Model Based Systems Engineering and Critical Function Security: Assessing CubeSats as an Exemplar Mission

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Ground Systems Architecture Workshop

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Outline

- Abstract
- Introduction
  - *Study Thesis*
  - *Background*
  - *Approach*
- Previous Efforts
- CubeSat Model and Applications
  - *Key Open-Source Tools*
  - *Executable CubeSat Simulation*
  - *CubeSat Tailored MBSE SysML Model*
- Study Assessment
  - *National Critical Functions*
  - *Mission Assessment*
- Summary and Conclusions

OMG Systems Modeling Language | SYSML

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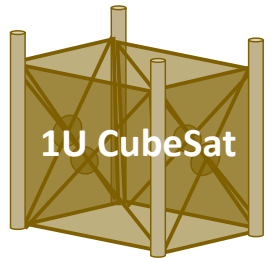
Abstract

- The purpose of this research project is to consider how an aggregation of open-source tools directed by a model-based system engineering control function can be useful for assessing critical system of system capabilities, which can also be called critical function security.
- The goal will be to use this capability to expose vulnerabilities from introducing new unvalidated capabilities and techniques.
- The chosen area of exploration is CubeSats where the proliferation of SmallSats in various ways is becoming common place, whether it be through p-LEO constellations, technology demonstrations, or university educational programs.
- The cost to build and deploy CubeSats is very modest as compared to large aggregated satellites.
- With methods that leverage previously defined approaches, which could be called design patterns, there is the possibility of introducing vulnerabilities and areas of concern that might not have been thought of when adopting resources that have been developed by others.
- Architecting system of systems unavoidably have to consider what exactly is being leveraged and what is the pedigree of those sources.



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Study Thesis

- Using MBSE tools can help frame the problem and potentially uncover issues, cause and effect implications, and vulnerabilities that may not have been previously characterized.
- Although a complete MBSE capability currently cannot be done with just one tool, there are efforts that are seeking to ever come closer to this goal.
- A NASA CubeSat example is included in this study.
  - *Each of these cases gives a context for what operationally is trying to be accomplished and what is most important to capture in the digital engineering process, where a clear understanding of what the performance truth is at each step in the process.*
- Other approaches exist, like the Aerospace Corporation's multi-prong exploration of enterprise system engineering, model bases systems engineering, and digital engineering.

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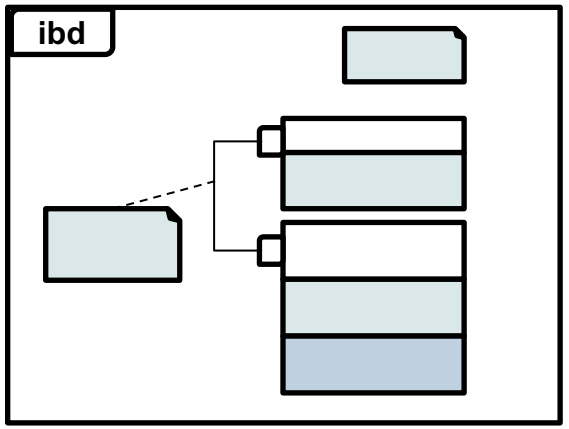
Modeling Purpose and Scope

- Framing the context of the modeling is an important first step

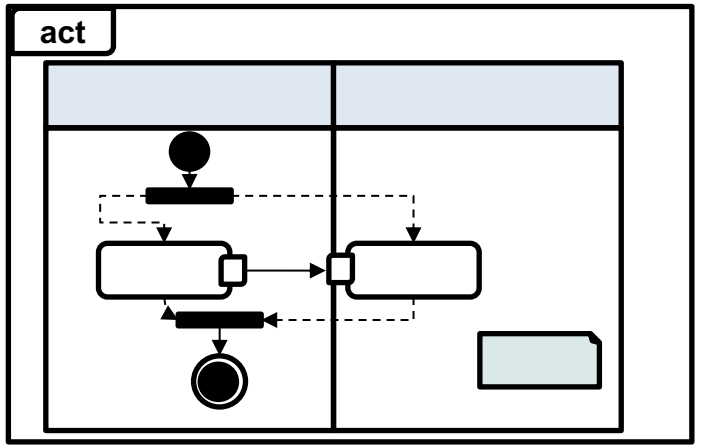
- What exactly should be modeled?
  - *A functional summary model of an academic CubeSat capability*
- What is the purpose of the model?
  - *To perform initial mission, architecture, and performance trades*
- What is the scope of the model?
  - *Create a framework that has enough detail to answer initial design questions*

Exemplar SysML Model Coupling

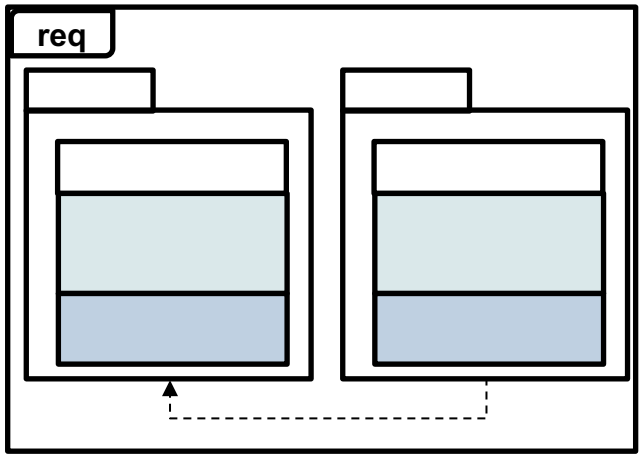
Structure



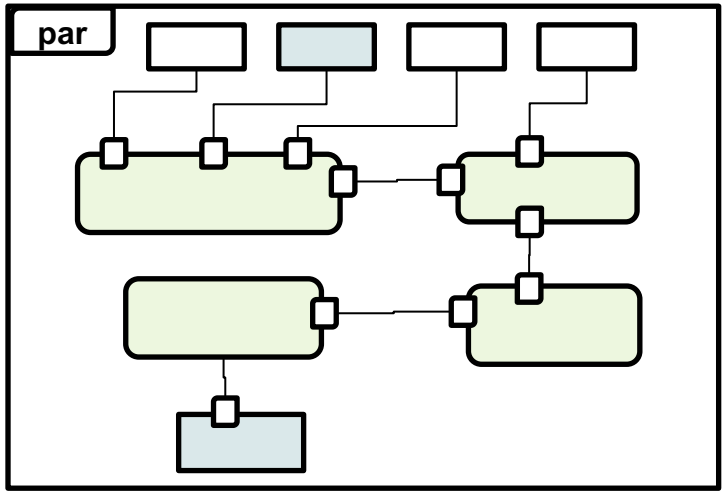
Behavior



Requirements



Parametrics



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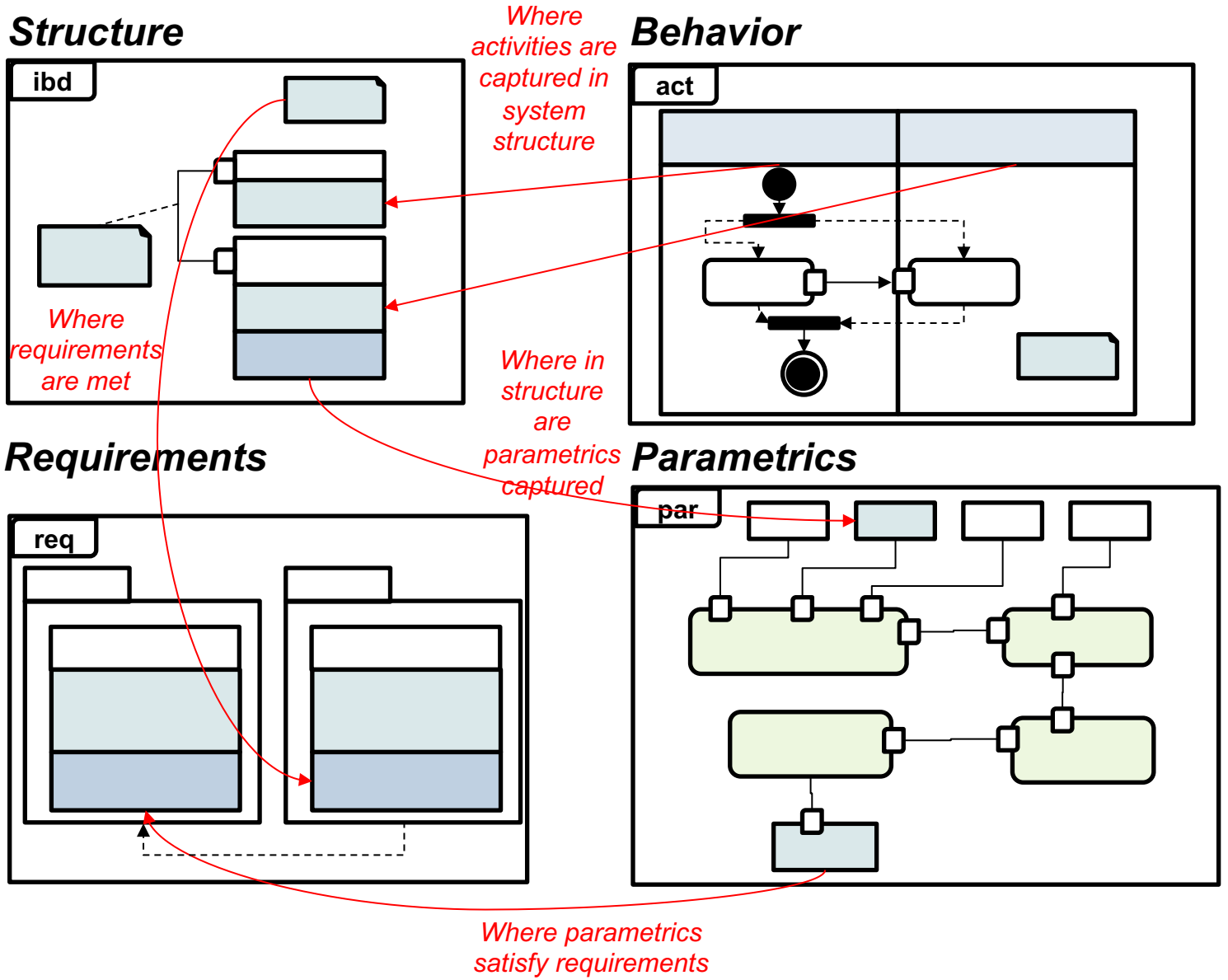
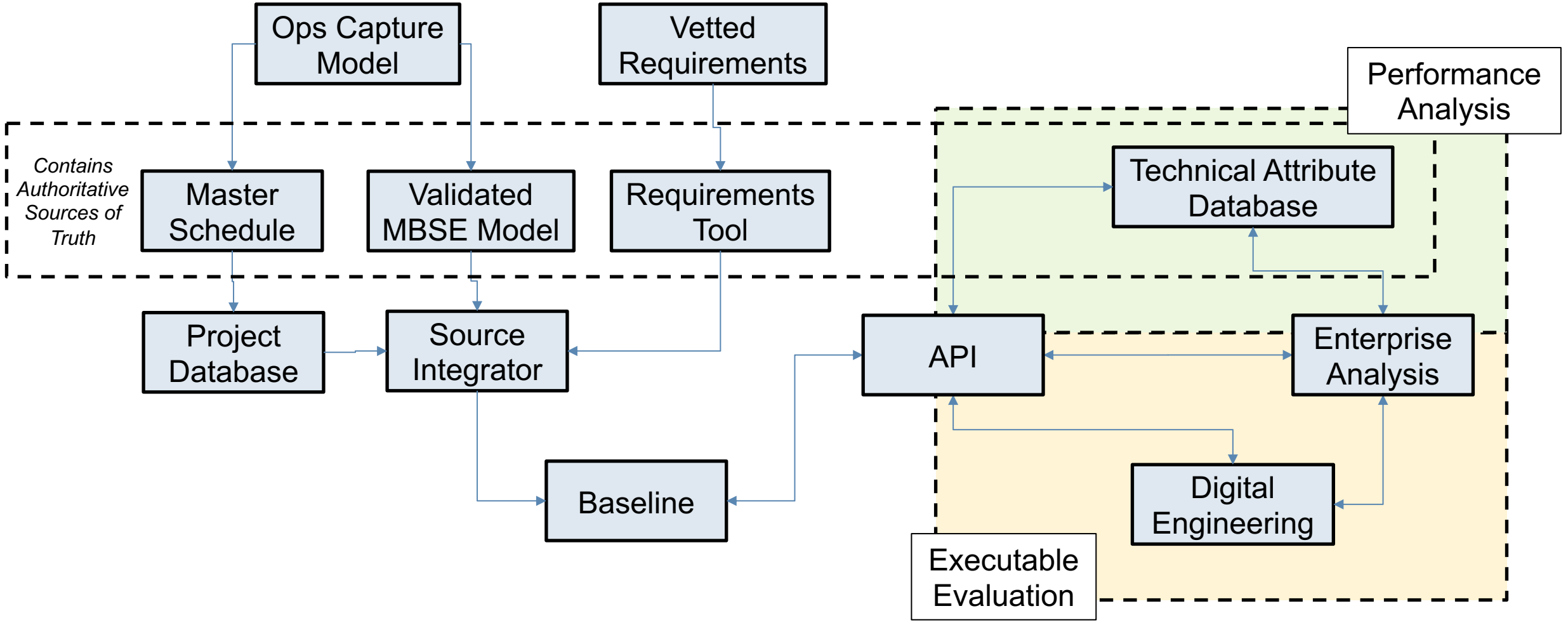


End-to-End MBSE Framework



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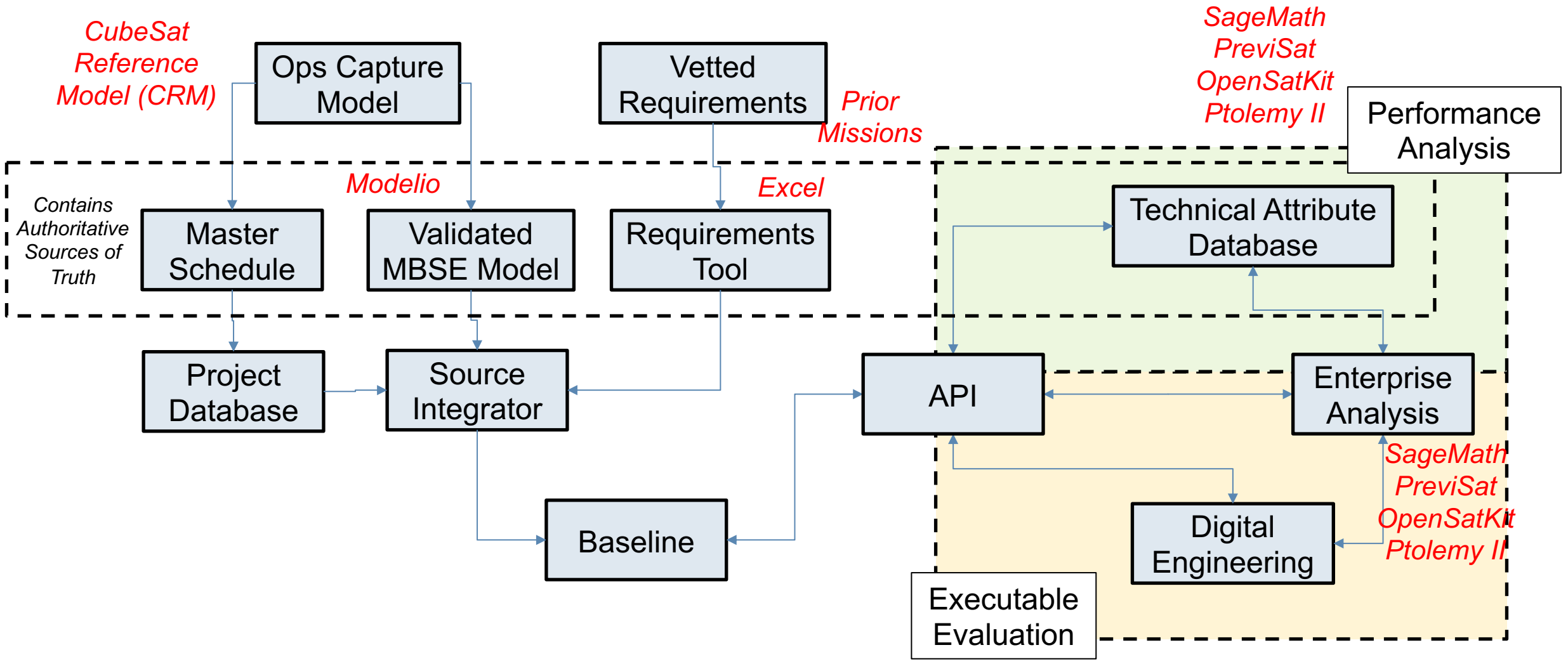
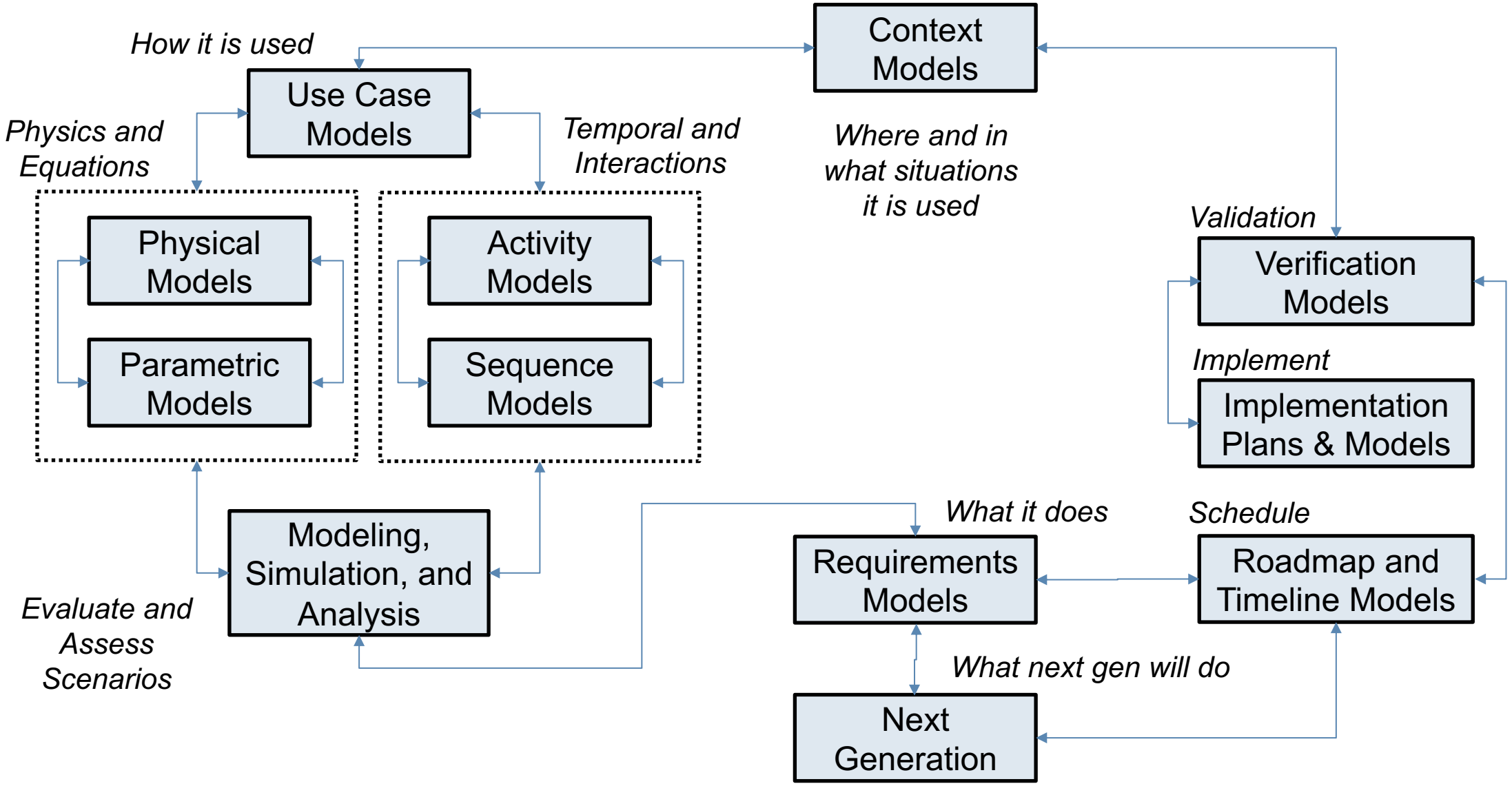


With Open-Source Tools Overlay

Development and Analysis Flows



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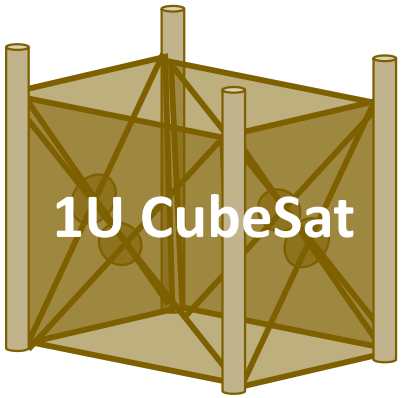
Previous CubeSat Efforts

- CubeSat Reference Mission
  - *International Council on Systems Engineering (INCOSE) Space Systems Working Group (SSWG) Space Systems MBSE Challenge team in 2007*
    - Since 2011 the SSWG Challenge team is investigating a MBSE CubeSat design
  - *Object Management Group (OMG) CubeSat Model*
    - Space Domain Task Force (SDTF) developed the CRM OMG specification
    - CRM used as a basis to design and build mission specific CubeSats
  - *MBSE CubeSat Reference Model Development*
  - *Verification and Validation (V&V) of a MBSE Compliant CubeSat Reference Model*
- NSF & NASA Radio Aurora Explorer (RAX) Mission MBSE CubeSat
  - *Project developed a rigorous attempt to embrace MBSE and SysML methods in a CubeSat design process*



RAX Mission

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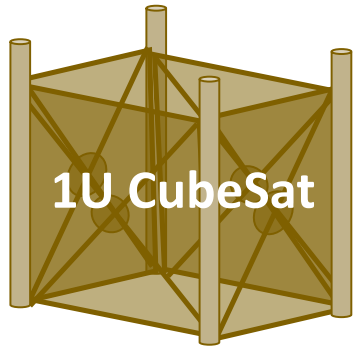
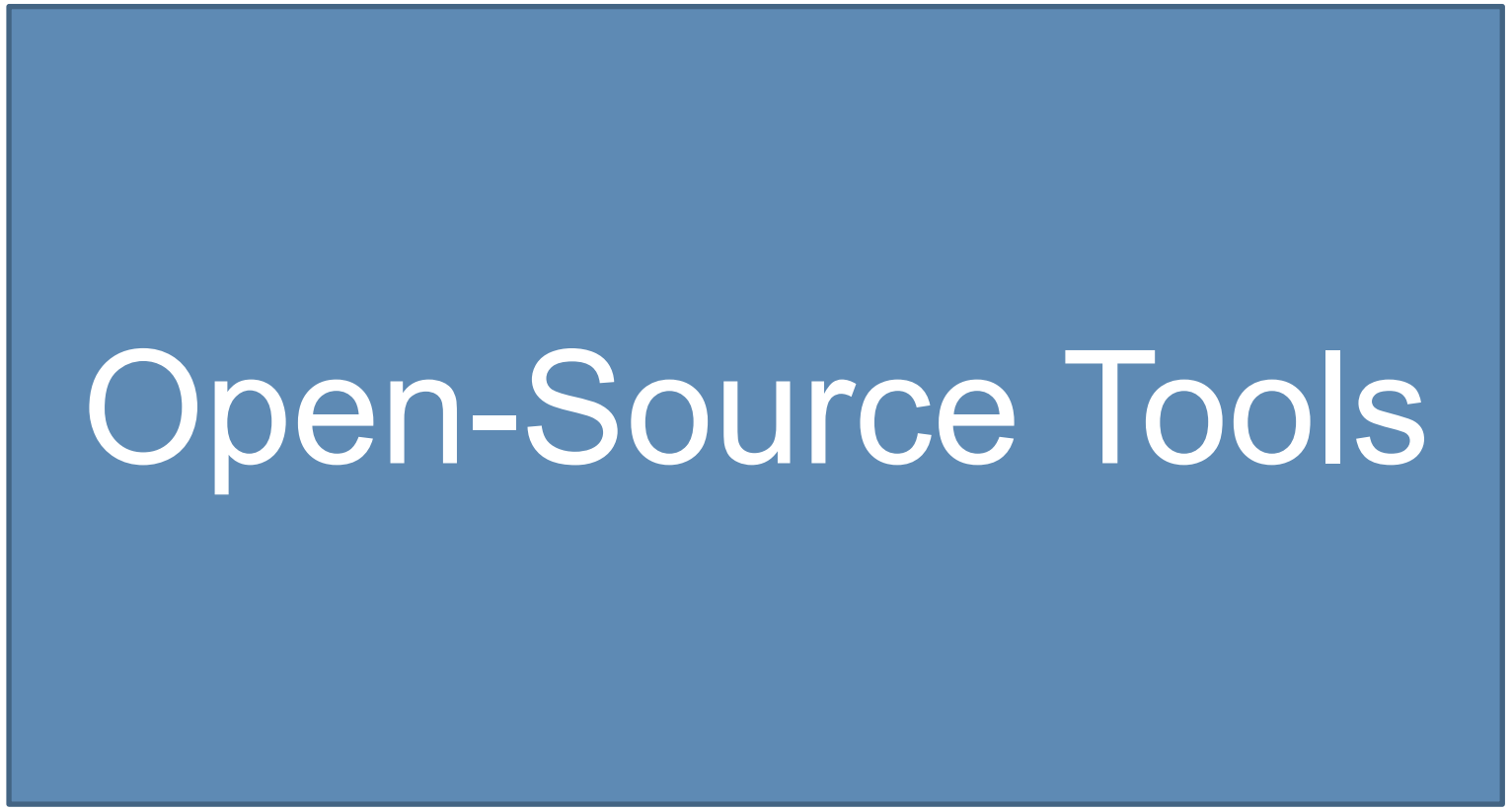
Exemplar CubeSat Mission Top Level Requirements

Requirement	Specification	Comments
Mission	LEO	LEO sun synchronous mission
Key Design Parameters		SWAP, focus of mission
Comm or Imaging mission		Streamline any mission expectations
Size	1U	
Weight	1 – 1.33 Kg	
Power	1 -2 W	
Cost ROM	$ 20,000	Cost separate from launch
Bus		
Structure	10x10x10 cm	Stick with a 1U platform
Computing	Microcontroller	ARM processor, Arduino, or microcontoller
Attitude Control	GPS, IMU	GNSS, and inertial references
Propulsion	Cold Gas	Simple and limited deltaV
Power		Size for worst case mission and eclipse season
Solar Panels		Body mounted
Battery		Size for 2X max power needed in worst case scenario
Thermal Management	Thermal Conduction	Use structures and distribute heat
Communication	VHF, UHF	Use amateur bands
Antennas	Body mount, Whip	Simple but with some gain
Payload		
Sensors	EO, GNSS, RF	Comm or simple RF mission
Communication	L Band	May use bus comm system
Computing	Microcontroller	May use bus microcontroller
Antenna	Whip	May use bus antenna



Key Open-Source Tools

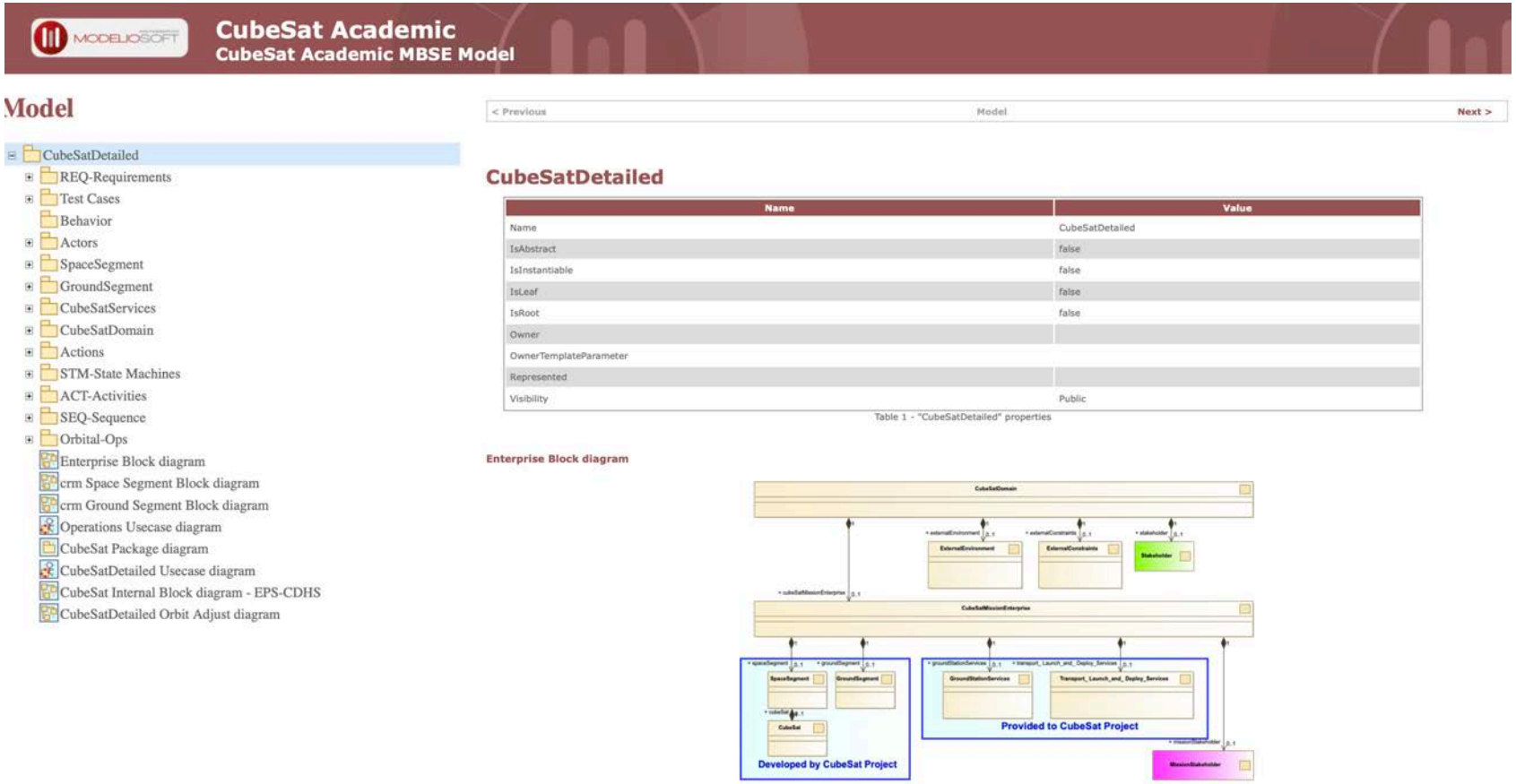
- Modelio
- PreviSat
- SageMath
- OpenSatKit
- Ptolemy II



Modelio

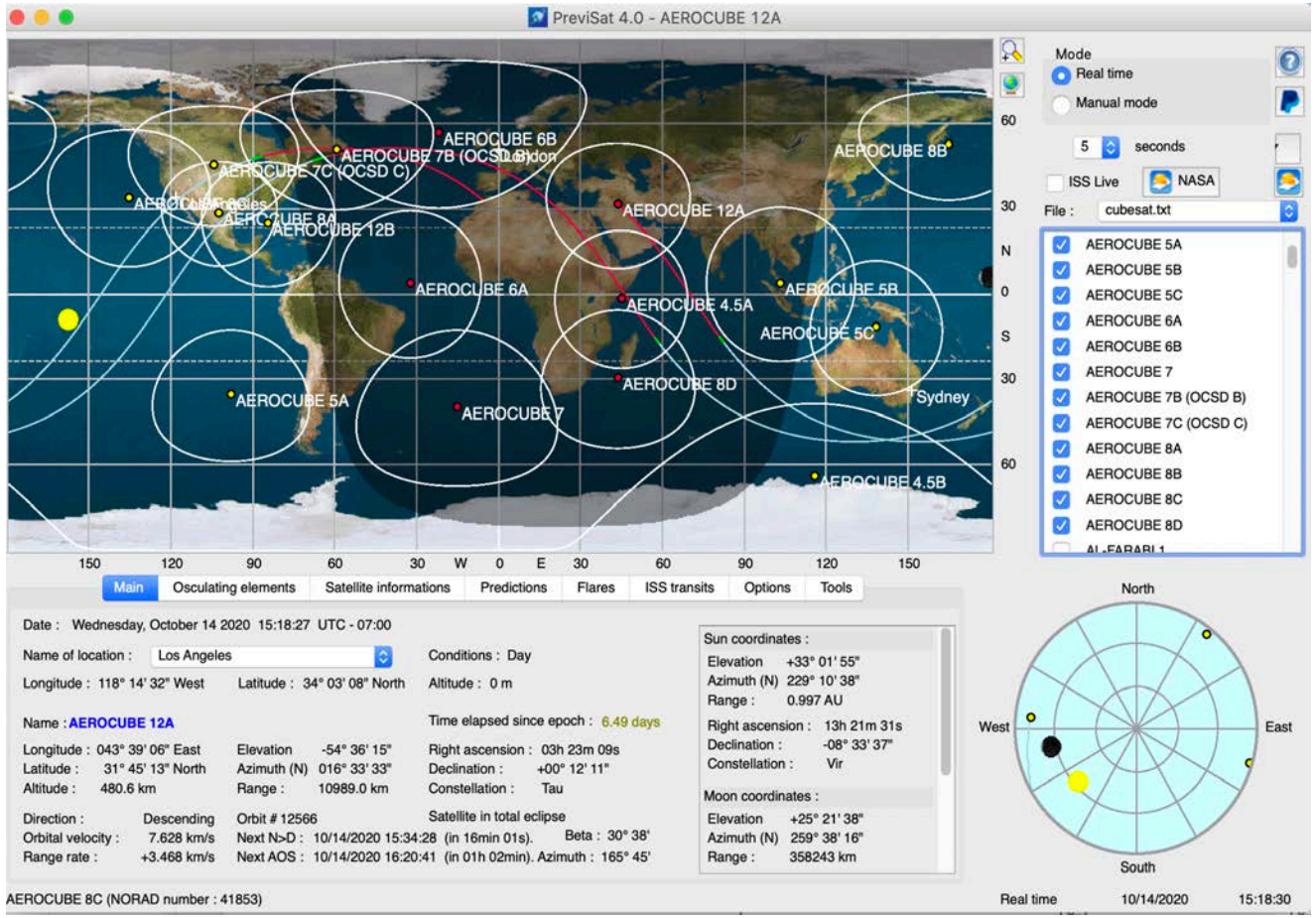
Open Source MBSE Tool

- *Flexible MBSE tool*
- *SysML, UML, BPMN, Java, TOGAF, etc.*
- *Ability to export code and model summaries*
- *www.modelio.org*



PreviSat

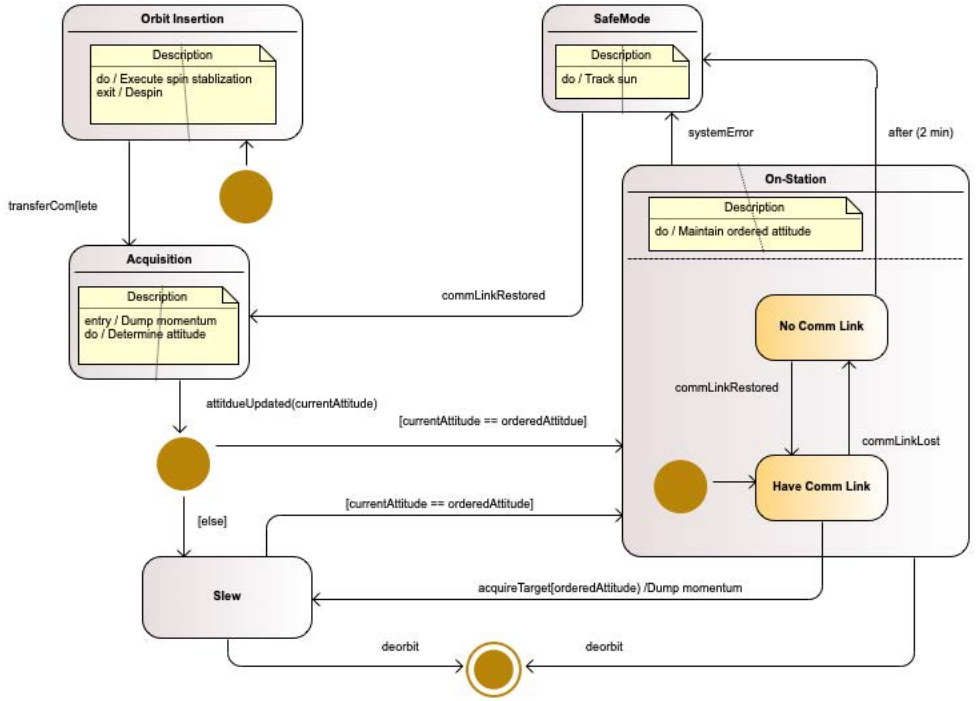
- Previsat provides a Cartesian map viewer of TLE such as what is available from Celestrack.com.
- The illustration below shows the main GUI with AeroCube results being shown.



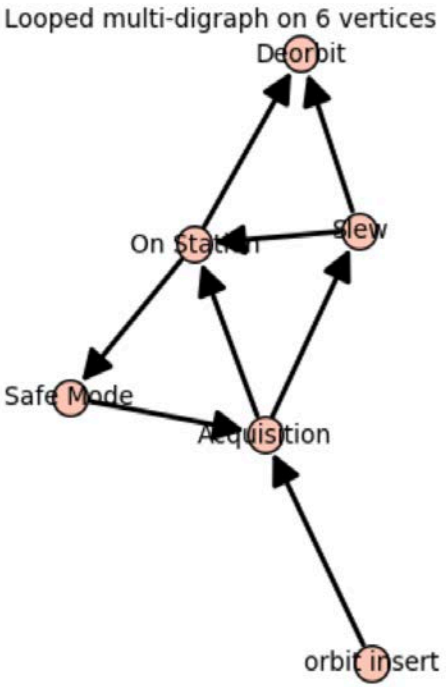
SageMath

- SageMath is a flexible tool suite that allows complex discrete mathematics computations with a scripting notebook approach. This open-source tool leverages Python and its resources along with other influences and has a feature layout similar to Mathematica. It can either be used as a desktop application or via a website using the SageMath Cell online server.
- SageMath https://www.sagemath.org/
- SageMath Cell https://sagecell.sagemath.org/

Satellite Orbital Control - State Machine Diagram

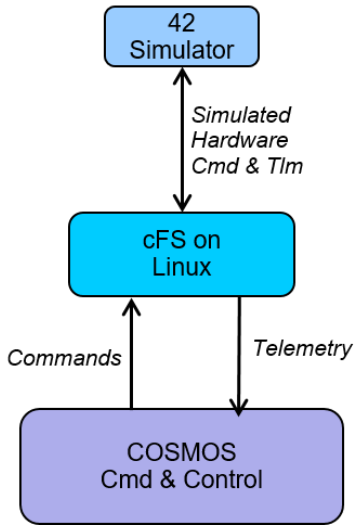


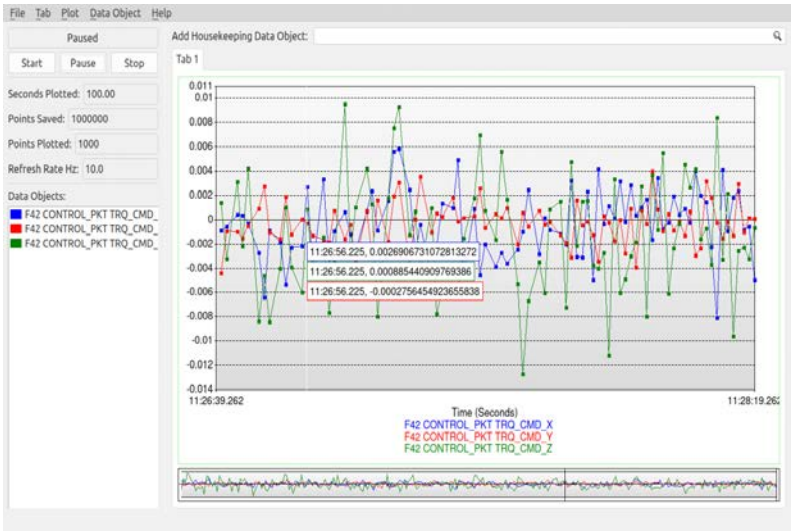

```
fsm = FiniteStateMachine([('orbit insert',
'Acquisition'), ('Acquisition', 'On Station'), ('On
Station', 'Safe Mode'), ('Safe Mode',
'Acquisition'),('Acquisition', 'Slew'), ('Slew', 'On
Station'), ('On Station', 'Deorbit'), ('Slew', 'Deorbit') ])
fsm1 = fsm.graph # used for assessment steps below
fsm.graph()
fsm1.is_planar(set_embedding=True)
True
fsm1.is_eulerian()
False
```

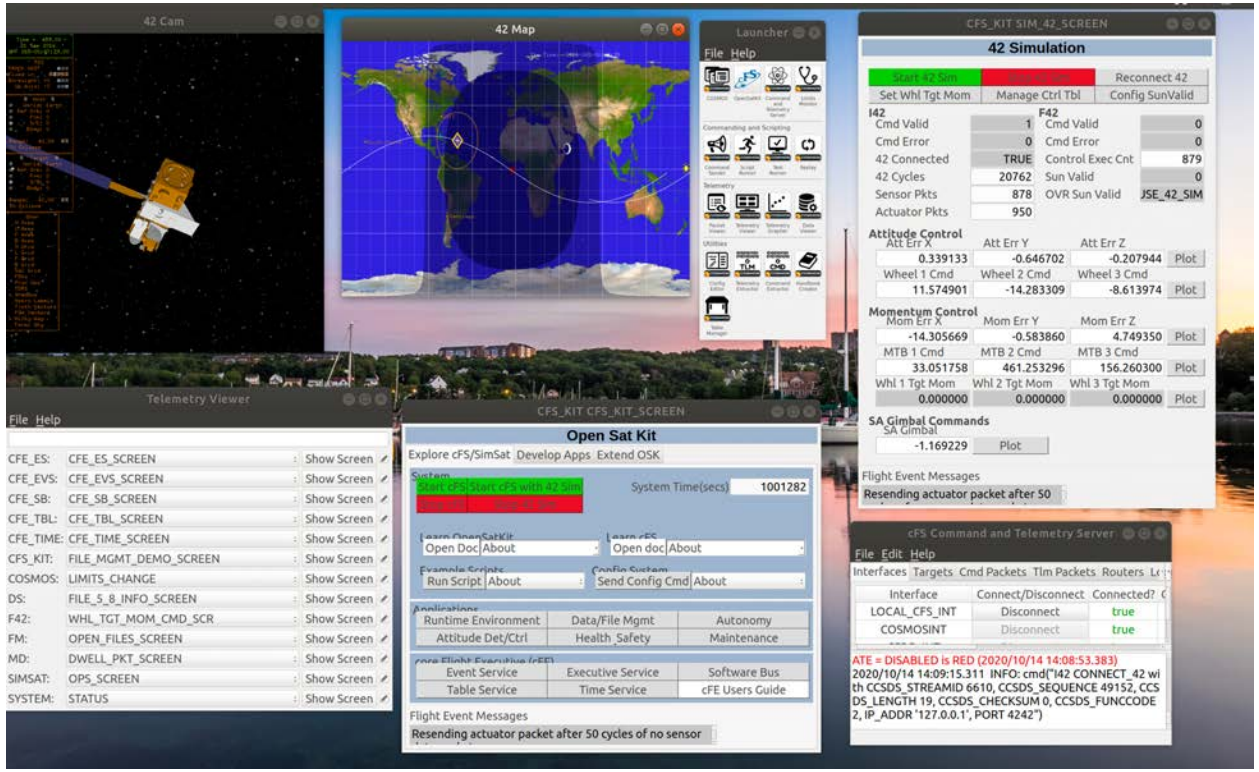


OpenSatKit

- OpenSatKit provides a mechanism to command a realistic CubeSat and analyze telemetry using the extensive tools that are packaged with NASA's flight qualified Core Flight System.
- The figure shows a top-level view of the major software elements running at the same time.
- A representative CubeSat mission is included, which can receive commands and process telemetry requests.
- The 42 Map shows a Cartesian map of the orbit, similar to what Previsat displays.

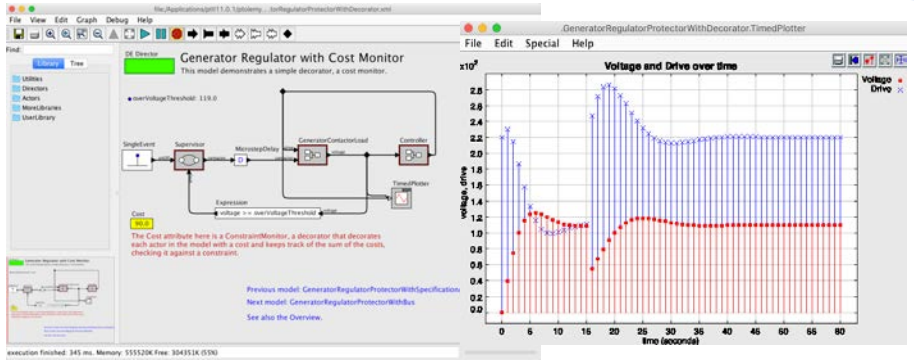


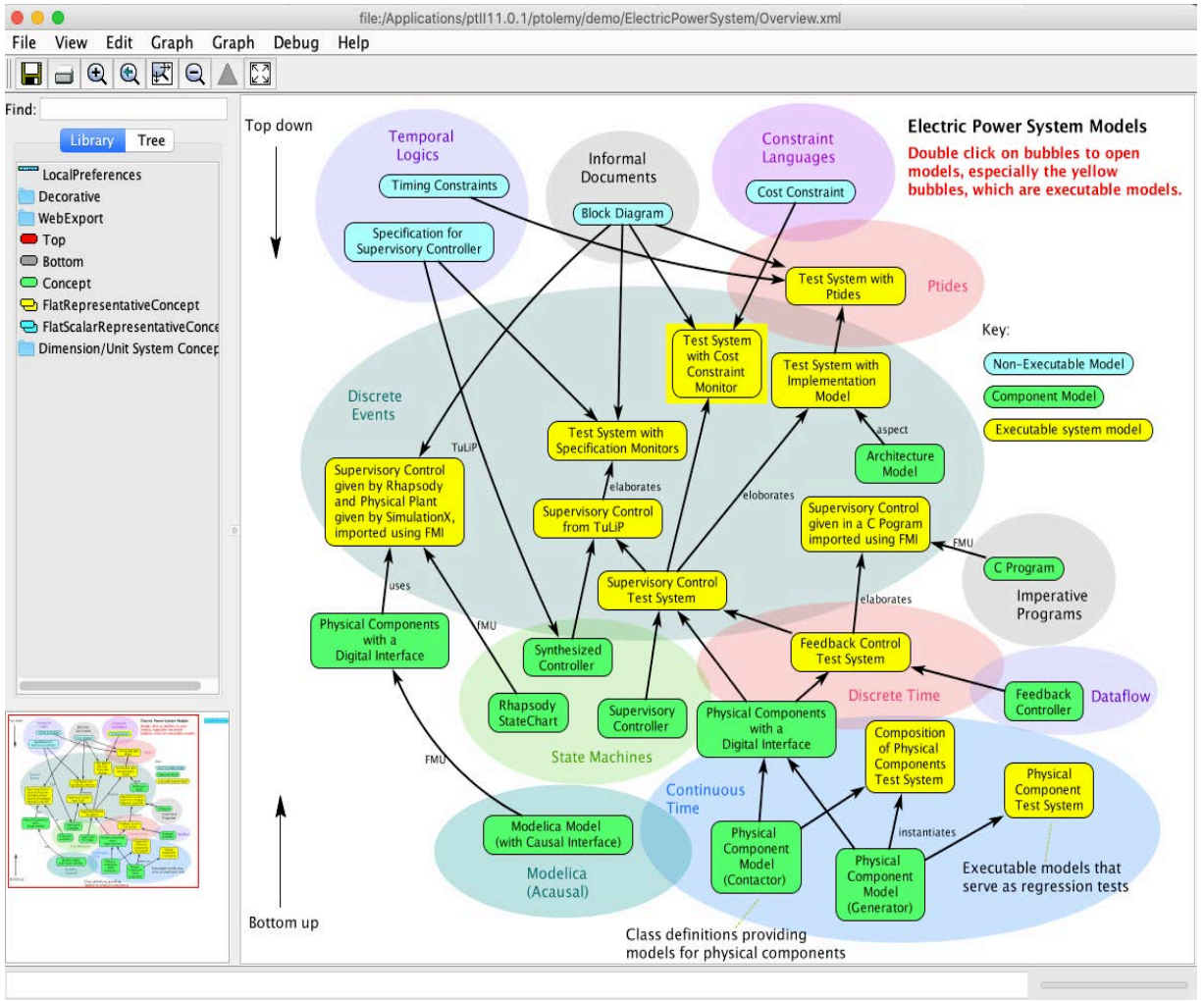




Ptolemy II

- Ptolemy II is an executable graphical block-diagram language composed of a number of preprogrammed modules that has been in development for over thirty years. It is an open-source simulation and modeling tool that is intended for experimenting with system design techniques, including the combination of different types of models. Creating executable scenarios are a straightforward process.
- Ptolemy II has many models of computation such as the following, (1) dataflow, (2) process networks and rendezvous, (3) synchronous-reactive, (4) finite state machines, (5) discrete event, (6) modal, (7) continuous time, (8) timed systems, and (9) event-oriented computation. The modeling infrastructure uses a package structure with actors and models of computing. Actos and various modes of computing can be invoked.
- Ptolemy II https://ptolemy.berkeley.edu/ptolemyII/index.htm
- Claudius Ptolemaeus, *System Design, Modeling, and Simulation: Using Ptolemy II* (Creative Commons, 2014, Version 1.02), xii-xvi, 1.





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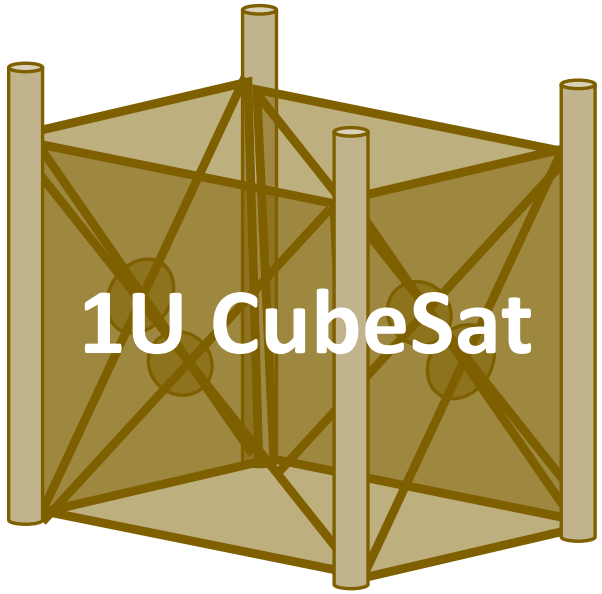
National Critical Functions

- DHS CISA defines national critical functions as "functions of government and the private sector so vital to the United States that their disruption, corruption, or dysfunction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof."
- A total of 55 critical functions are discussed, and the national critical functions "allows for a more robust prioritization of critical infrastructure and a more systematic approach to risk management."
- Of the four critical function groups of connect, distribute, manage, and supply CubeSats contribute to all critical functions as currently conceived.
- National Critical Functions, https://www.cisa.gov/national-critical-functions
- National Critical Functions Status Update, https://www.cisa.gov/sites/default/files/publications/ncf-status-update-to-critical-infrastructure-community_508.pdf

National Critical Functions Alignment

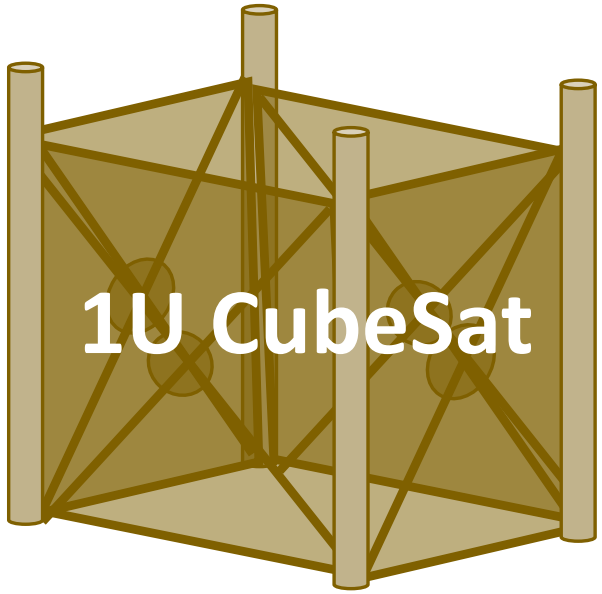


National Critical Function Major Categories

Connect	Distribute	Manage	Supply

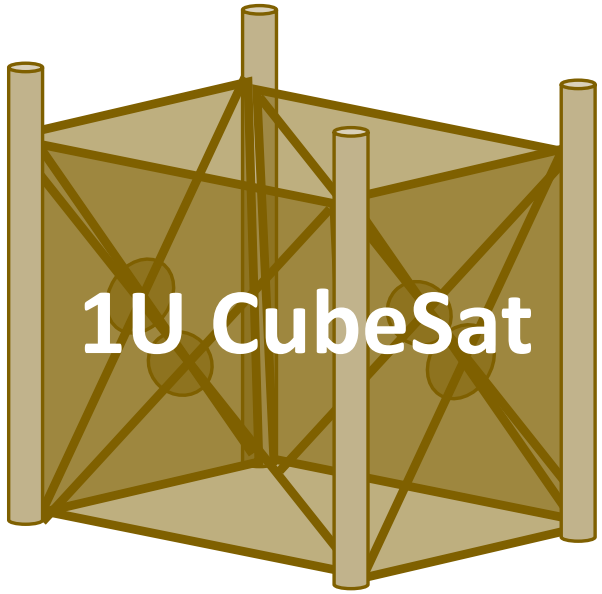
		Function		CubeSat
Connect	1	Operate Core Network		
	2	Provide Cable Access Network Services		
	3	Provide Internet Based Content, Information, and Communication Services		
	4	Provide Internet Routing, Access, and Connection Services		
	5	Provide Positioning, Navigation, and Timing Services		X
	6	Provide Radio Broadcast Access Network Services		X
	7	Provide Satellite Access Network Services		X
	8	Provide Wireless Access Network Services		
	9	Provide Wireline Access Network Services		
Distribute	10	Distribute Electricity		
	11	Maintain Supply Chains		X
	12	Transmit Electricity		
	13	Transport Cargo and Passengers by Air		
	14	Transport Cargo and Passengers by Rail		
	15	Transport Cargo and Passengers by Road		
	16	Transport Cargo and Passengers by Vessel		
	17	Transport Materials by Pipeline		
	18	Transport Passengers by Mass Transit		

National Critical Functions Alignment



		Function		CubeSat
Manage	19	Conduct Elections		
	20	Develop and Maintain Public Works and Services		
	21	Educate and Train		
	22	Enforce Law		X
	23	Maintain Access to Medical Records		X
	24	Manage Hazardous Materials		
	25	Manage Wastewater		
	26	Operate Government		X
	27	Perform Cyber Incident Management Capabilities		X
	28	Prepare for and Manage Emergencies		
	29	Preserve Constitutional Rights		
	30	Protect Sensitive Information		
	31	Provide and Maintain Infrastructure		
	32	Provide Capital Markets and Investment Activities		
	33	Provide Consumer and Commercial Banking Services		
	34	Provide Funding and Liquidity Services		
	35	Provide Identity Management and Associated Trust Support Services		
	36	Provide Insurance Services		
	37	Provide Medical Care		
	38	Provide Payment, Clearing, and Settlement Services		
	39	Provide Public Safety		X
	40	Provide Wholesale Funding		
	41	Store Fuel and Maintain Reserves		
	42	Support Community Health		X

National Critical Functions Alignment



		Function		CubeSat
Supply	43	Exploration and Extraction of Fuels		
	44	Fuel Refining and Processing Fuels		
	45	Generate Electricity		
	46	Manufacture Equipment		
	47	Produce and Provide Agricultural Products and Services		
	48	Produce and Provide Human and Animal Food Products and Services		
	49	Produce Chemicals		
	50	Provide Metals and Materials		
	51	Provide Housing		
	52	Provide Information Technology Products and Services		X
	53	Provide Materiel and Operational Support to Defense		X
	54	Research and Development		X
	55	Supply Water		

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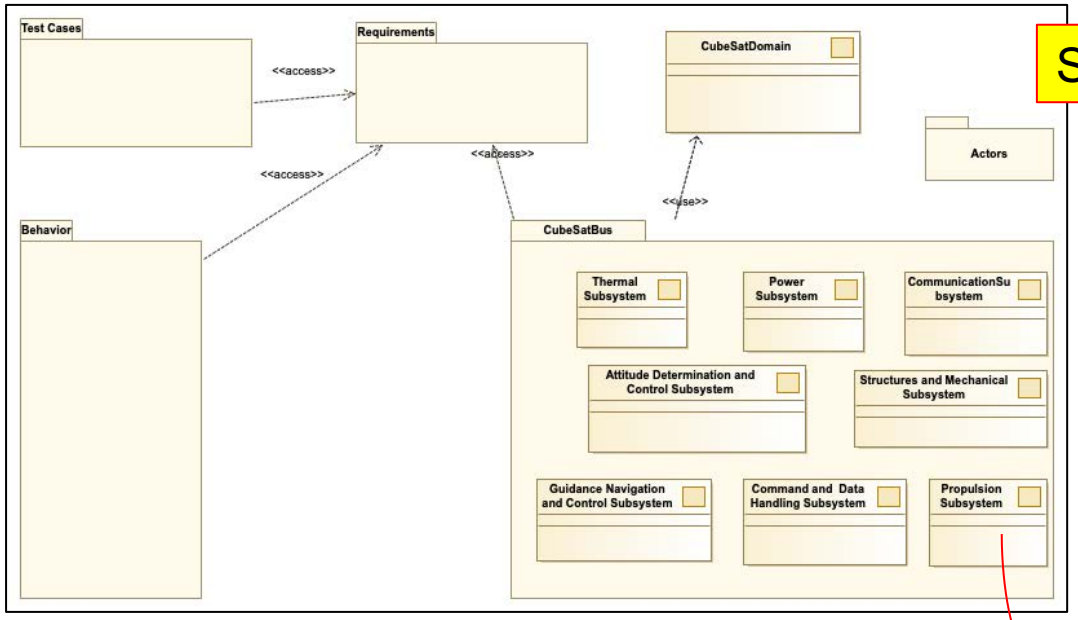
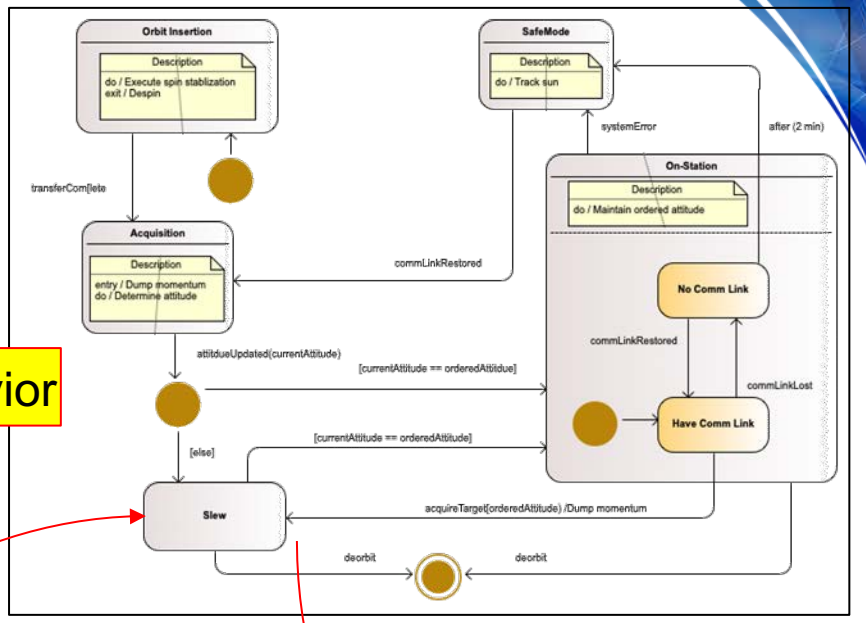
CubeSat SysML Model - Maneuver

Structure



Behavior



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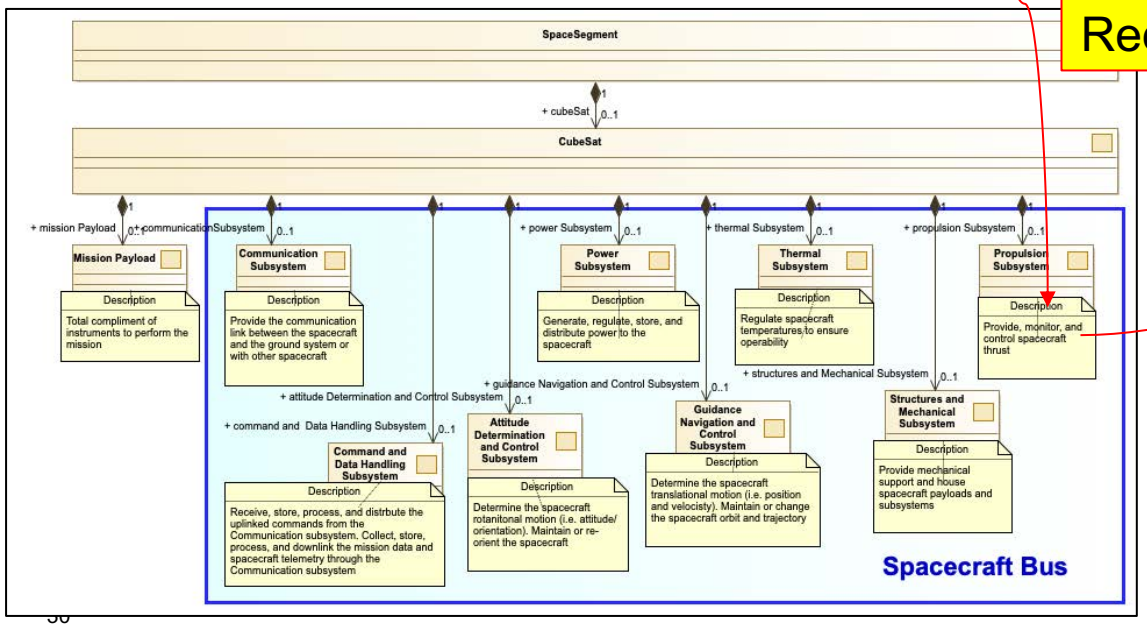

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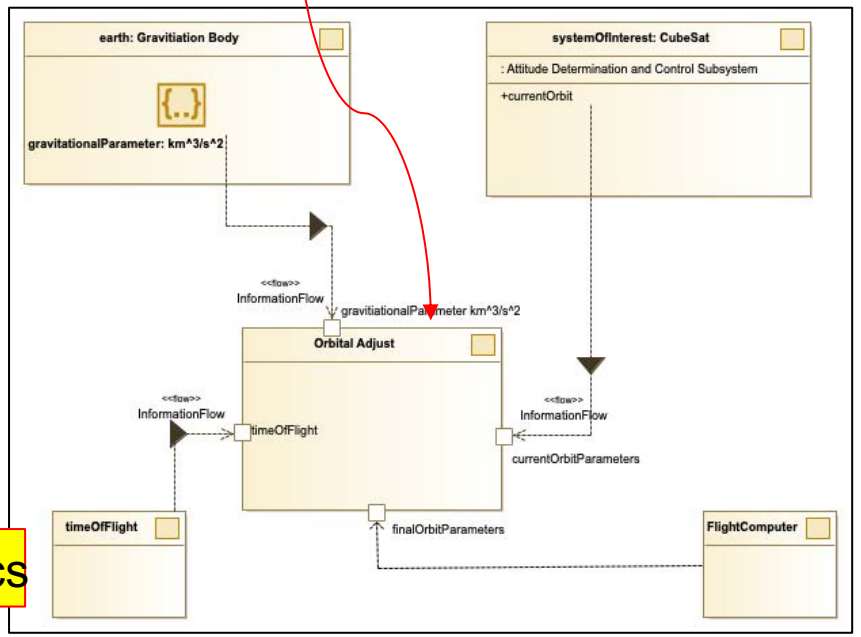
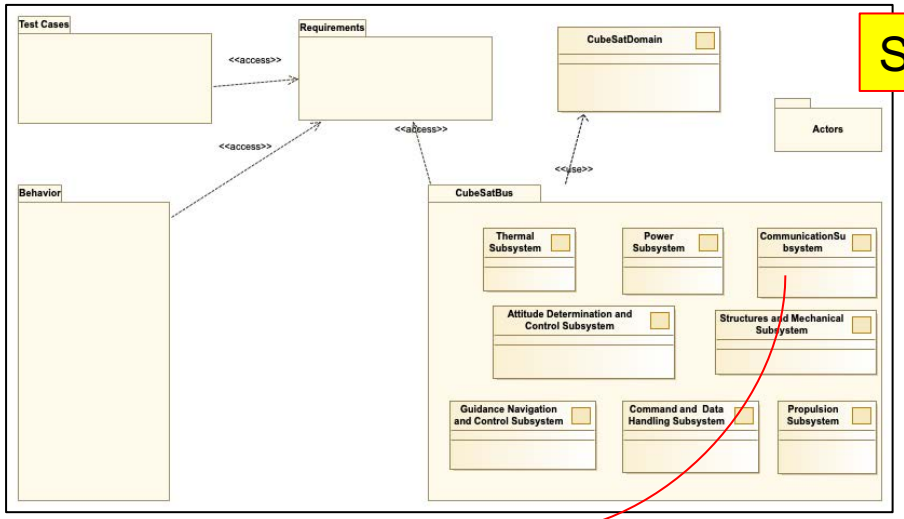


CubeSat SysML Details – Comm & Tlm



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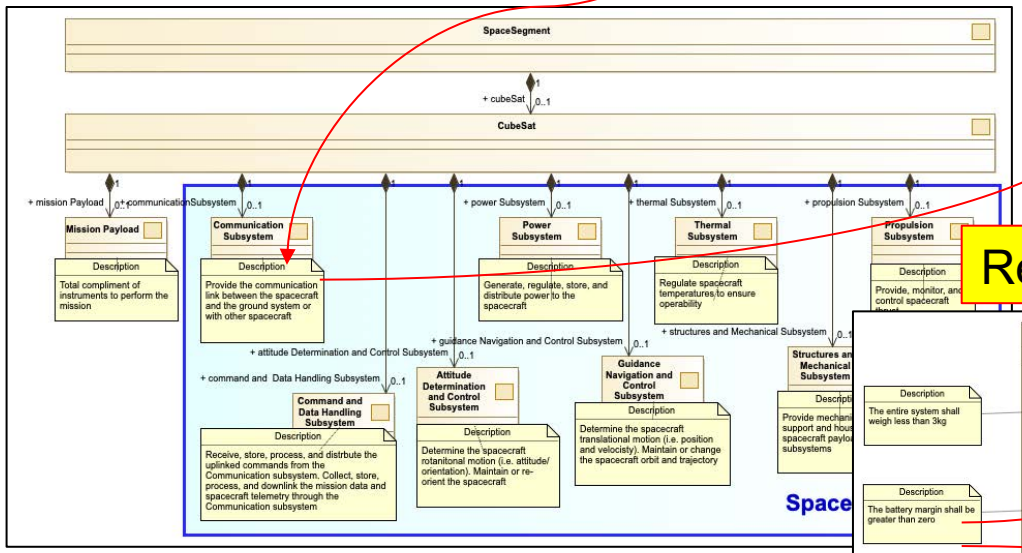

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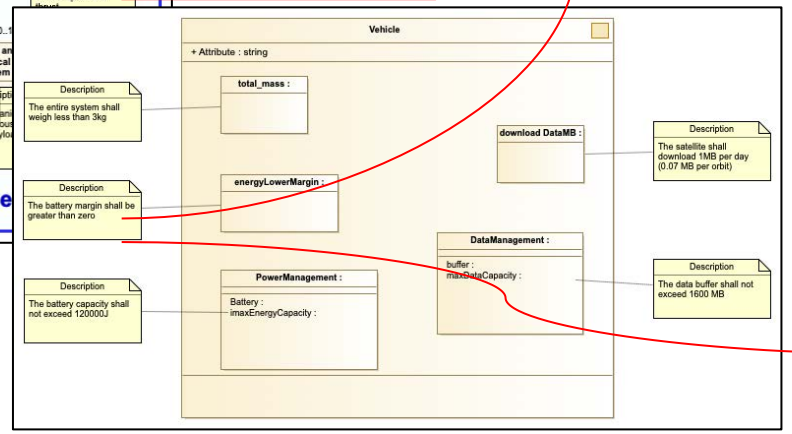
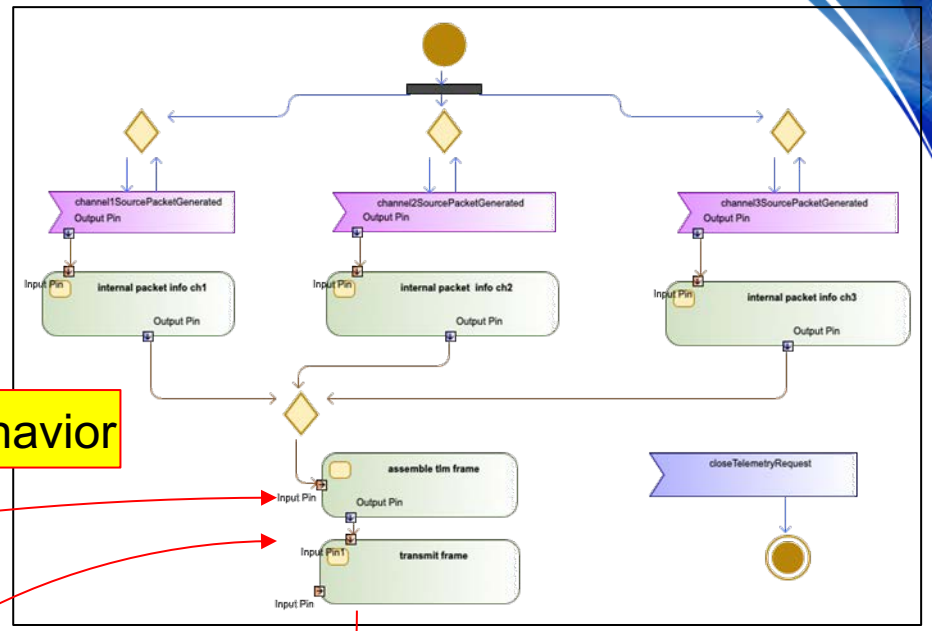
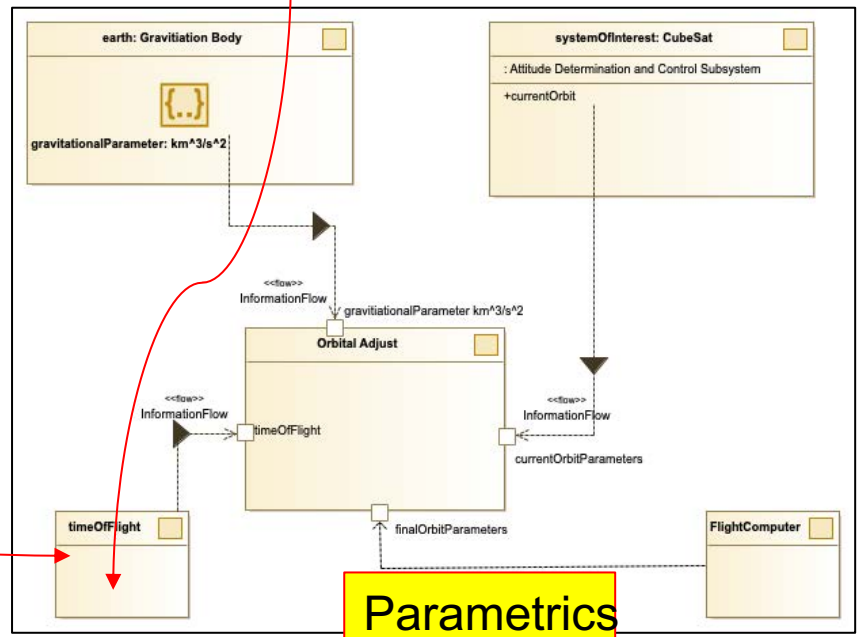


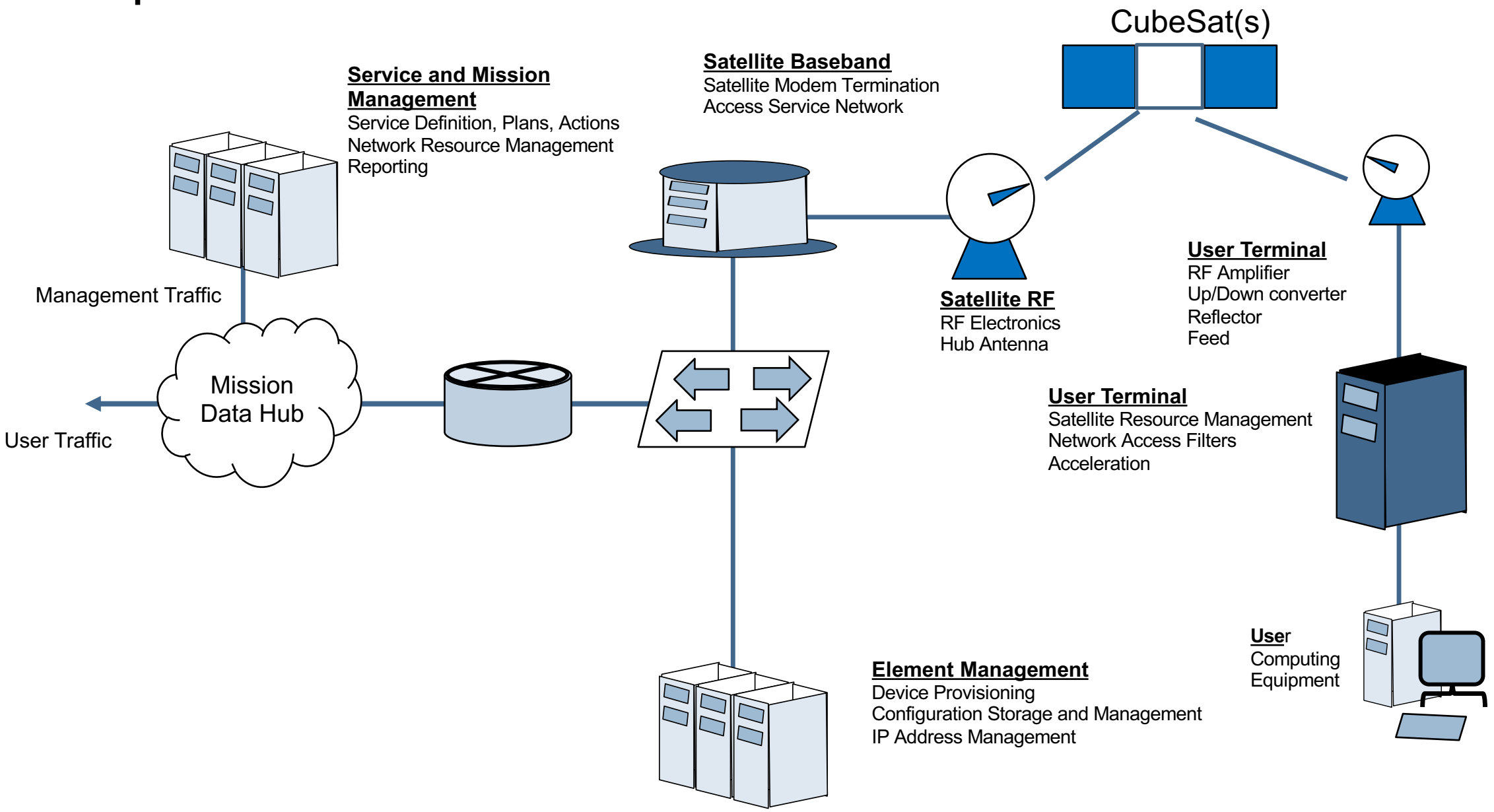


Behavior

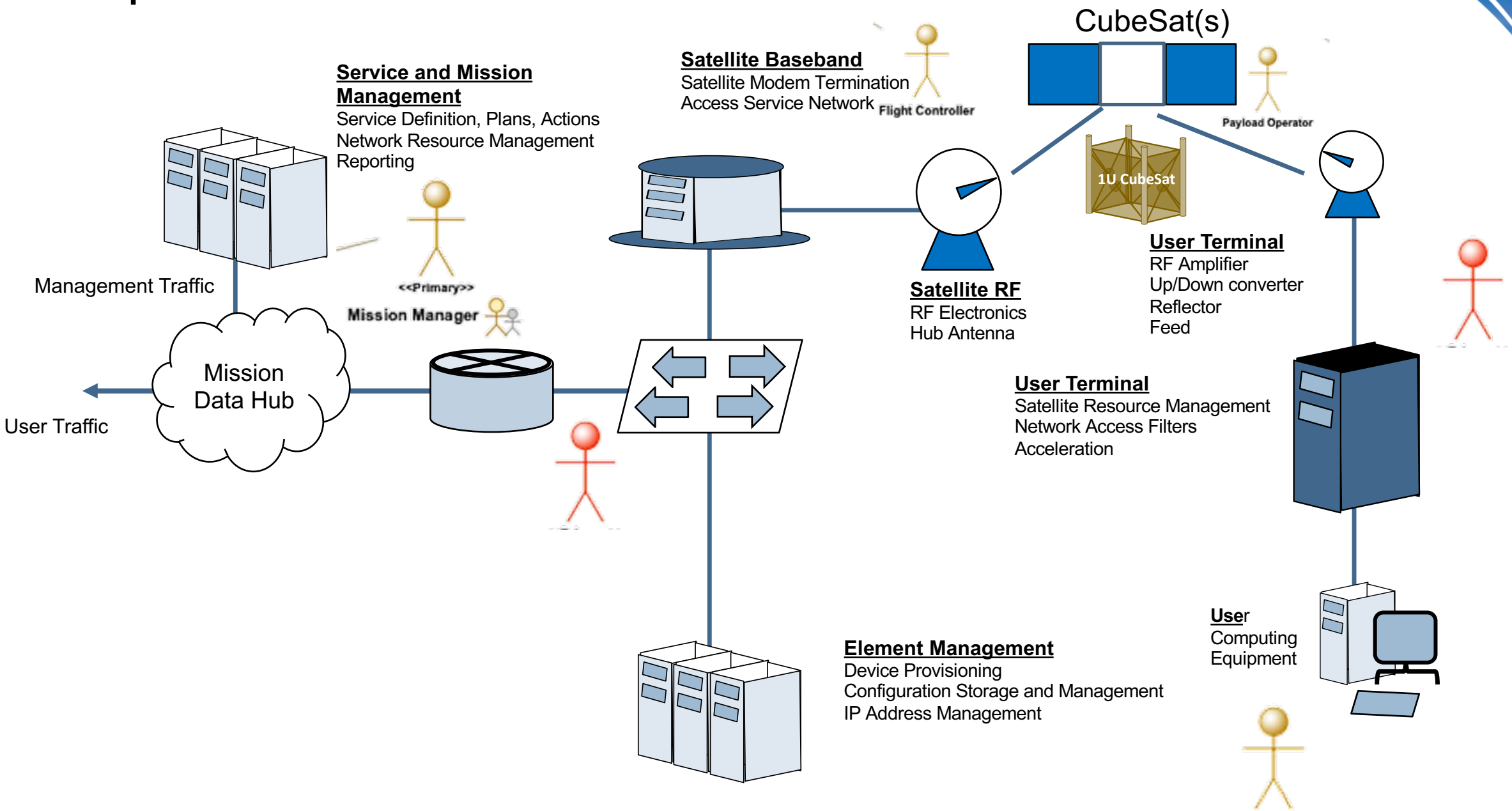


Parametrics

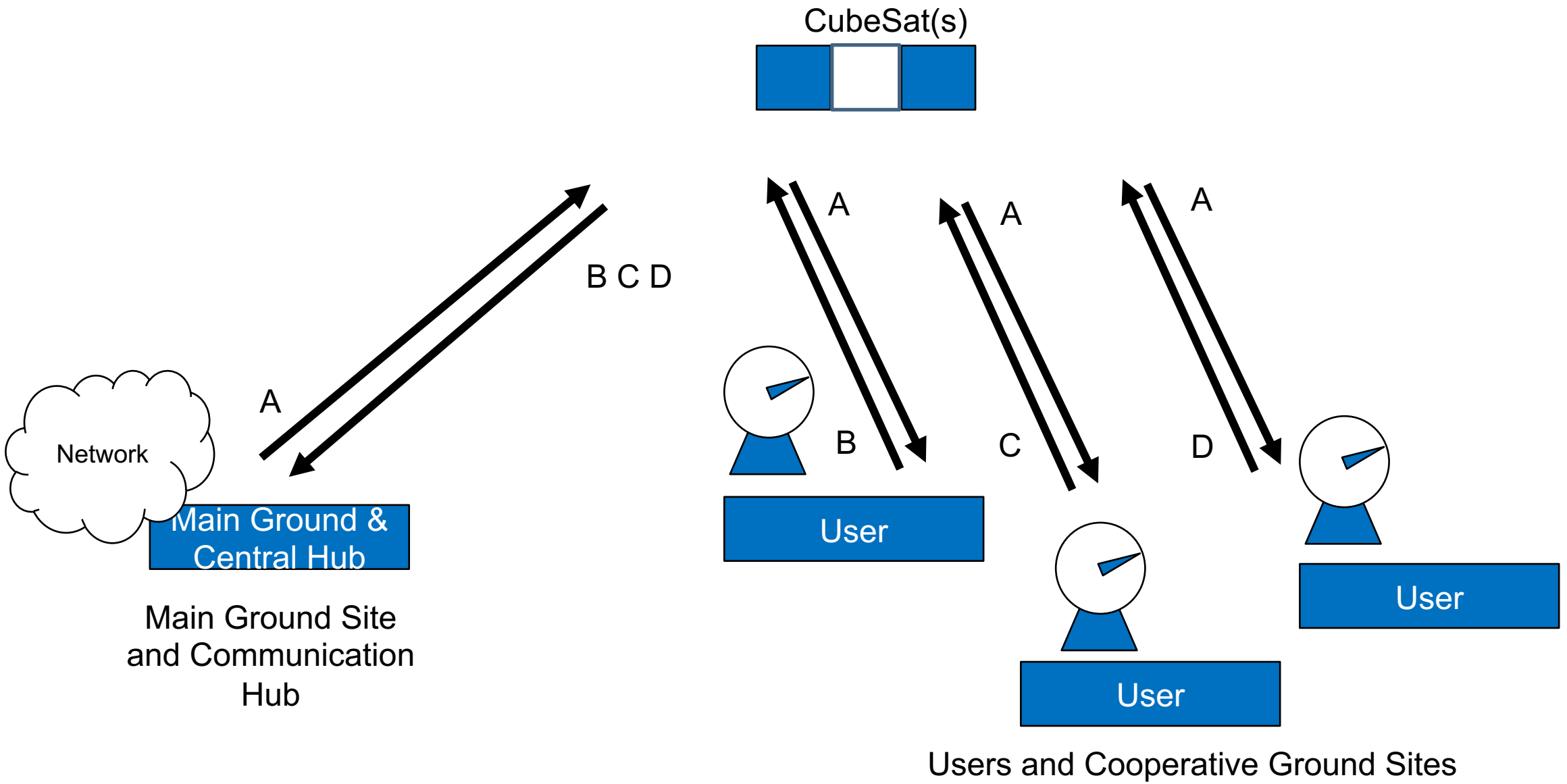
Exemplar Communication CubeSat Mission Ground



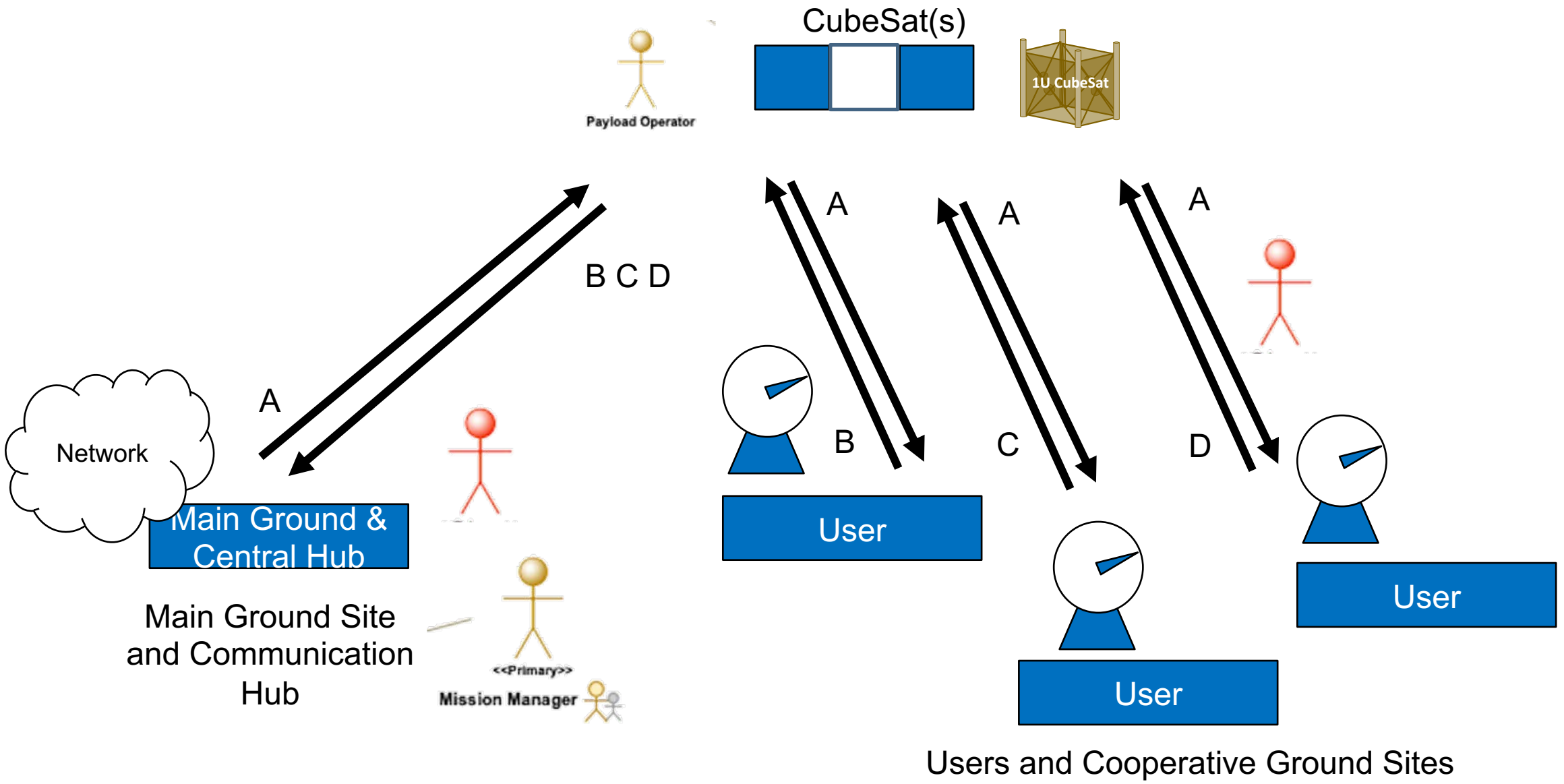
Exemplar Communication CubeSat Mission Ground



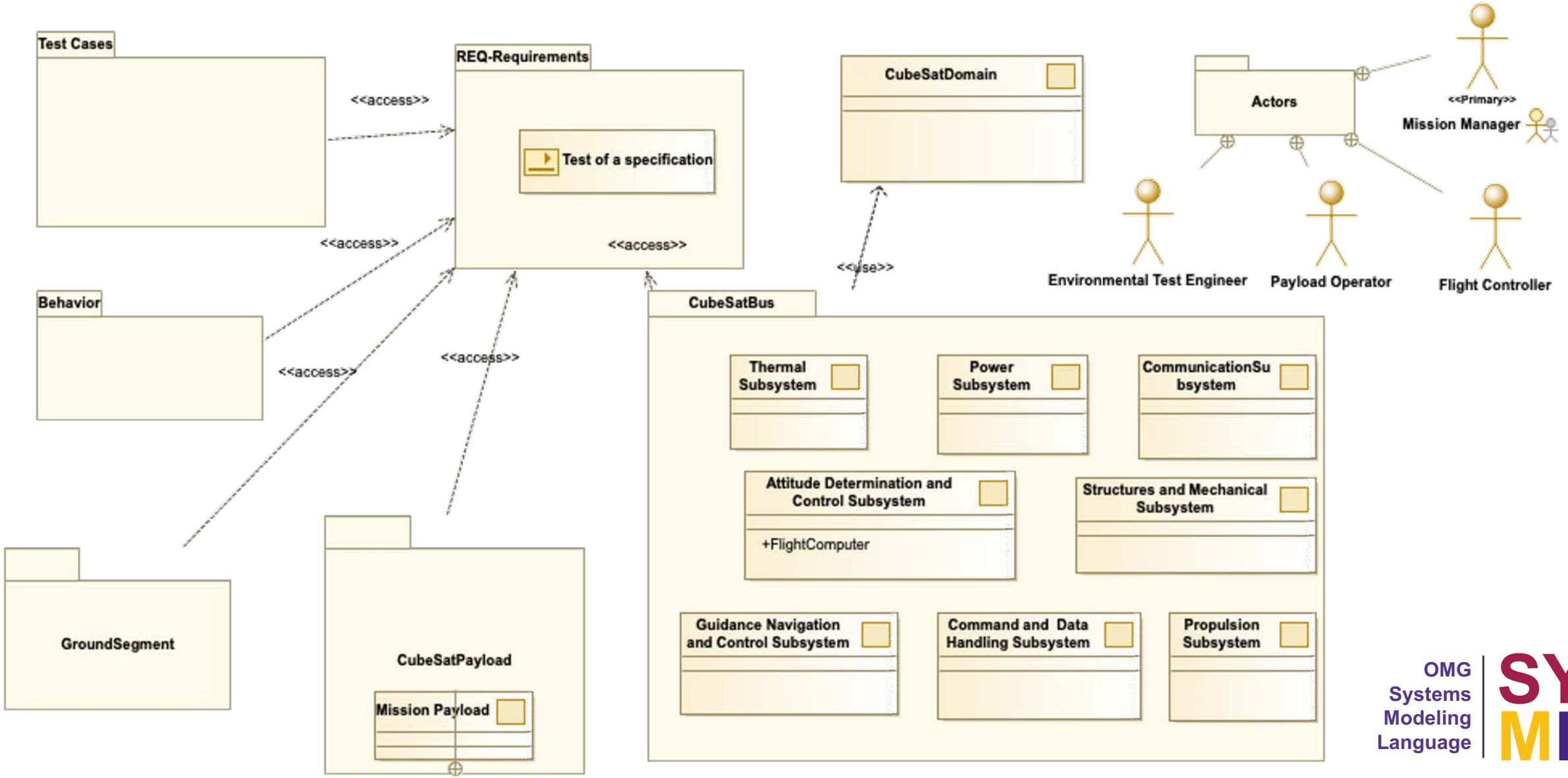
Exemplar CubeSat(s) Communication Network



Exemplar CubeSat(s) Communication Network



CubeSat Mission - Package Diagram



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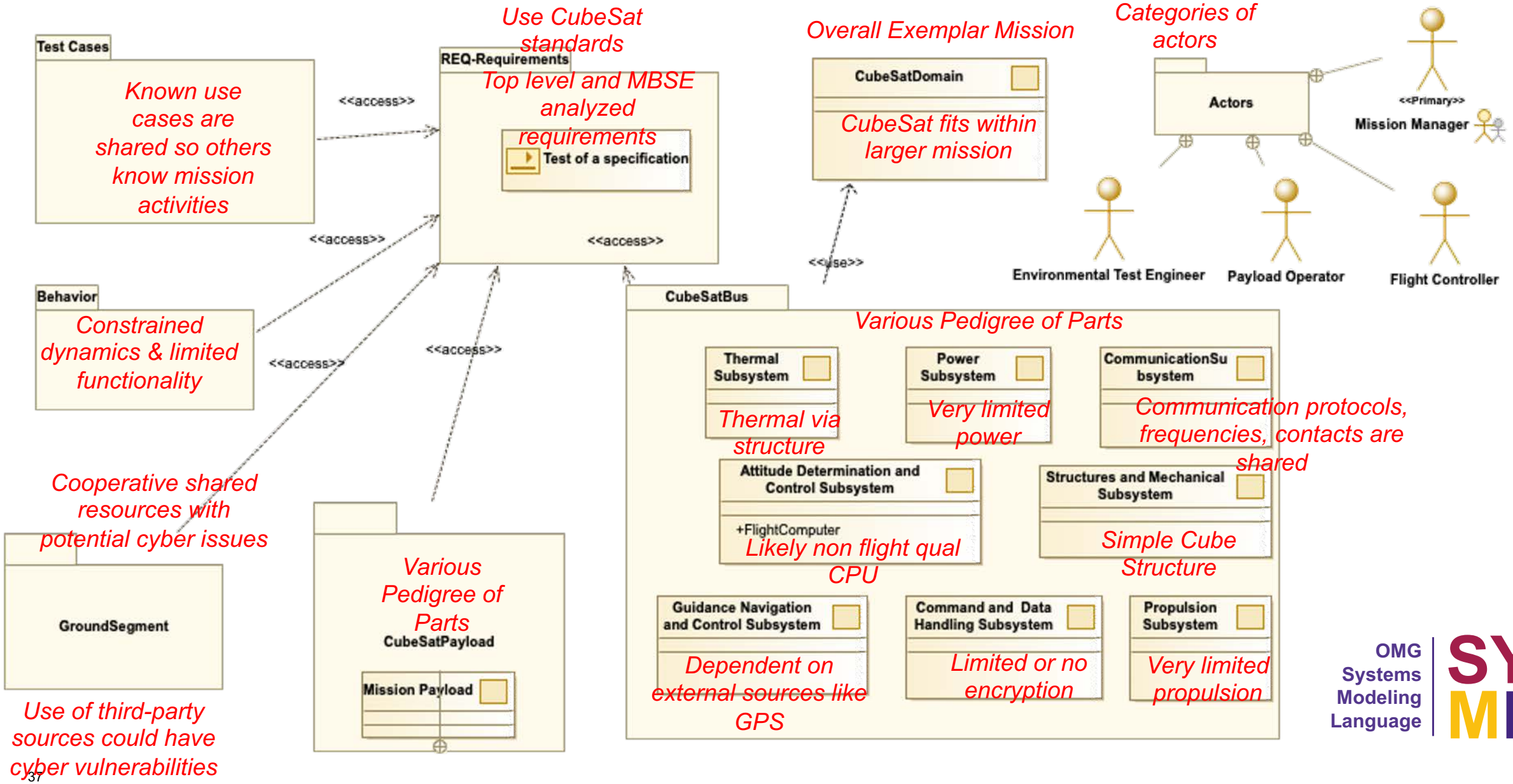
CubeSat Mission - Package Diagram



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CubeSat Function and Cyber Access

Function	Remote Cyber Access	Software Updates	Firmware Updates	NCF Use	Mission Use
CubeSat Bus	X				
CubeSat Bus Subsystems					
Flight Software	X	X			
CubeSat Payload	X				
CubeSat Payload Subsystems					
Ground Station	X	X	X		X
Mission Operations	X	X			
Mission Controllers and Access	X	X			
Mission System Users	X			X	X
Mission Data Users	X			X	X
Terrestrial Relay	X			X	X
Cooperative Amateur Ground Sites	X	X			
Professional Services e.g., AWS	X				X
Amateur Networks AMSAT	X				
Open-Source Software		X			
Open-Source Hardware			X		

Outline

- Abstract
- Introduction
  - *Study Thesis*
  - *Background*
  - *Approach*
- Previous Efforts
- CubeSat Model and Applications
  - *Key Open-Source Tools*
  - *Executable CubeSat Simulation*
  - *CubeSat Tailored MBSE SysML Model*
- Study Assessment
  - *National Critical Functions*
  - *Mission Assessment*
- **Summary and Conclusions**

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Summary and Conclusions

(1) MBSE Tool Maturity

- MBSE tools continue to mature and show promise for reducing cost, capturing design details more effectively, and offer tools to adapt to changes as required.
- This includes using these tools for the type of missions CubeSats would address.
- Often these include new entrants into the space market, including academic institutions and new service providers.
- System engineering methods can greatly be aided by both MBSE and digital engineering methods.

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Summary and Conclusions

(2) CubeSat Exemplar Design Evaluation

- In this study the use of open source MBSE tools were applied towards a CubeSat reference mission.
- There is work up front required to properly seed the model.
- Once this is done it rapidly gets easier to take next steps in the assessment phase.

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(3) Critical Function Assessment

- With this model in place, the assessment looked at national critical functions and how CubeSats can contribute to ensuring these infrastructural elements are maintained.
- With the four DHS national critical function categories of connect, distribute, manage, and supply CubeSats contribute to all, at least as a contributor, as discussed in this study. Communication and focused sensing in the manage category is a key area of the mission CubeSats may be able to contribute.

Summary and Conclusions

(4) Mission Assessment and Cyber Vulnerability

- There are various areas where cyber access could be accomplished by undesired actors.
- This must be monitored when navigating between openness and ensuring the CubeSat mission can contribute productively to missions in science, communication, navigation, search and rescue, etc.
- Use of various pedigree of parts can inadvertently create single points of failure.
- Lack of diligent upgrades of firmware and software can leave the system at risk.

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Back Up

SysML Summary

- SysML is a richly expressive graphical modeling language that you can use to visualize the structure, behavior, requirements, and parametrics of a system and communicate that information to others.
- SysML defines nine kinds of diagrams that you can use to convey all this system design information; each kind serves a specific purpose and conveys specific information about an aspect of a system.

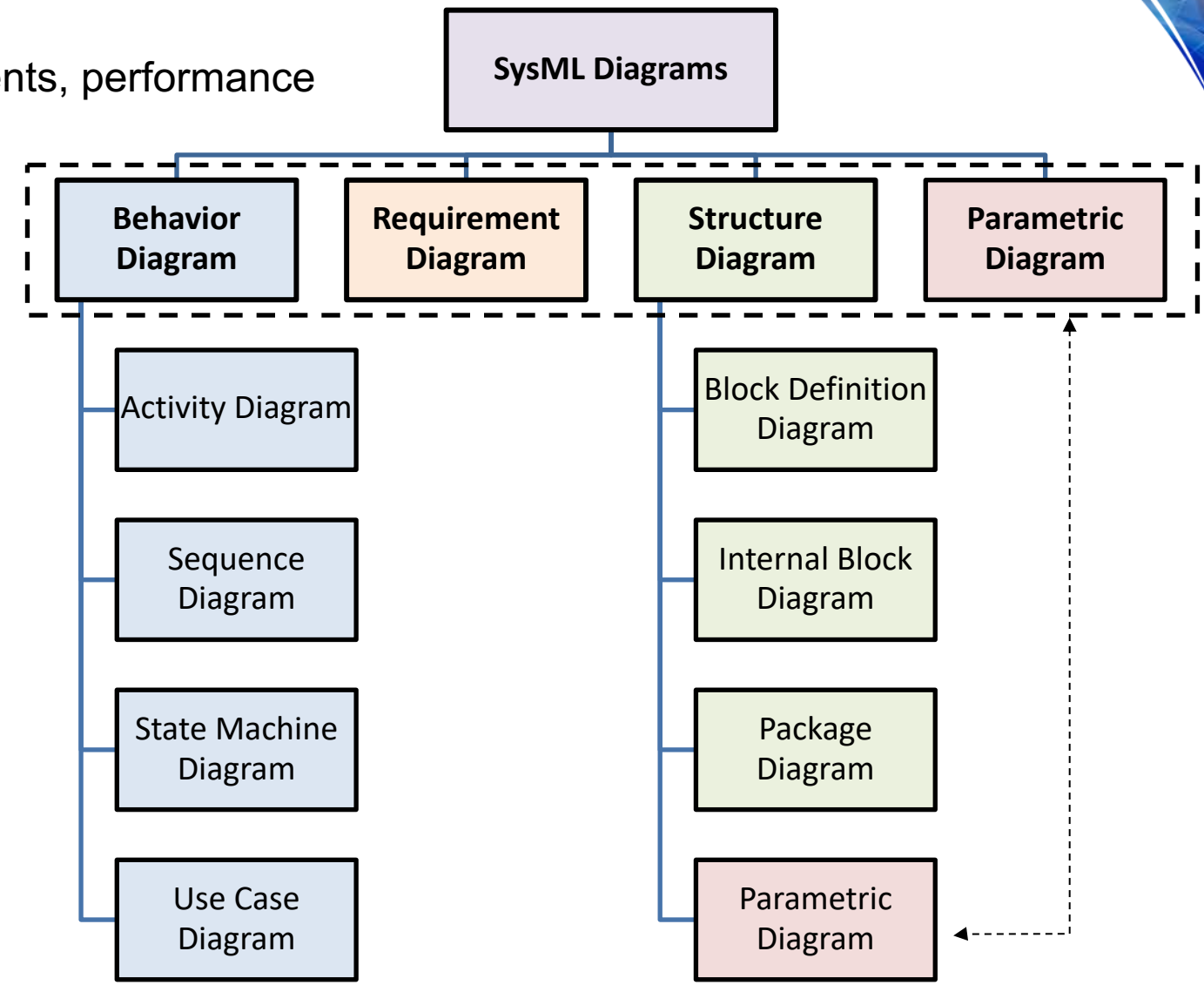
SysML Distilled, 21

MBSE SysML Diagrams and Application

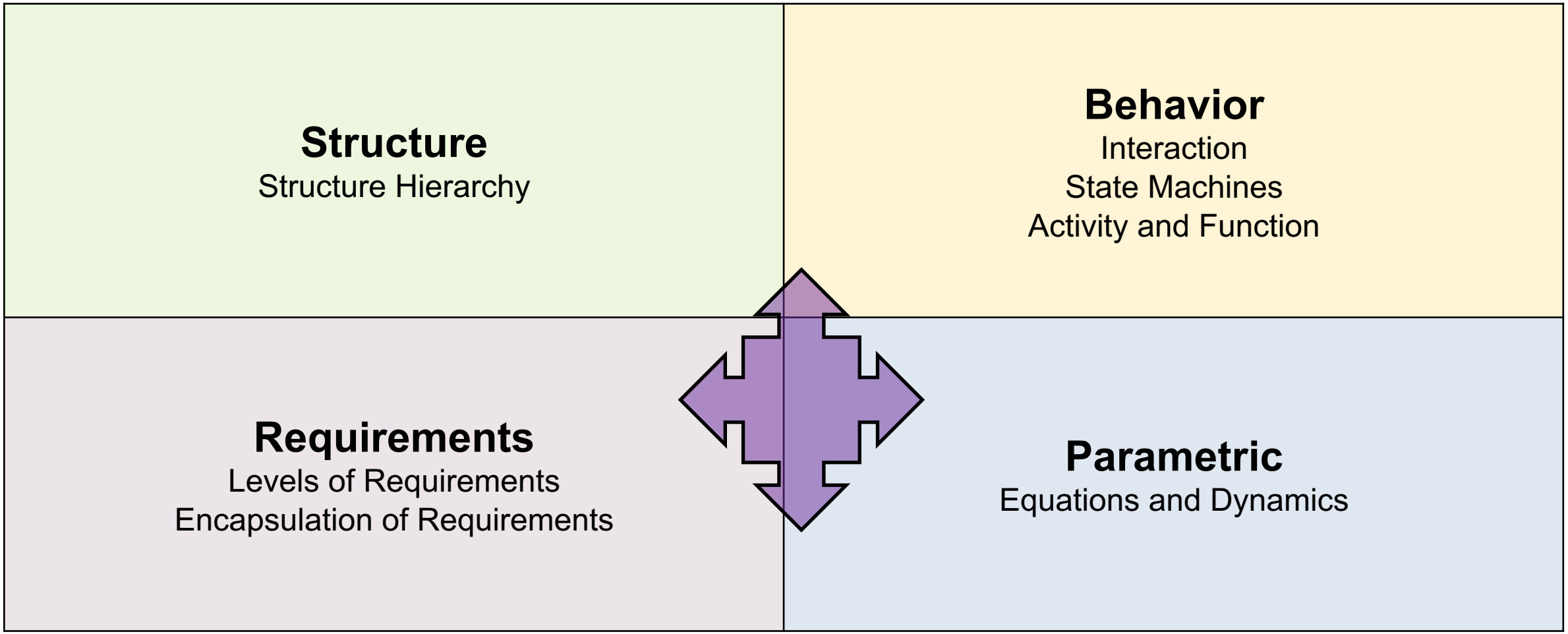
- **Block Definition** – how major elements relate to one another
- **Package** – encapsulation of design elements
- **Requirement** – capturing performance capability
- **Use Case** – how specific scenarios work
- **Internal Block** – internal organization
- **Activity** – system function activity flows
- **Sequence** – temporal relationships for an architectural element
- **State Machine** – what are the relationship between states in a functional element
- **Parametric** – capture interfaces, constraints, dynamics

Capturing Content

- Use SysML to capture system design, requirements, performance



Four Pillars of SysML Linked Together



SysML Diagram Types

- SysML-defined diagram abbreviations
  - *bdd - block definition diagram*
  - *ibd - internal block diagram*
  - *uc - use case diagram*
  - *act - activity diagram*
  - *sd - sequence diagram*
  - *stm - state machine diagram*
  - *par - parametric diagram*
  - *req - requirements diagram*
  - *pkg - package diagram*

Allowable Model Element per Diagram Kind

Diagram Kind	Allowable Model Element Types
Block definition	diagram package, model, modelLibrary, view, block, constraintBlock
Internal block diagram	block
Use case diagram	package, model, modelLibrary, view
Activity diagram	activity
Sequence diagram	interaction
State machine diagram	stateMachine
Parametric diagram	block, constraintBlock
Requirement diagram	package, model, modelLibrary, view, requirement
Package diagram	package, model, modelLibrary, view, profile

SysML Distilled, 20

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- Key tool used to create and evaluate the CubeSat architecture and design

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SYSML