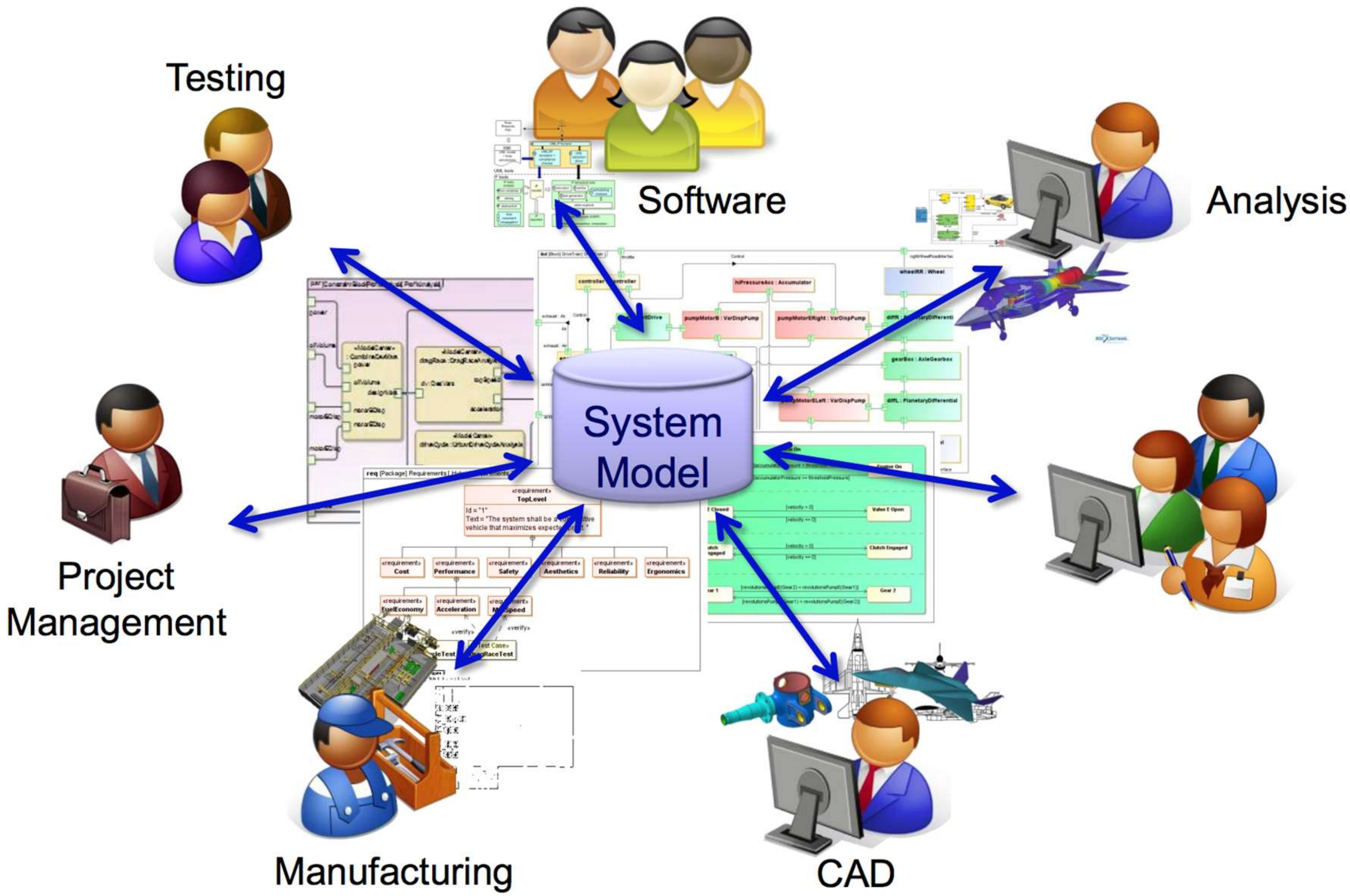
Not just spacecraft missions! Not just early phases of design!

- MELs, PELs, resource allocation and analysis, system decomposition, libraries / capturing reusable models, etc.

➔ We use MBSE to do SE

MBSE is Much More Than Just Applied SysML

Information Management Across All Disciplines and the Life Cycle



Source: Paredis, 2012

TMT MBSE follows a well defined Modeling Approach

- Object-Oriented Systems Engineering Methodology (**OOSEM**), but with additional activities focusing on building an executable model (= specification)
- Use case driven model development
- Challenges:
  - JPL is a **supplier** for a number of subsystems of the TMT (the **customer**)
  - Model is used by a number of teams, including TMT

ESEM = OOSEM + Executability

Executable SE Approach focuses on Key SE Artifacts

- Emphasize executable models to enhance understanding, precision, and verification of requirements
- Executable Systems Engineering Method (**ESEM**) augments the OOSEM activities by enabling executable models
  - ESEM defines executable SysML models that verify requirements
  - Includes a set of analysis patterns that are specified with various SysML structural, behavioral and parametric diagrams
  - Also enables integration of supplier/customer models and analysis

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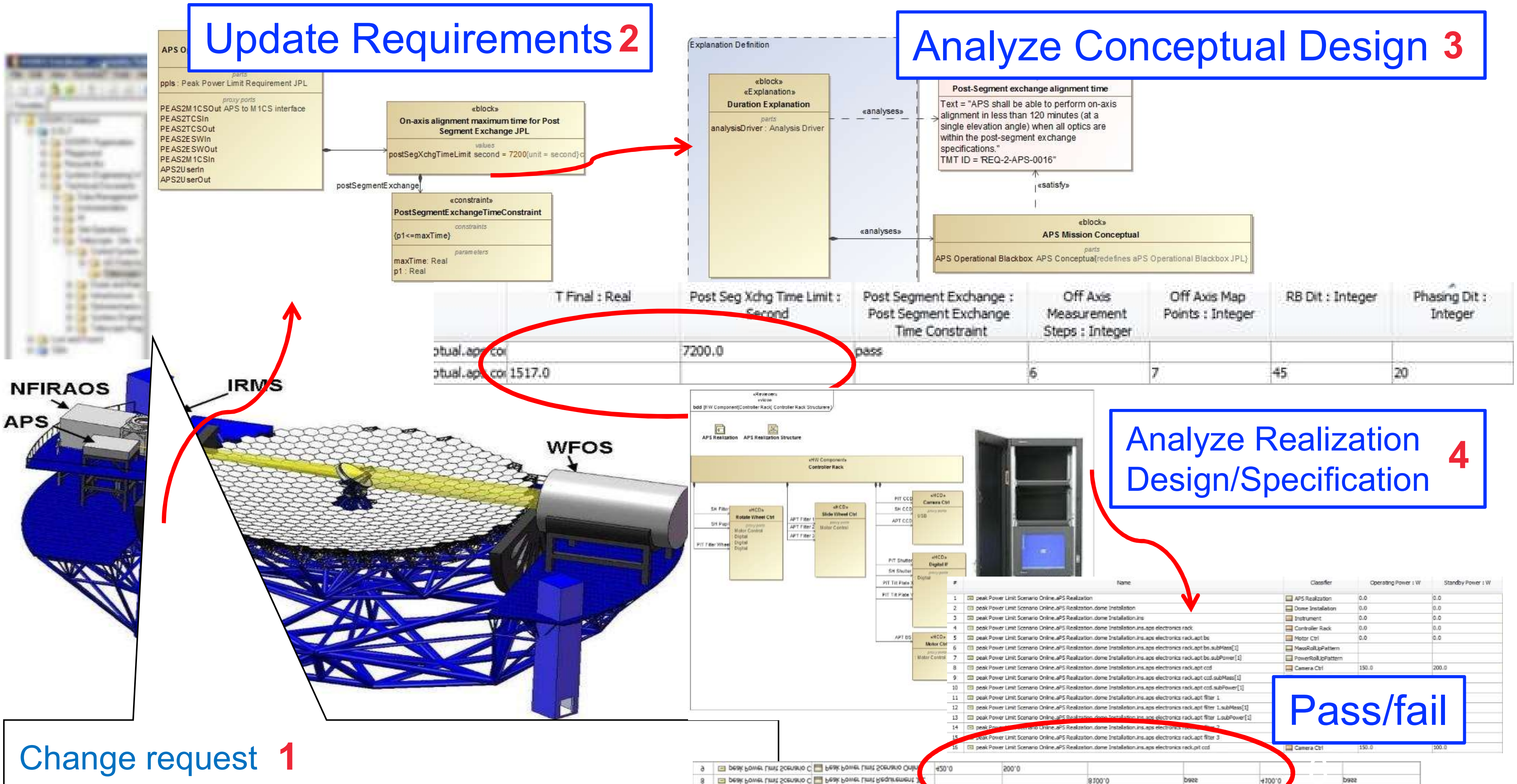
OpenSE Cookbook addresses Systems Engineering Concerns

- Provides goal oriented guidance using patterns, e.g.
  - How-to Verify Requirements
  - How-to Roll-up Technical Resources
- Driven by Systems Engineering Workflows
- Enables combining patterns into more complex recipes
- Demonstrates how to build system models with available tooling - How/where do I start?
- Includes known usages in TMT production model as reference
- Commoditizes Executable Systems Engineering

TMT Analysis workflows drive the OpenSE Cookbook



Change request 1

Max duration Post-segment exchange: ~~7200s~~ 5000s

Number of exposures of 45s 4 ~~6~~

Max peak power consumption in dome: 8.5kw ~~8.1kw~~

Number of motors with 50W 10 1~~2~~

Produce Engineering Documents 5

Systems Model is developed according to ESEM using Cookbook Patterns

- Define APS Mission boundaries
- Elaborate Conceptual Architecture
- Capture Component Behavior and Characteristics
- Specify Interactions between Components
- Run Analyses

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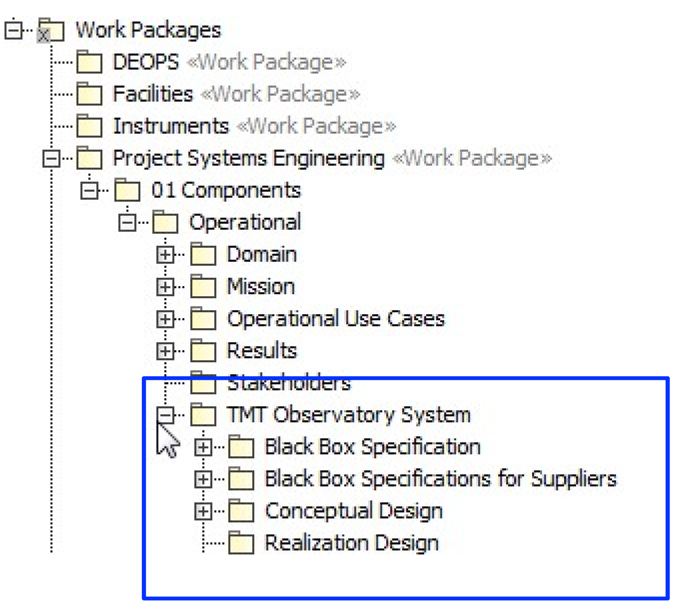
Requirements Verification

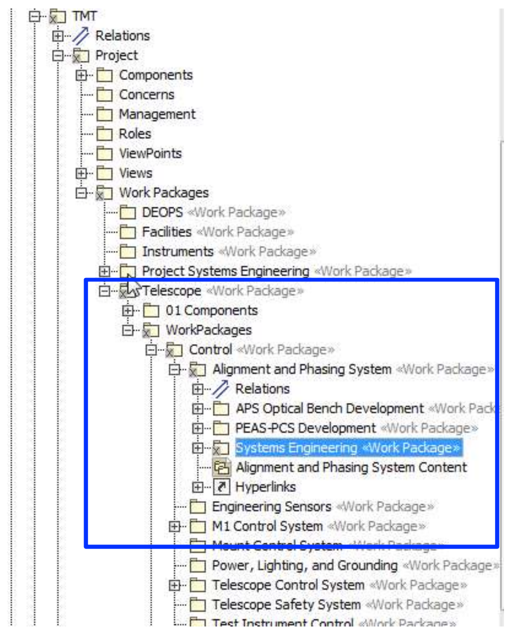
- **Intent**
  - Validate requirements, verify as designed system against requirements and publish analysis results
- **Cookbook Volume**
  - System Requirements Management
- **Educational example**
  - Autonomous Ferry Transportation
- **Known Uses**
  - APS - Post-segment exchange timing requirements
- **Tooling**
  - Cameo Systems Modeler and Simulation Toolkit, View Editor
- **Notes**
  - Property Based Requirements links Requirements Management and System Design

Package Organization

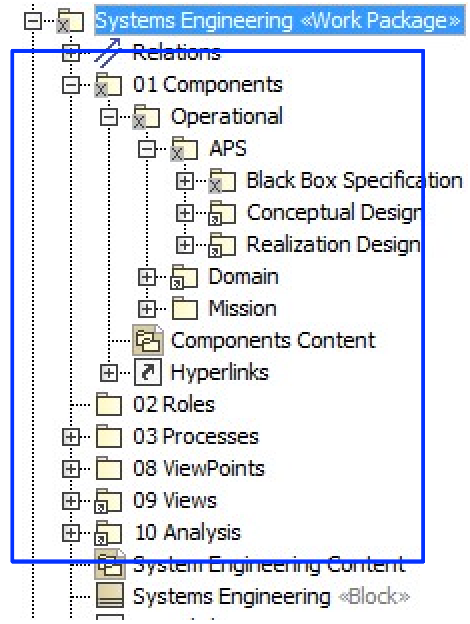
Model Organization Principles



Customer / supplier relationship



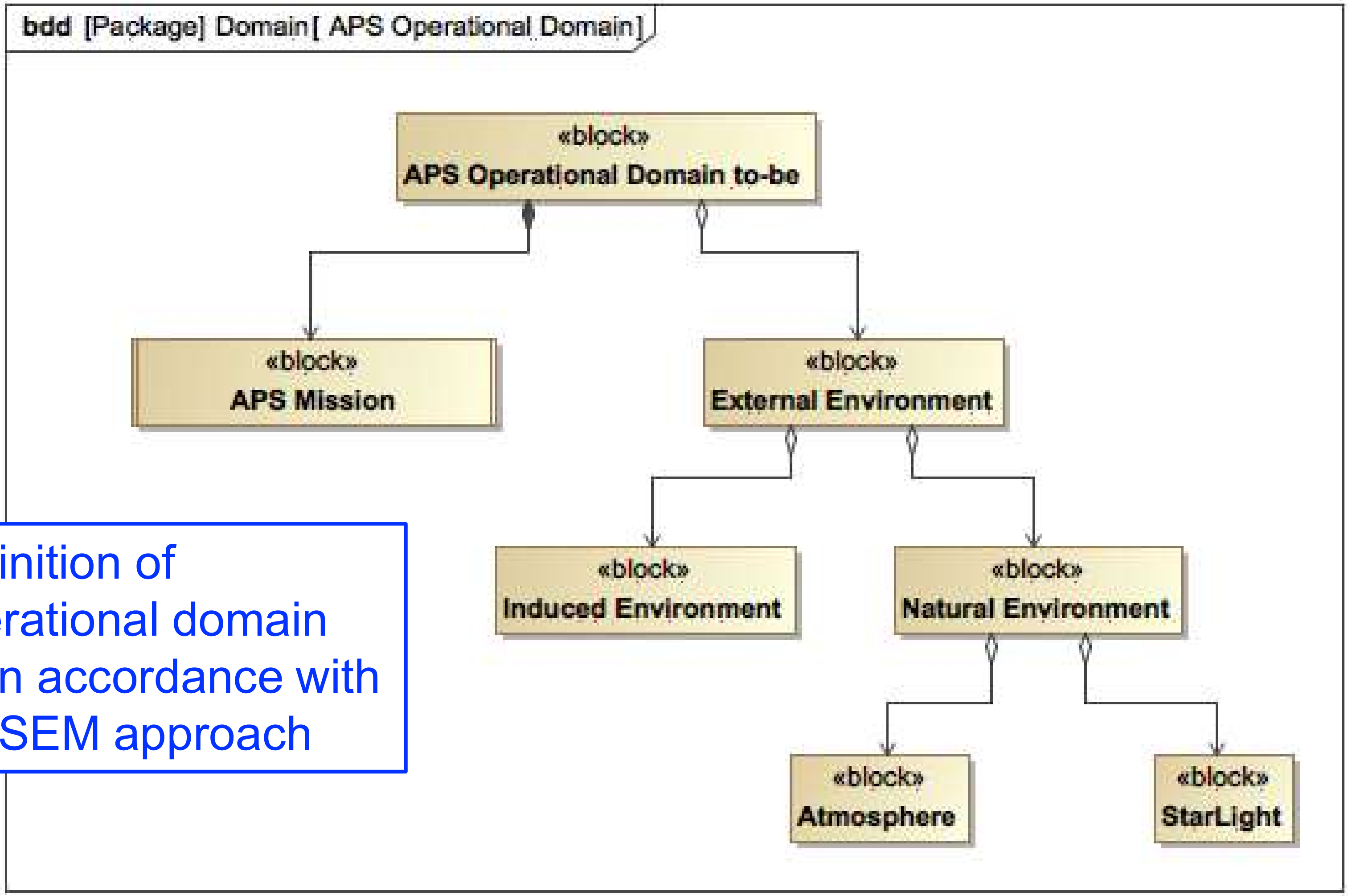
OOSEM abstraction layers



Work breakdown structure

Operational Domain

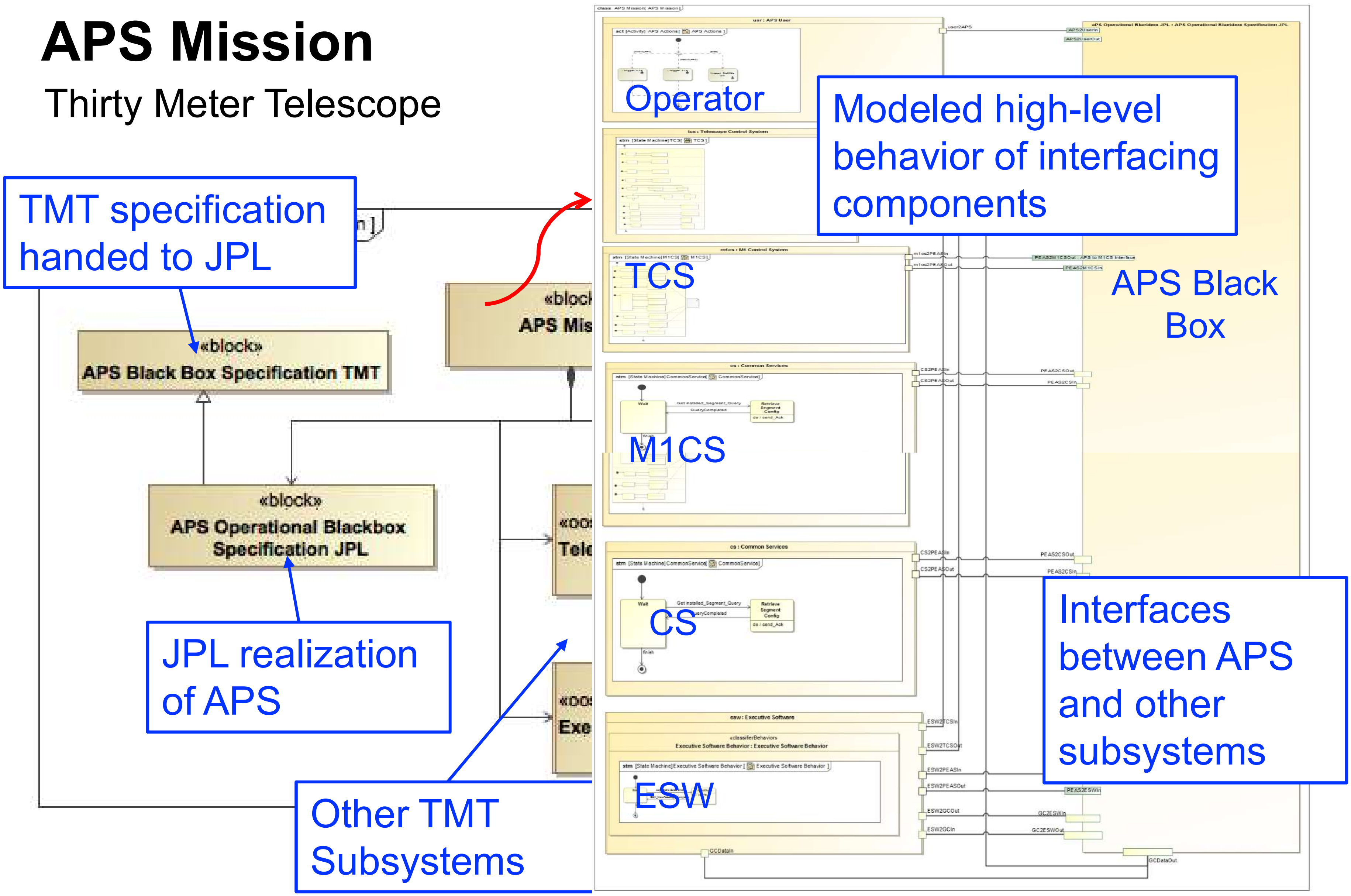
Thirty Meter Telescope



Definition of operational domain as in accordance with OOSEM approach

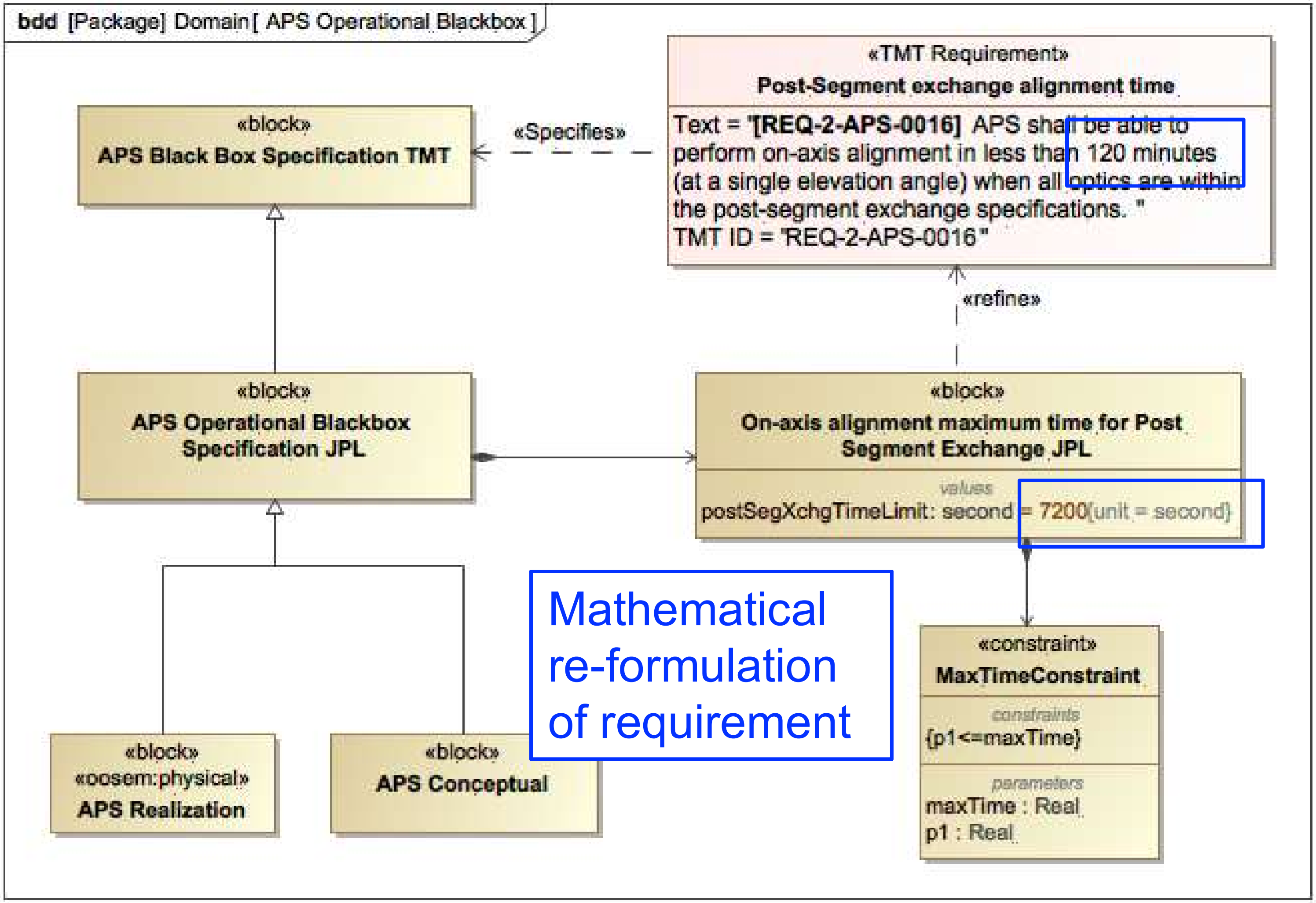
APS Mission

Thirty Meter Telescope



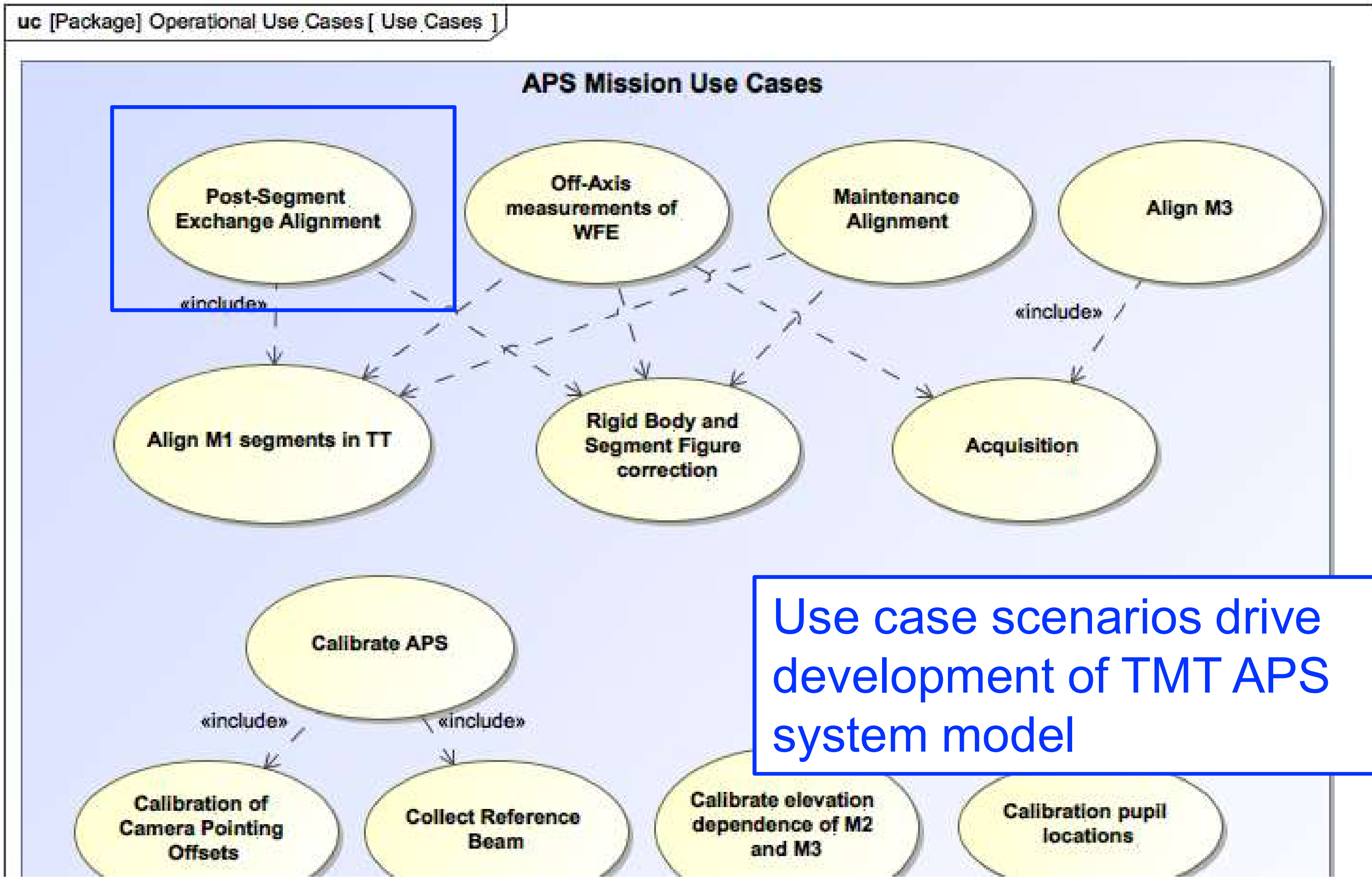
Formalizing Requirements

Thirty Meter Telescope



Use Cases

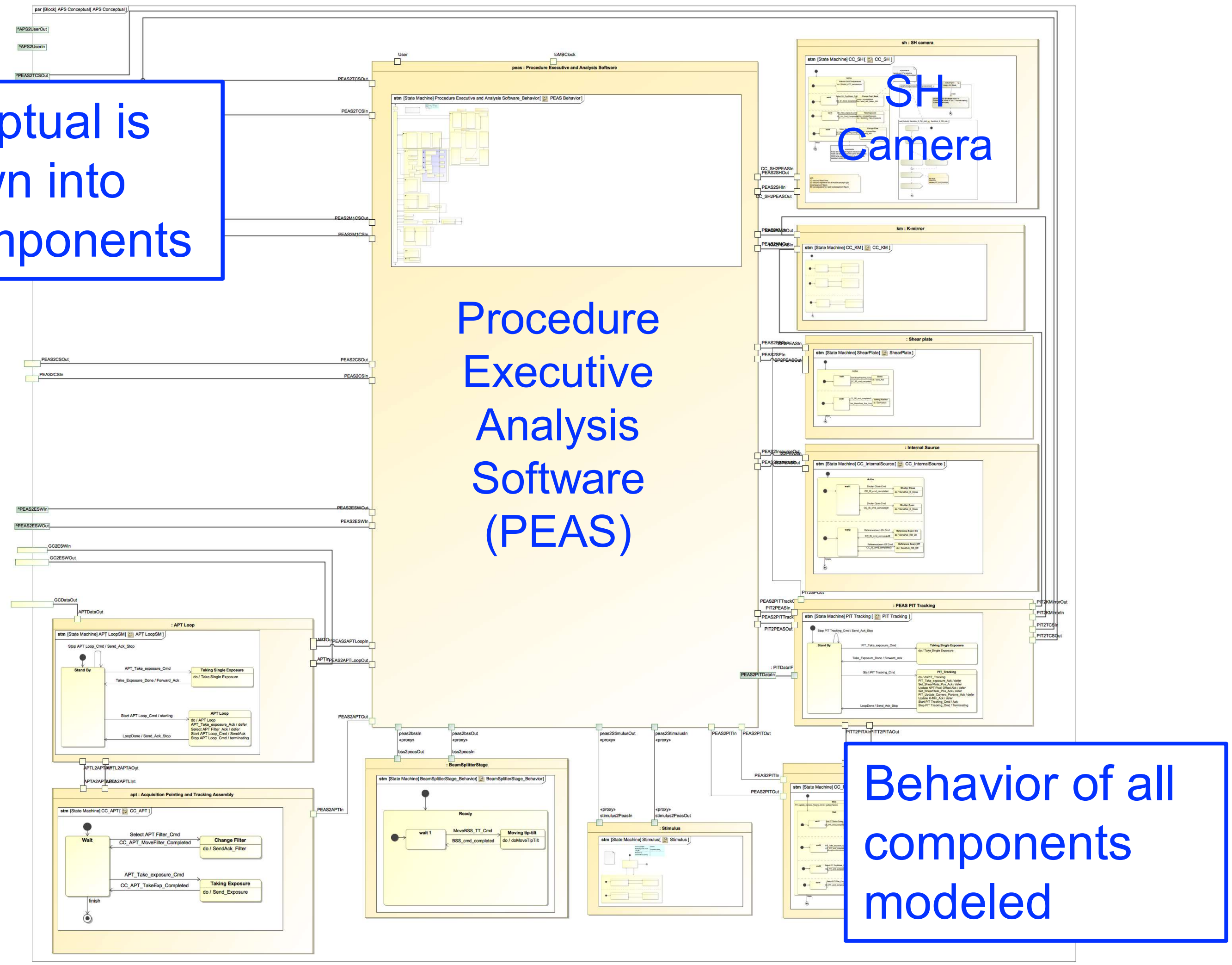
Thirty Meter Telescope



Use case scenarios drive development of TMT APS system model

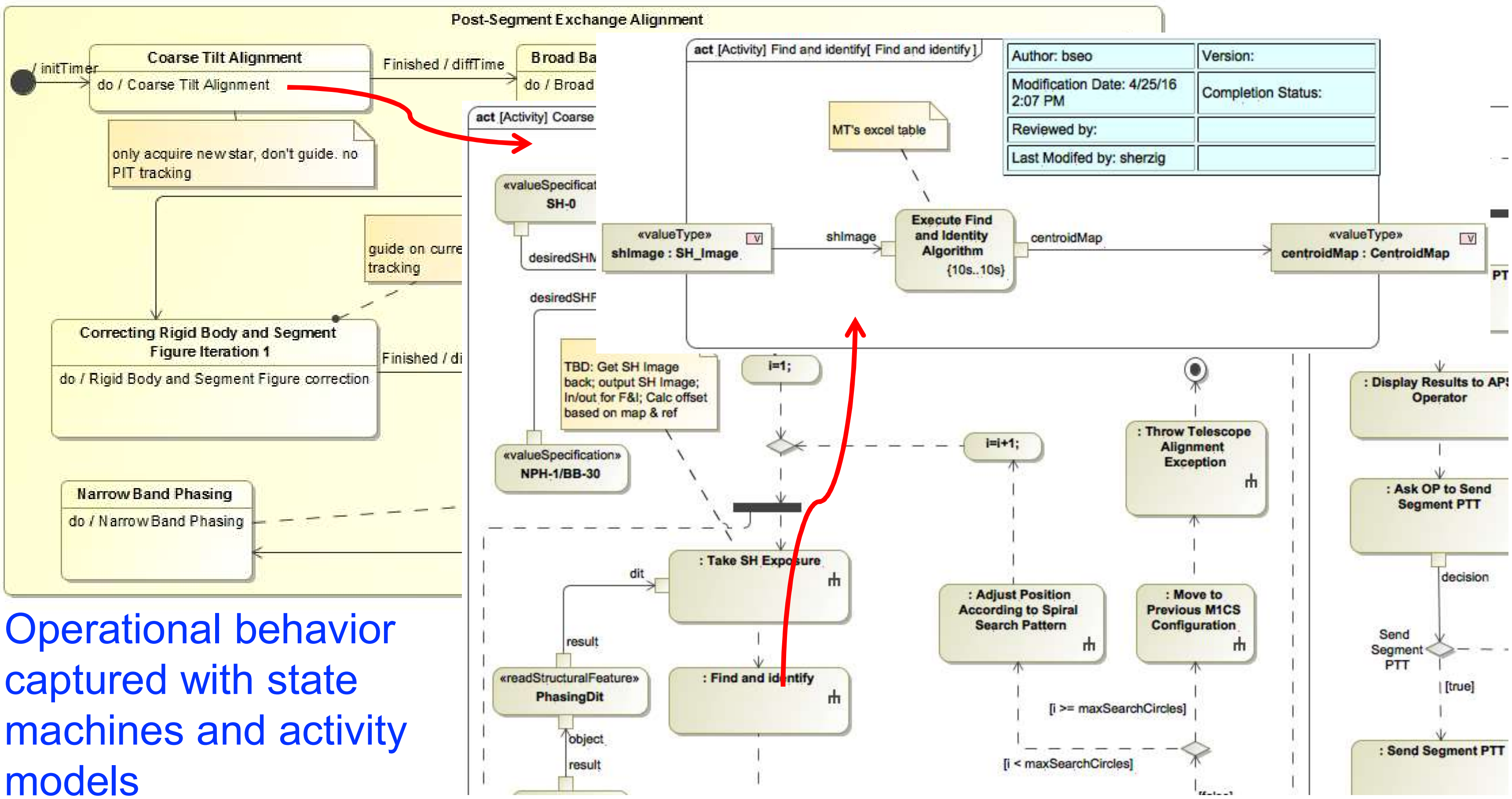
Conceptual Architecture

Thirty Meter Telescope



Modeling Behavior

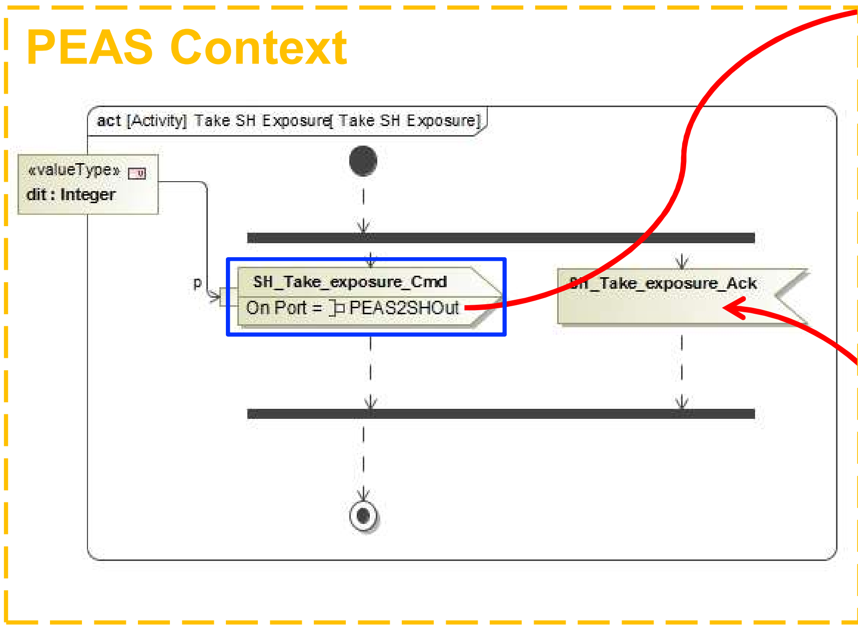
Thirty Meter Telescope

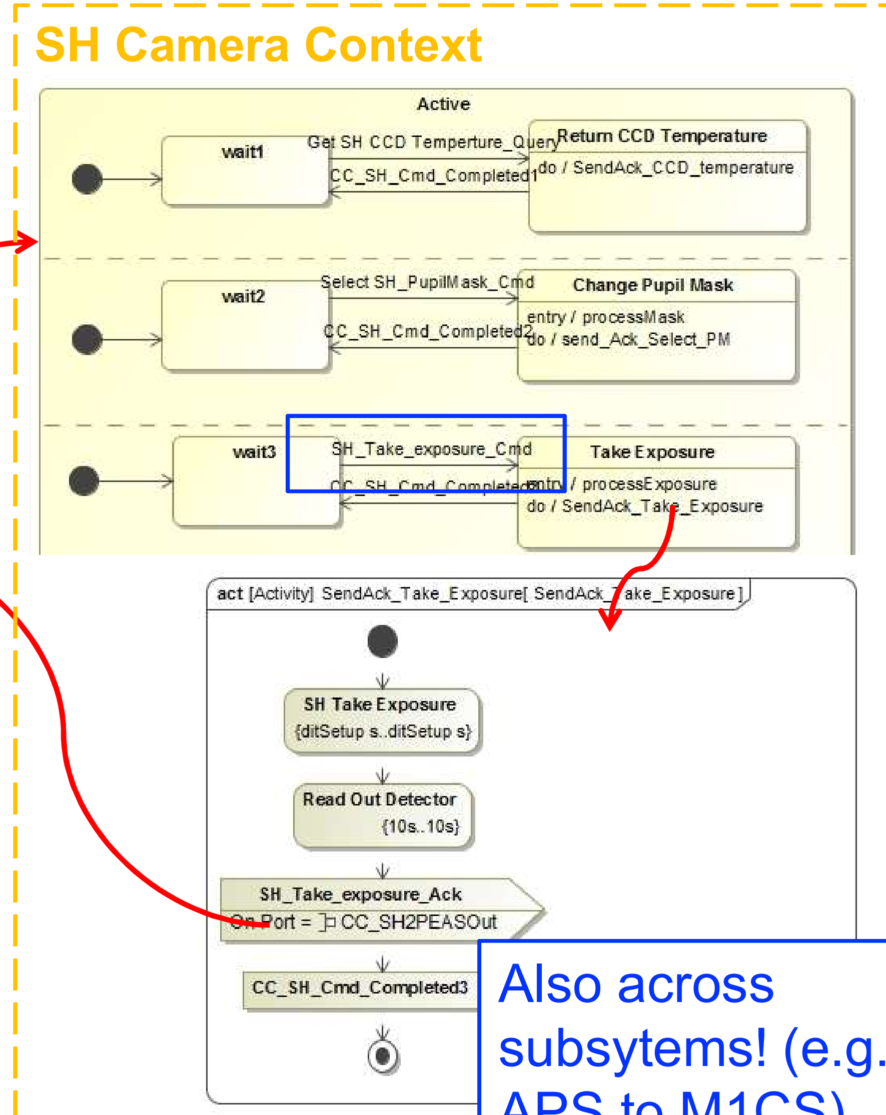


Operational behavior captured with state machines and activity models

Interactions Between Components

Thirty Meter Telescope



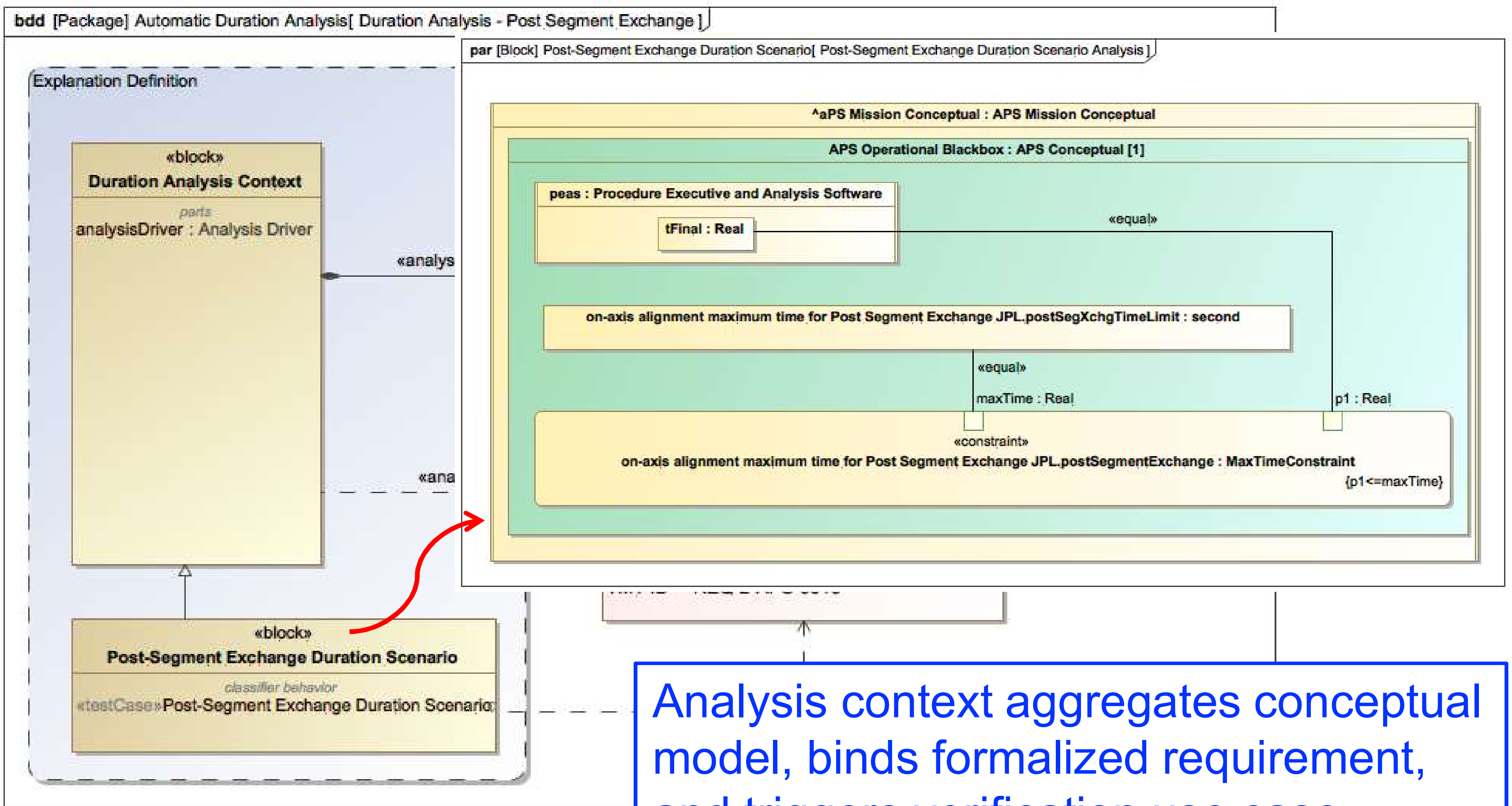


Use of signals sent over ports to simulate a message passing mechanism between components

Also across subsytems! (e.g., APS to M1CS)

Verifying Timing Requirements by Simulation

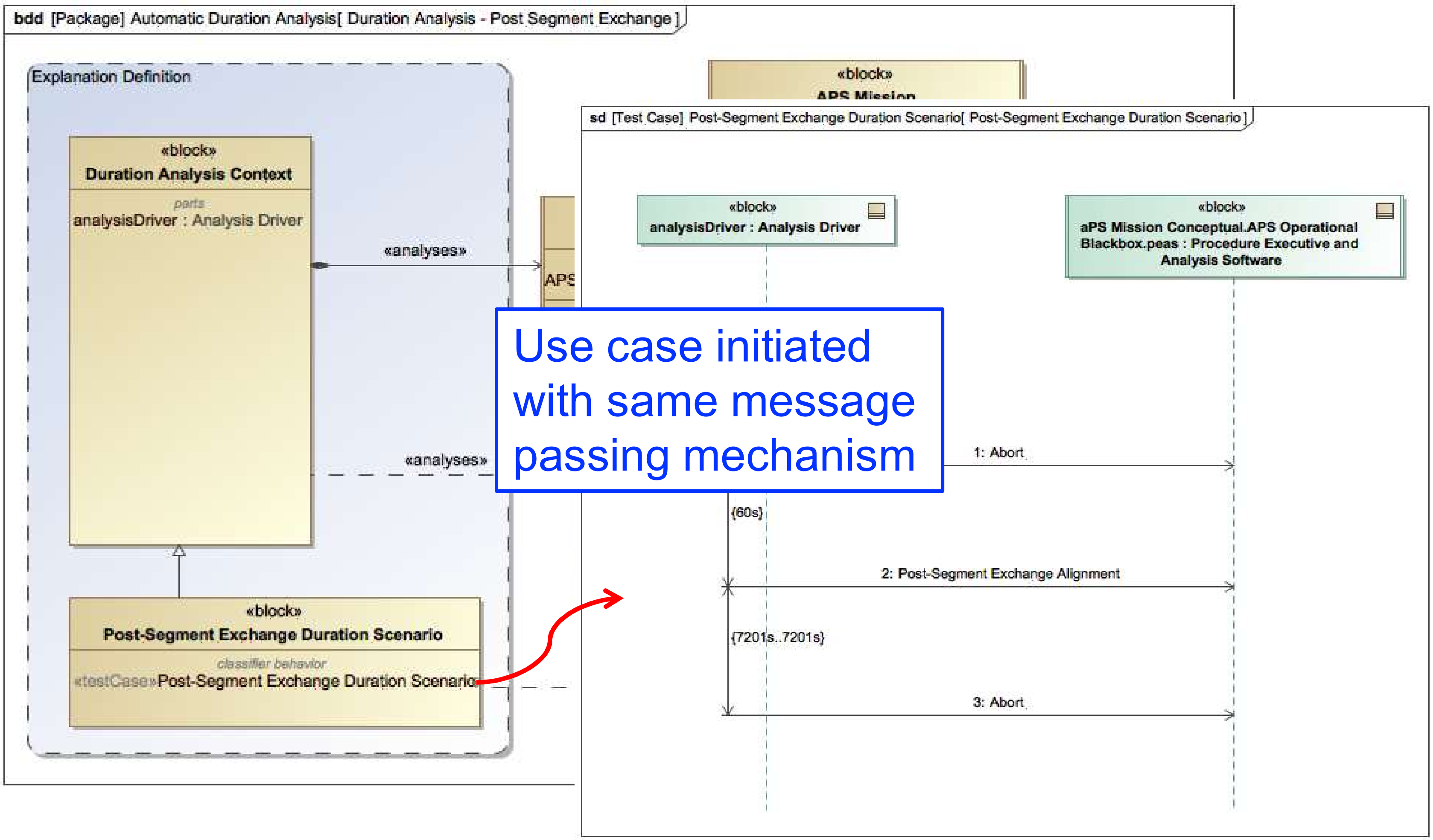
Thirty Meter Telescope



Analysis context aggregates conceptual model, binds formalized requirement, and triggers verification use case

Verifying Timing Requirements by Simulation

Thirty Meter Telescope



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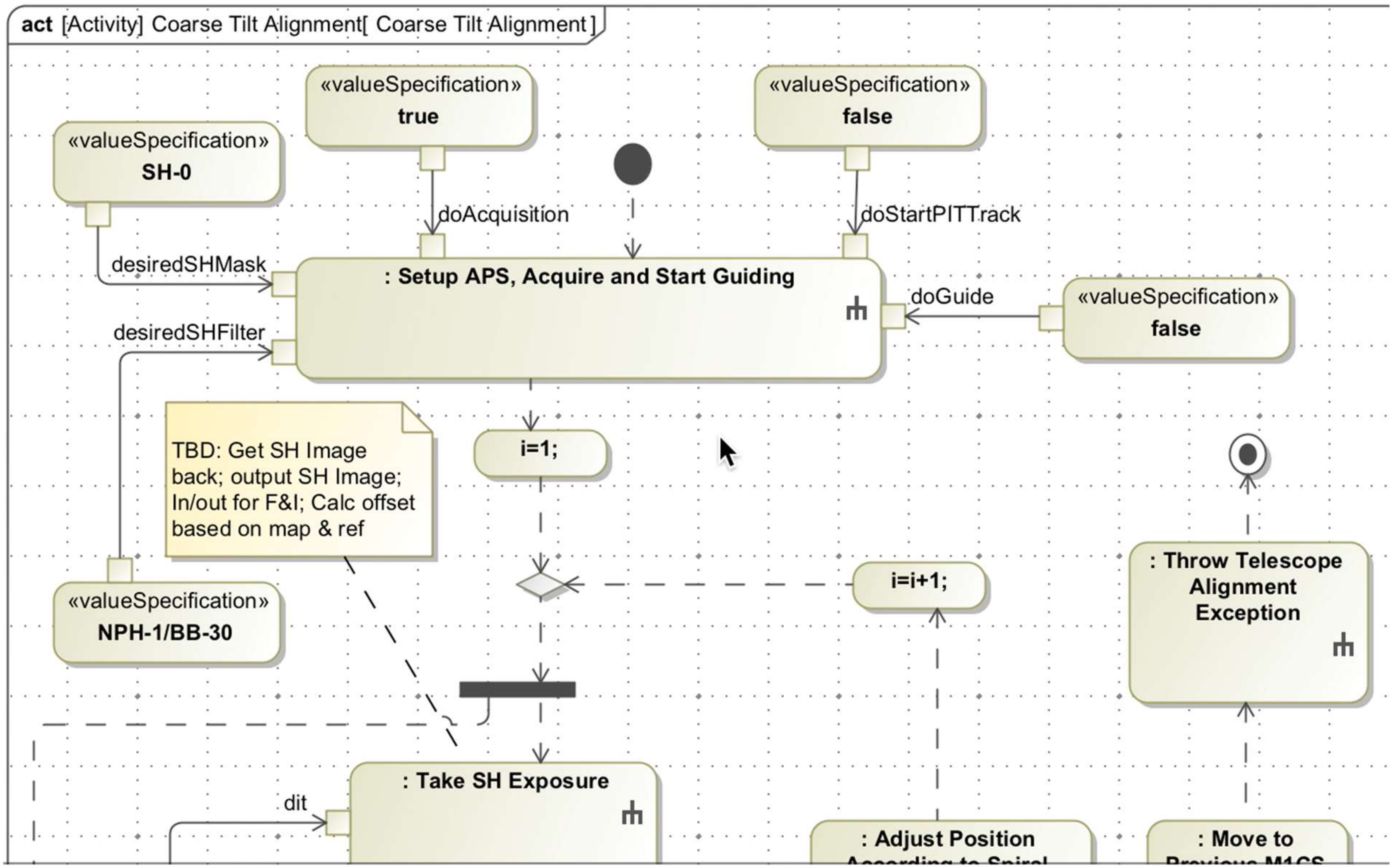
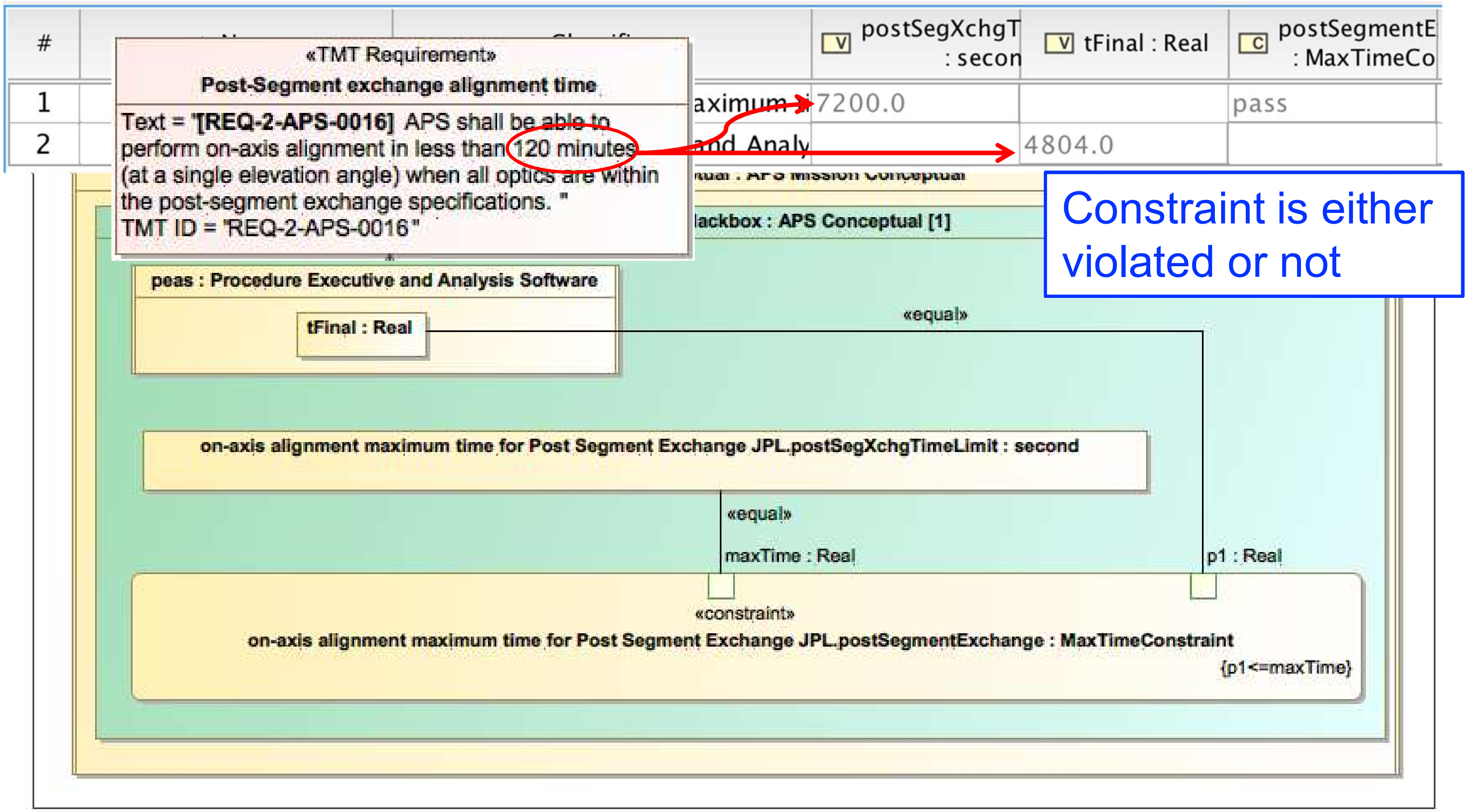


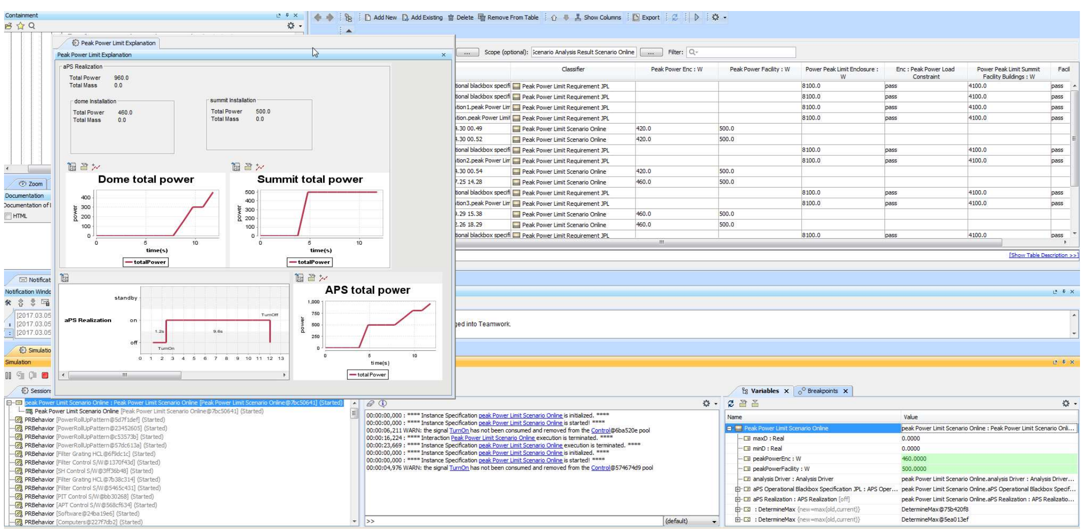
Verifying Timing Requirements by Simulation

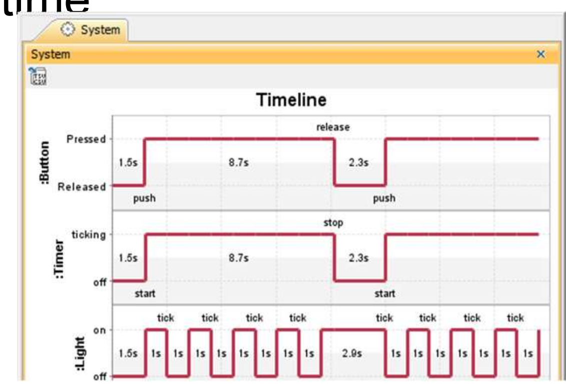
Thirty Meter Telescope

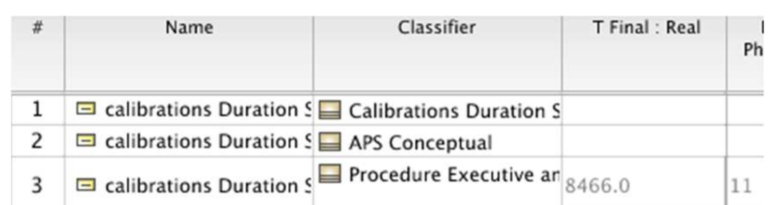


Run Analyses

- Run a configured analysis with a simulation engine on the initial conditions to get the final conditions
- Produce the analyses declaratively, repeatably (in any system), without a single line of project-specific code -> reducing time and resources
- Produce the following views on final conditions
  - **Table** showing final analysis values (e.g. peak power) and the constraint’s pass/fail status for each scenario
  - **Timelines**: state changes for components over time
  - **Value profiles**: total rolled up values over time

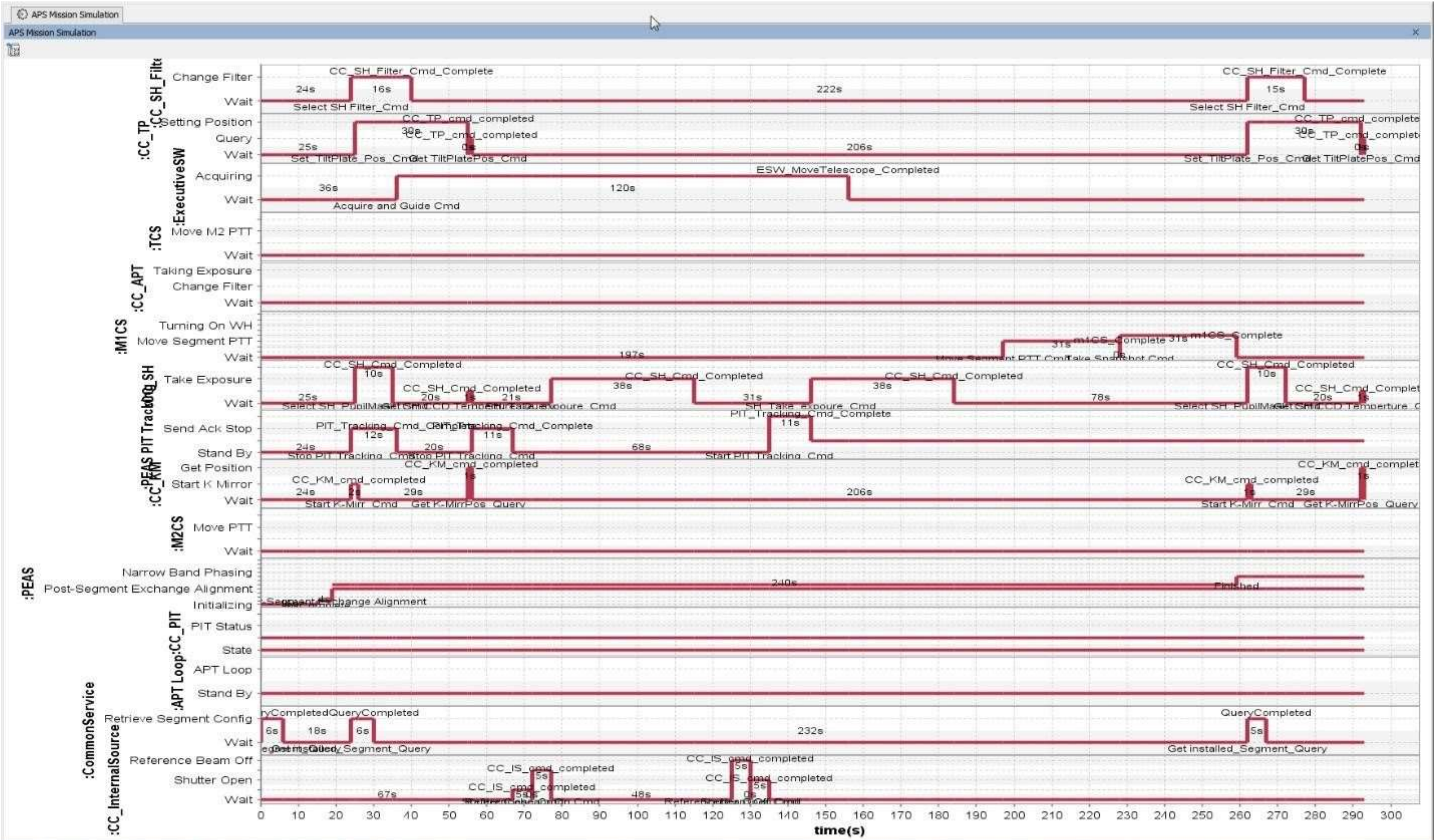




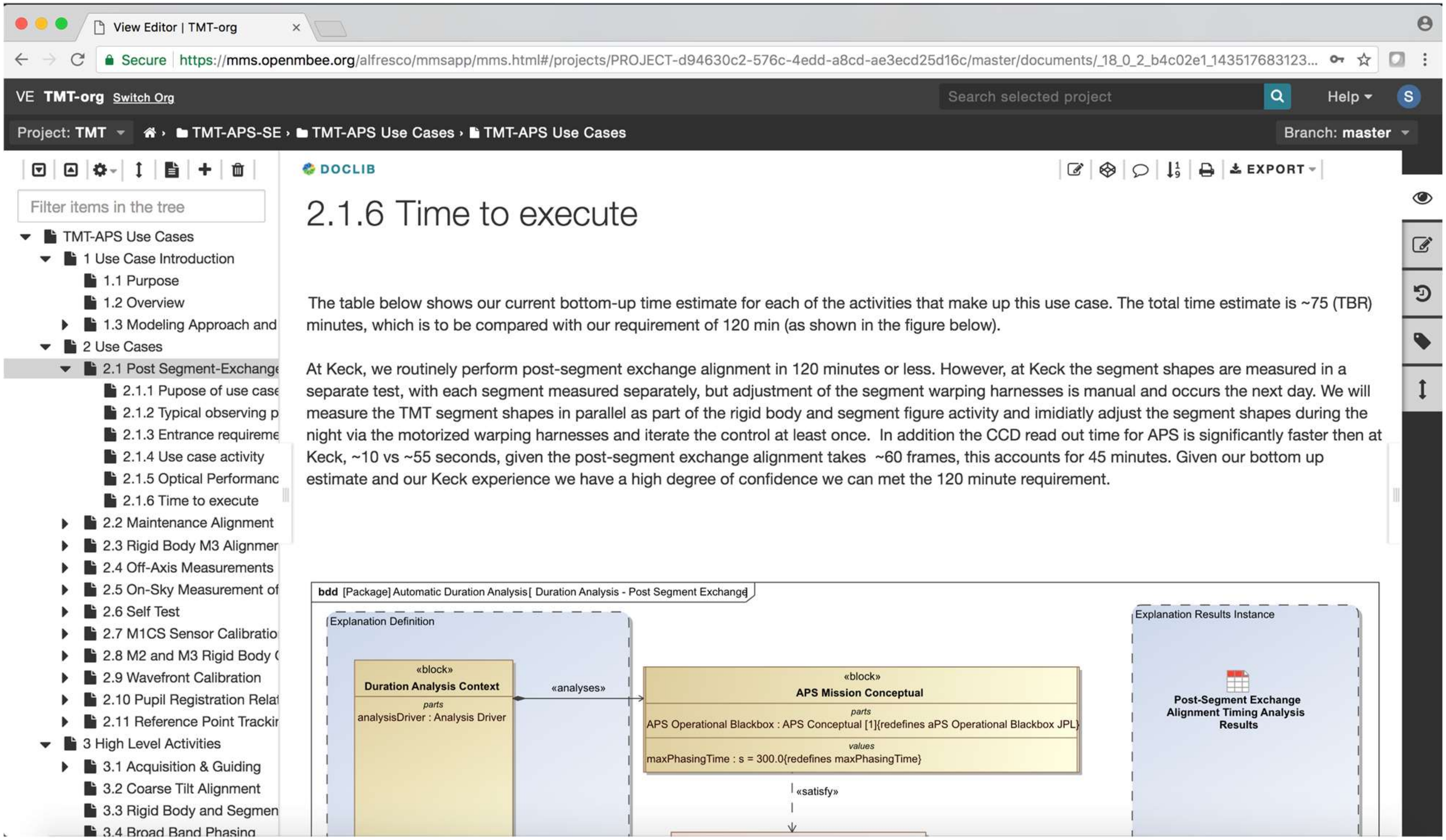


#	Name	Classifier	T Final : Real	Ph
1	calibrations Duration S	Calibrations Duration S		
2	calibrations Duration S	APS Conceptual		
3	calibrations Duration S	Procedure Executive ar	8466.0	11

Timeline of component states

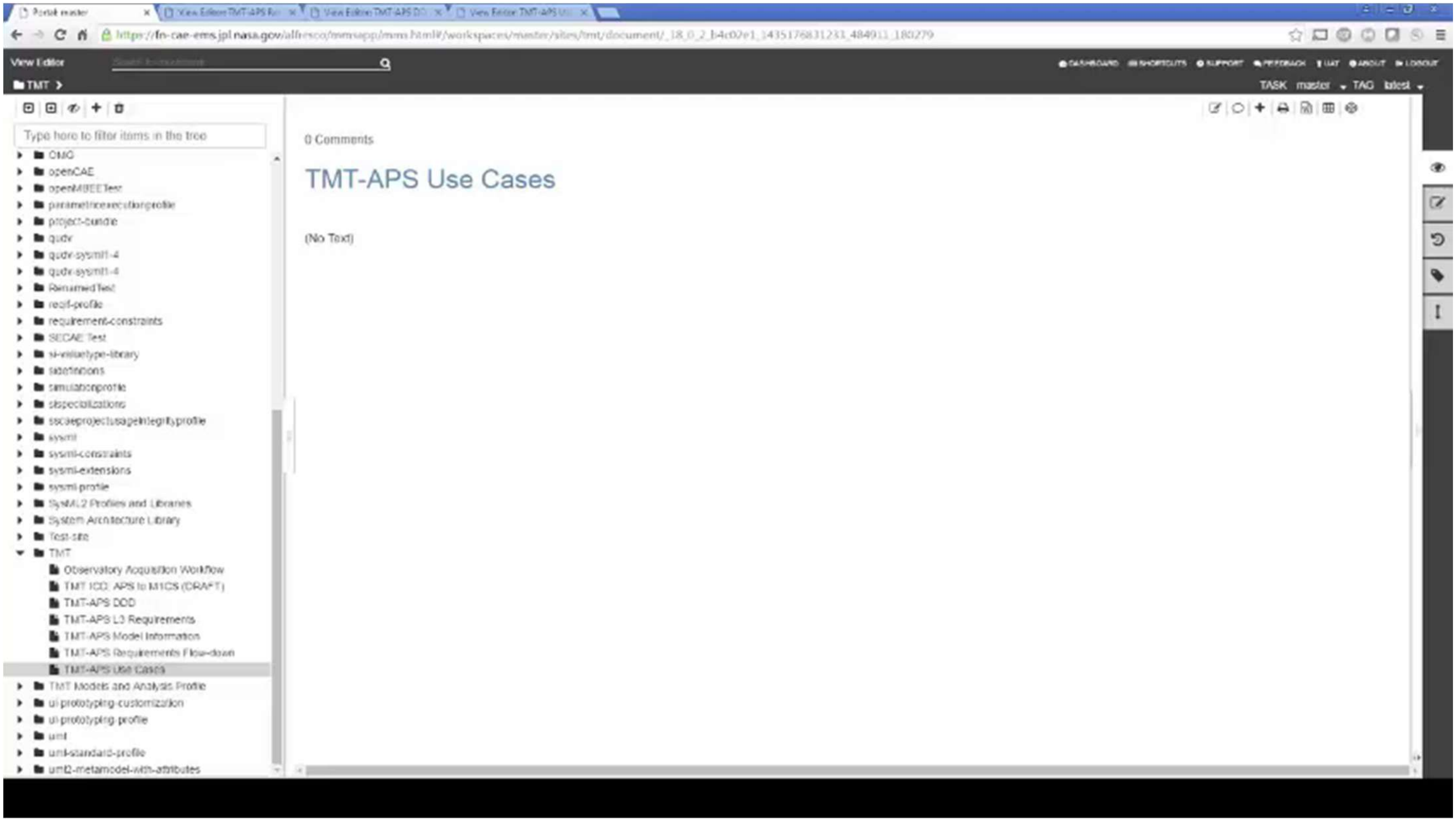


Document & Report Generation via View Editor



* OpenMBEE / ViewEditor is open source, and available at https://www.openmbee.org

System Level Analysis



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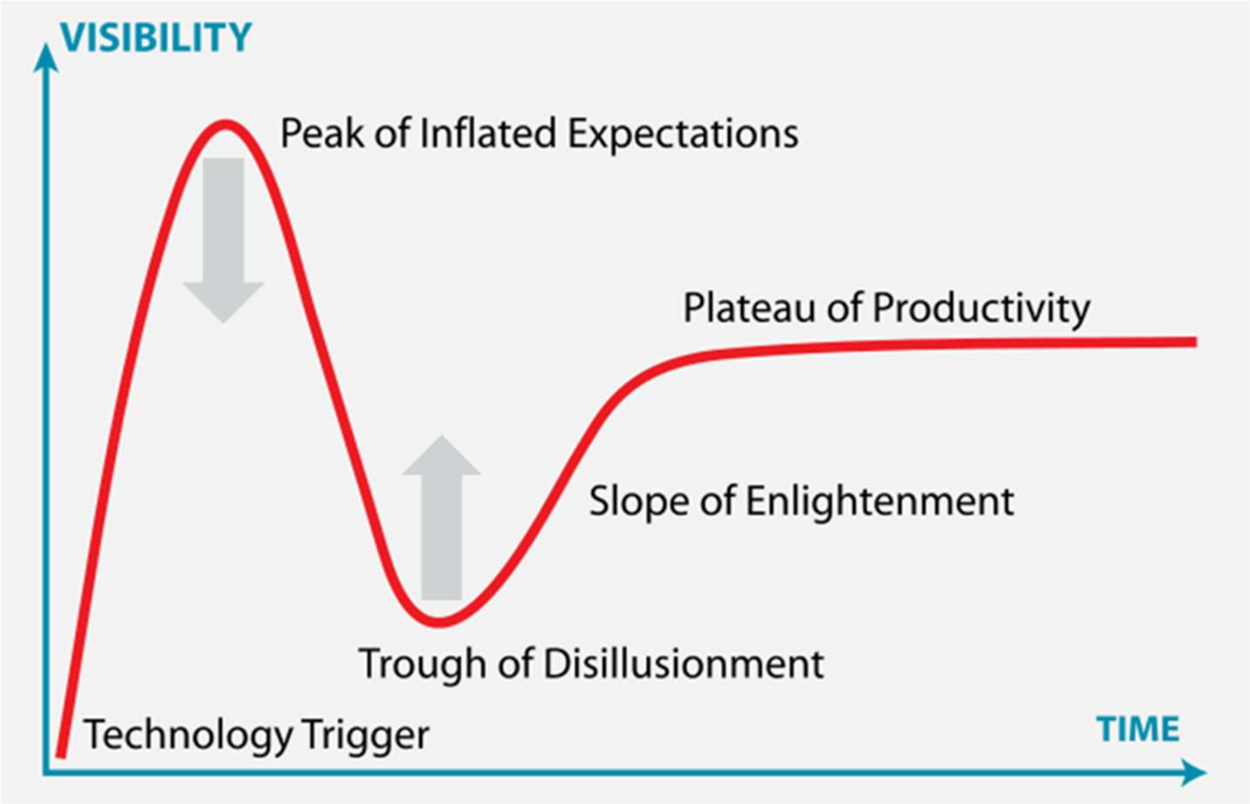
JPL Computer Aided Engineering (CAE)

- JPL Computer Aided Engineering provides the Laboratory's Engineering Staff and Scientific communities with tools and technical expertise
- Four Environments:
  – Systems Environment
  – Software Environment
  – Mechanical Environment
  – Electrical Environment

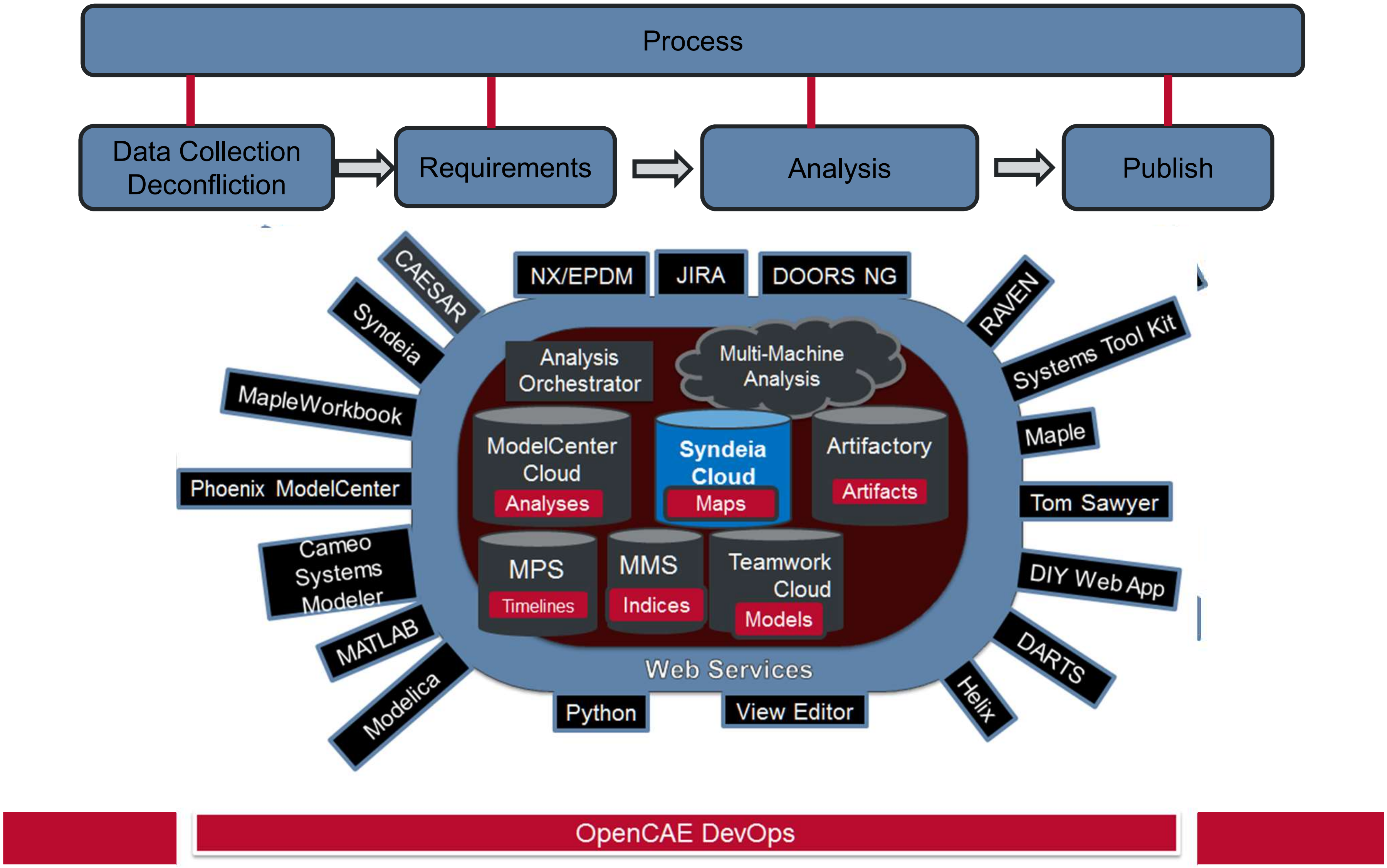
OpenCAE provides the engineering platform

- A platform for engineering tools to work together
- Incorporate tooling from systems, software, mechanical, and electrical domains
- Platform integrates heterogenous data sources
- Emphasize standards for data interchange
- Case studies inform the architecture of the engineering environments
- Multi-model environment

Lifecycle of new applications



JPL CAE Systems Environment provides integrated Life-Cycle Support



JPL develops requirements for Systems Environment (tooling) through Case Studies

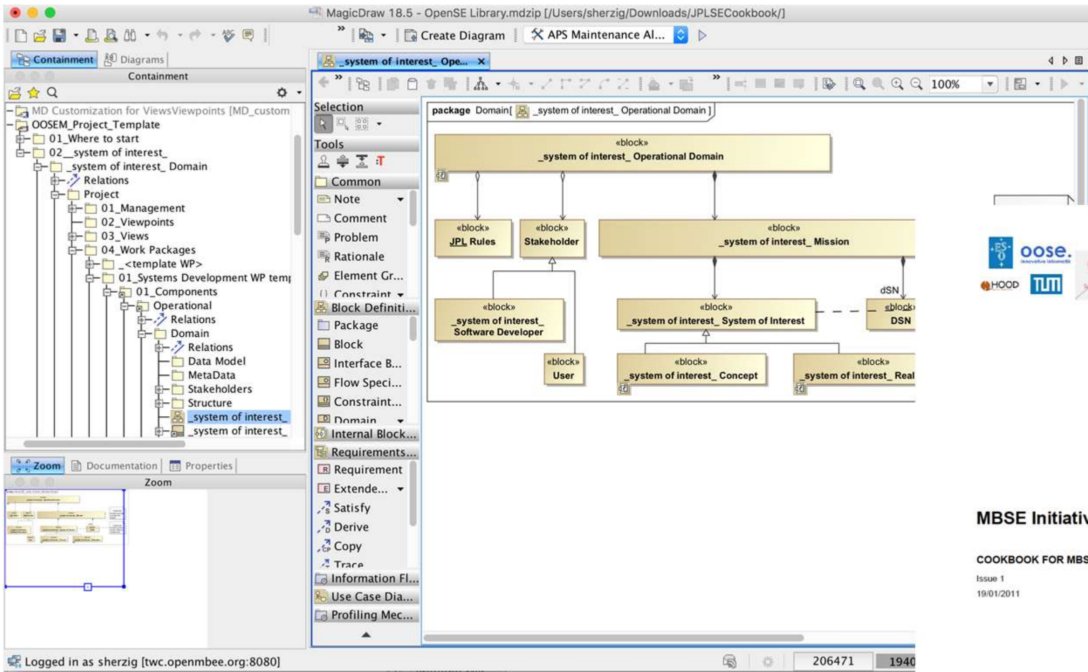
For Example:

- Requirements Management
- Interface Management
- Design Management
- Trade Studies
- Interdisciplinary Integration
- Analysis Pipeline
- Resource Management
- Timeline Management

OpenSE Cookbook combines different aspects

- Update 2012 “Cookbook for MBSE with SysML”
  - Focus on structure and requirements using European FP7 Active Phasing Experiment (APE) as case study
- Include Patterns developed for TMT
  - Focus on behavior and analysis workflows
- Guided by ESEM methodology
- Describe tooling support provided by JPL Systems Environment
- OpenSE model library provides commonly used elements
- Instructional examples
- Application to actual engineering team, i.e. TMT
- Template Models and recommended model organizations

OpenSE Cookbook and Template Model

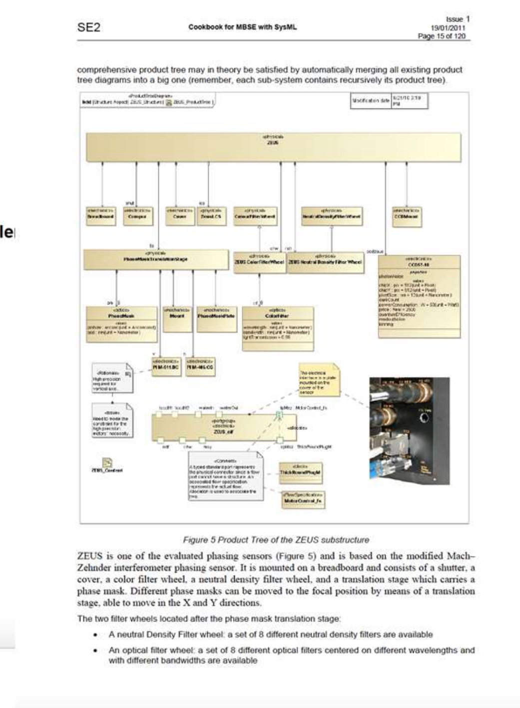


MBSE Initiative – SE2 Challe

COOKBOOK FOR MBSE WITH SYSML

Issue 1

19/01/2011



SE2 Cookbook for MBSE with SysML Issue 1 19/01/2011 Page 15 of 120

comprehensive product tree may in theory be satisfied by automatically merging all existing product tree diagrams into a big one (remember, each sub-system contains recursively its product tree).

Figure 5 Product Tree of the ZEUS substructure

ZEUS is one of the evaluated phasing sensors (Figure 5) and is based on the modified Mach-Zehnder interferometer phasing sensor. It is mounted on a breadboard and consists of a shutter, a cover, a color filter wheel, a neutral density filter wheel, and a translation stage which carries a phase mask. Different phase masks can be moved to the focal position by means of a translation stage, able to move in the X and Y directions.

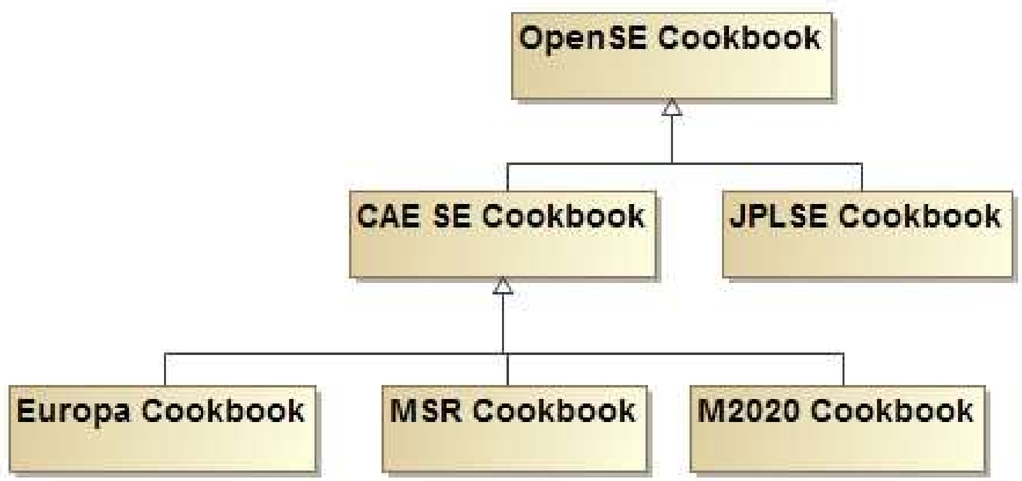
The two filter wheels located after the phase mask translation stage:

- A neutral Density Filter wheel: a set of 8 different neutral density filters are available
- An optical filter wheel: a set of 8 different optical filters centered on different wavelengths and with different bandwidths are available

Template models to be used by projects as a starting point, with recommended organization, model libraries, etc.

OpenSE Cookbook promotes re-use

- OpenSE Cookbook contributes to JPL institutional and project specific Cookbooks
- Project-independent modeling patterns as guidelines
- Project-specific modeling patterns for common modeling tasks



OpenSE Cookbook is used as reference

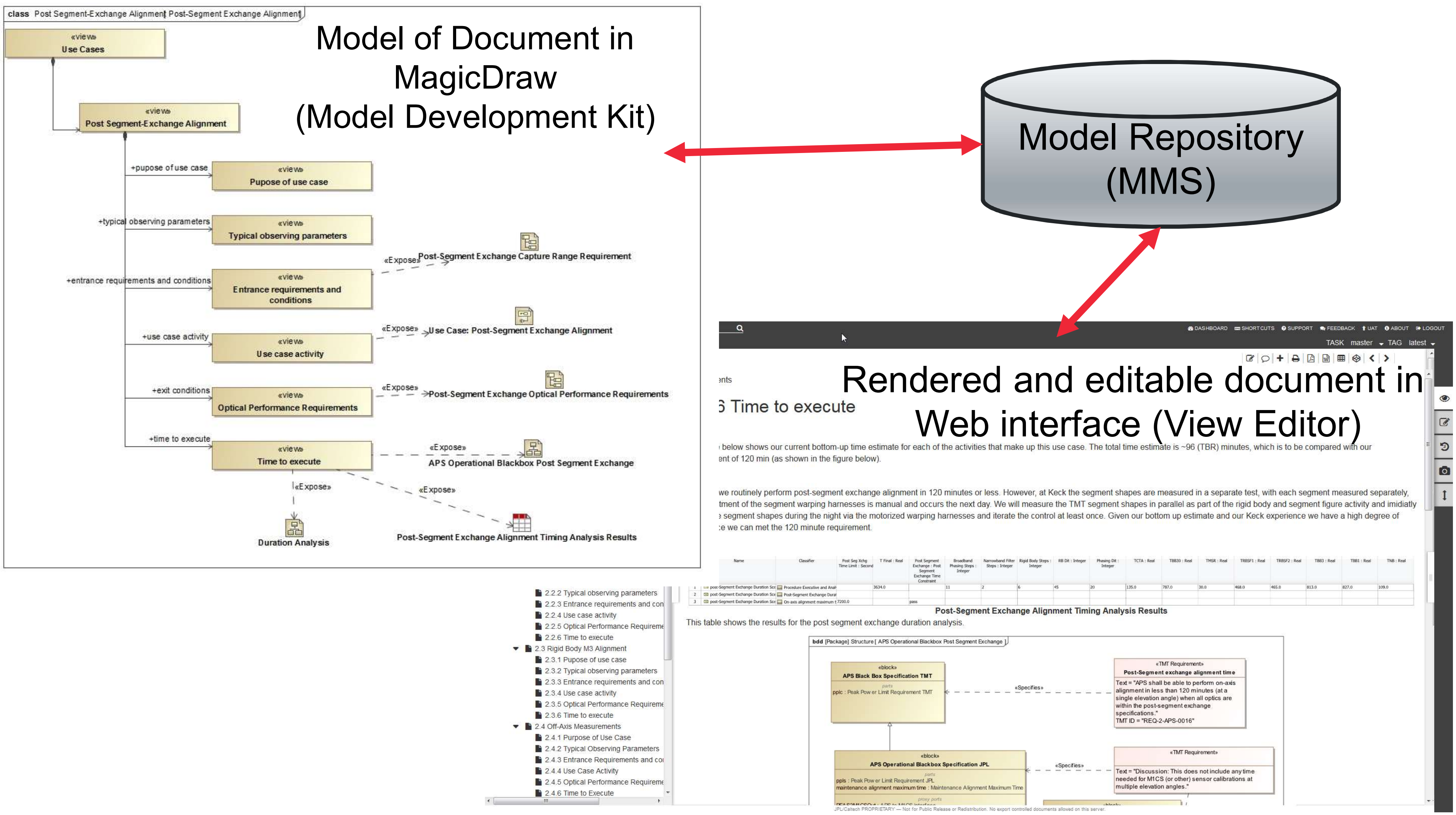
- OpenSE cookbook and TMT model used as reference model for the OMG SysML 2 standard
  - Demonstrate how SysML 2 will improve, simplify, change model wrt SysML 1.x
- Training material and knowledge transfer
- Promote standards and conventions
- Used by vendors as reference to test and evolve products

openmbee.org

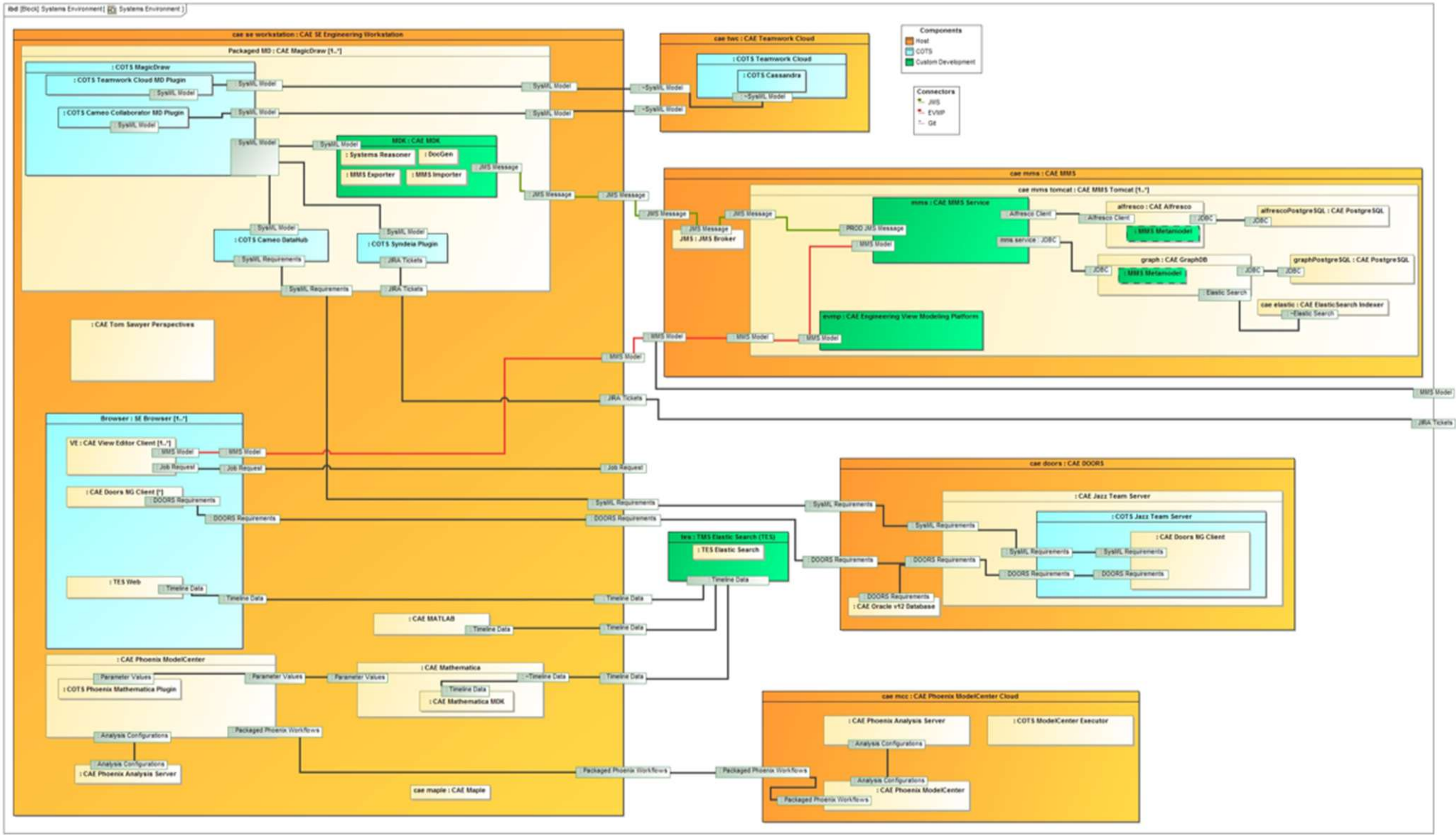
Open Model Based Engineering Environment

- OpenMBEE is a community for open-source modeling software and models
  - Number of open source software activities
  - Number of open source models
- JPL is a participant and adopter of OpenMBEE software and models
- Along with Boeing, Lockheed, OMG, NavAir, Ford, Stevens, GaTech, ESO
- Vendor participants
- ~300 members

Core Integration of MMS, MDK, and VE



Interactions Within CAE Systems Environment



Managed Excel

Summary & Conclusions

- JPL is successfully applying MBSE with SysML to numerous projects - large and small – over different life cycle phases
- Clear benefits: early verification, consistency, less ambiguity
- There has been tremendous progress in tools and methods in the past decade – and we're only just starting
  - Many lessons learned, tools, techniques integrated from MBSE practice
  - Strong developments in methodology and theory
- Magnitude of paradigm shift still leads to skepticism and adoption challenges ➔ transition inevitable, but slow

Acknowledgements

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- Open Source Engineering Environment: https://www.openmbee.org
- https://www.jpl.nasa.gov/spaceimages/

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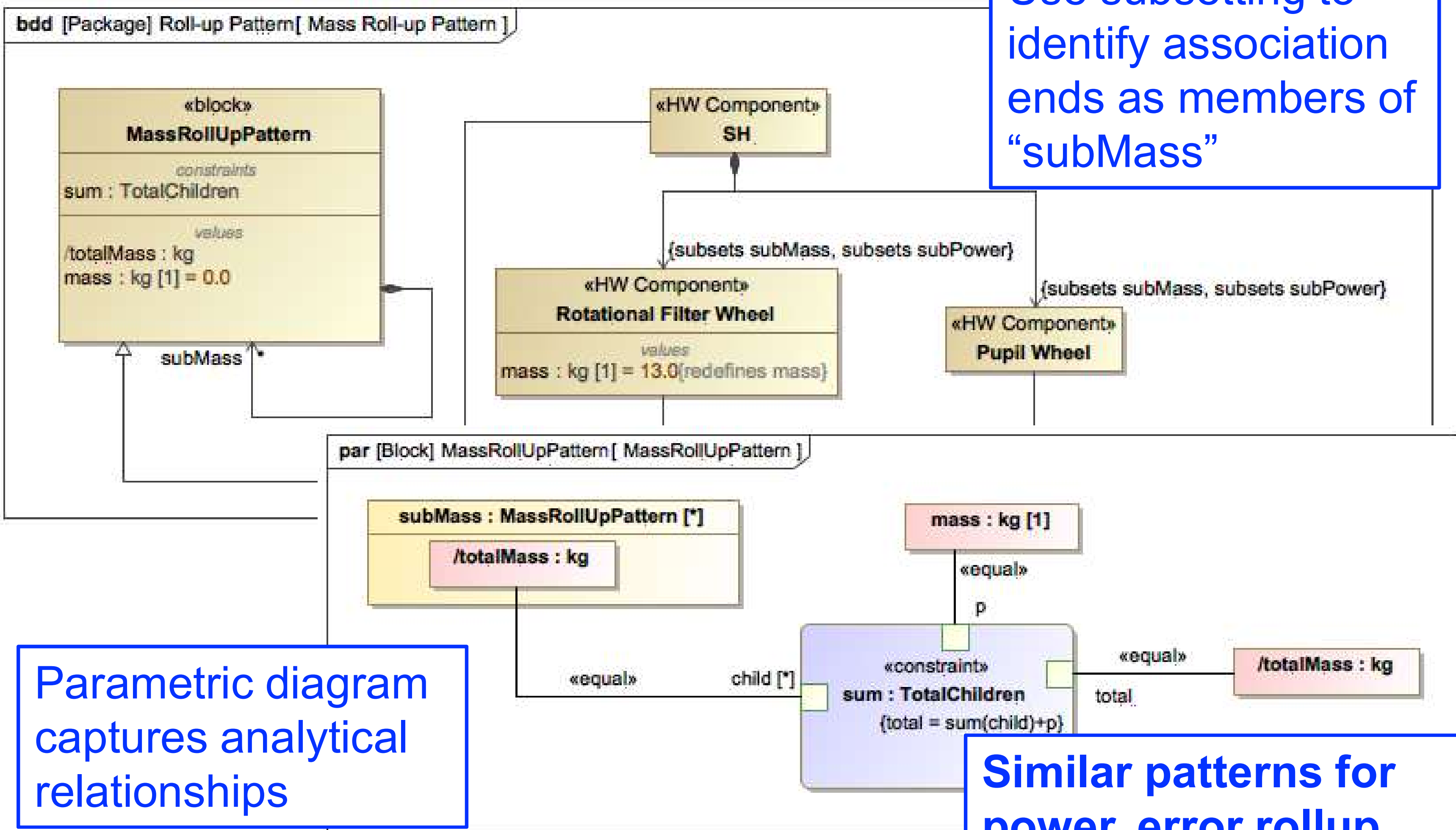
BACKUP SLIDES

“Static” Rollup Analyses – Example: Mass

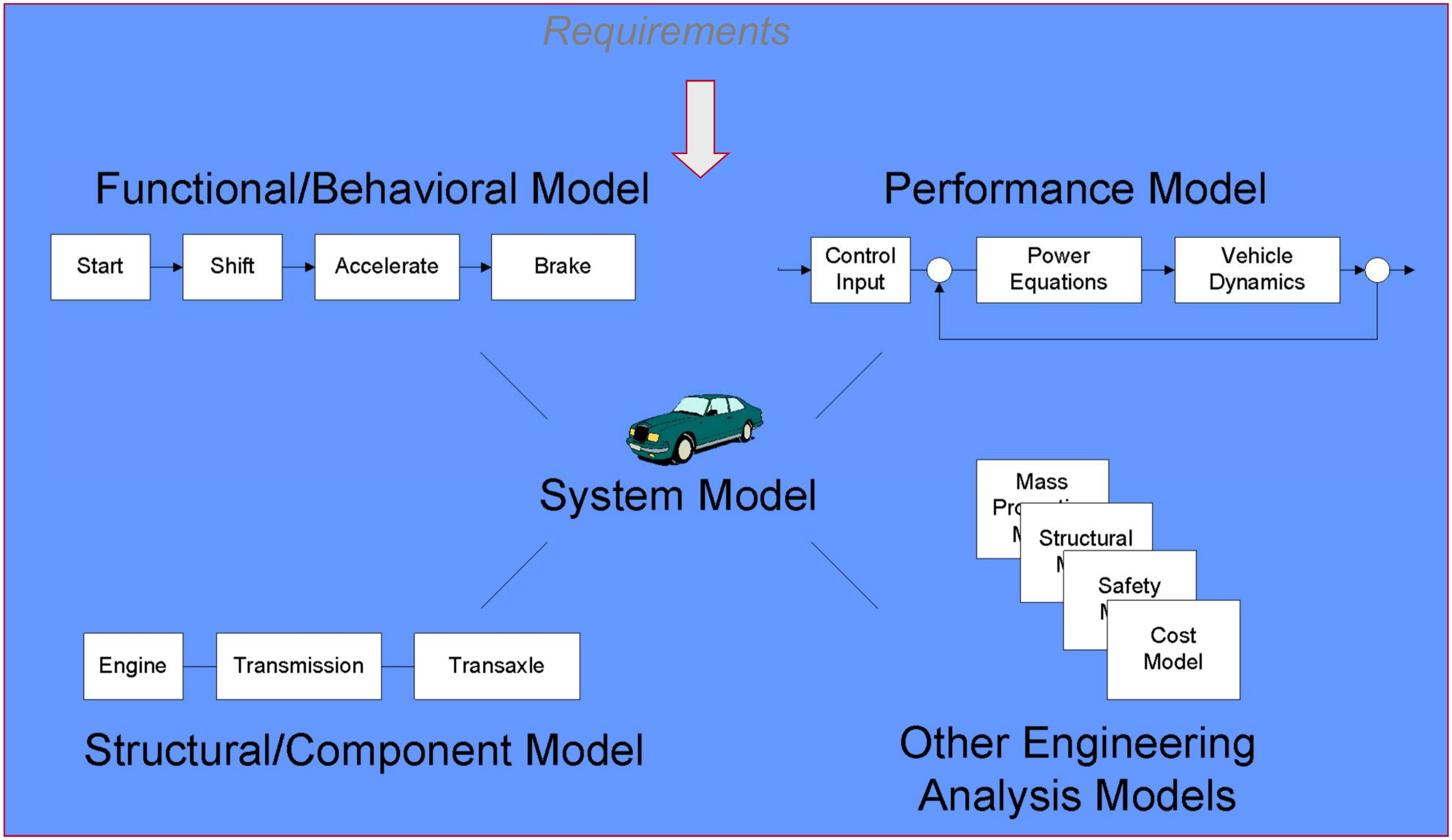
Thirty Meter Telescope



Use subsetting to identify association ends as members of “subMass”

Parametric diagram captures analytical relationships

Similar patterns for power, error rollup, …



Integrated System Model Must Address Multiple Aspects of a System

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