Modeling & Simulation of CubeSat Mission

Model-Based Systems Engineering (MBSE) Behavioral Modeling and Execution

Integration of MagicDraw, Cameo Simulation Toolkit, STK, and Matlab using ModelCenter

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System Engineering Challenges

Motivation
Overview
Modeling
Simulating
Design Trades
Reflections
Future Work

Conventional approaches:

- Focus on subset of subsystems
  - Over-simplified, low fidelity
  - Neglect subsystem interactions
- Requirements verification using average/best/worst-cases
  - Fail to capture realistic “dynamic” nature of missions
- Models and simulations are not integrated!
  - “Hacked” together for one-off cases
  - Not modular, extensible, reusable

Why? Lack of integrated modeling/simulation tools to enable system-level engineering design/analysis.

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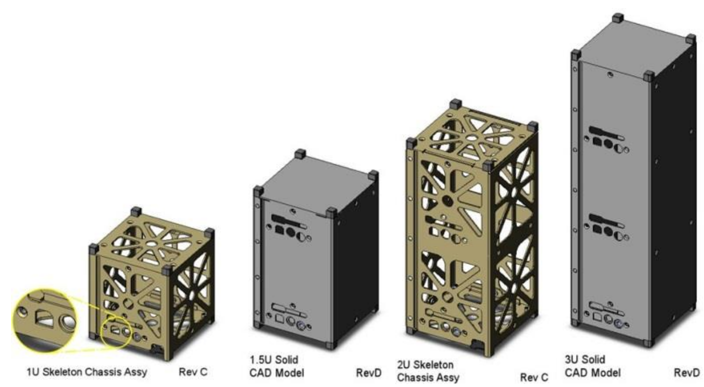
System Engineering Challenges

Particularly an issue for CubeSats[1] because:

- Physical components physically integrated
- Extremely constrained:
  - Limited ability to collect and store energy (e.g. batteries)
- Operational constraints/ decisions coupled
  - When to collect data versus download data?
- Obits are unknown/ dynamic
  - Little/ no control over launch orbit
  - Experience variation in eclipse duration, may de-orbit
- Operate in inefficient/ stochastic environments

Integrated models and tools are critical to design and plan for these missions!



[1]Type of miniature spacecraft (1U = 10cm^3, <1 kg)

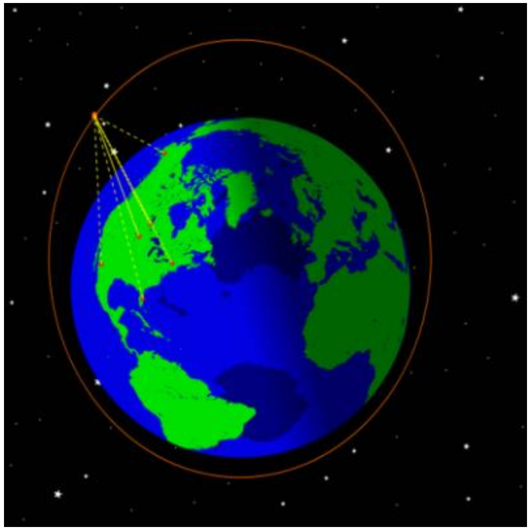
Image Credit: www.cubesatkit.com

Model-Based Systems Engineering (MBSE[1])

Why MBSE?

1) Enables system-level model capture

- Formal, accurate, authoritative single source
- Contains elements, relationships, interactions
- Multiple compatible views, e.g. physical/ functional
- Requirements verification and traceability



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[1] "Formal" model to support requirements, design, analysis, verification

Image Credit: Ph.D. Thesis, S. Spangelo, 2012

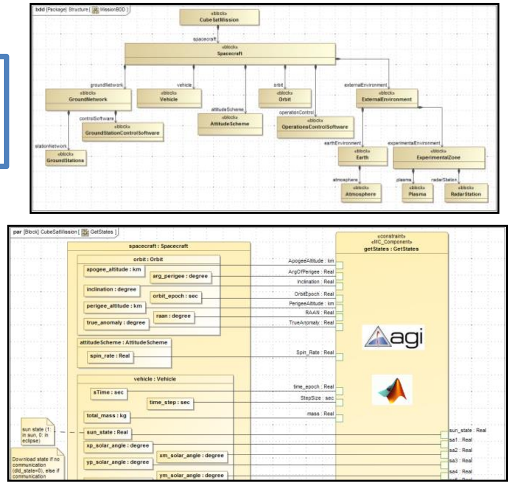
Model-Based Systems Engineering (MBSE)

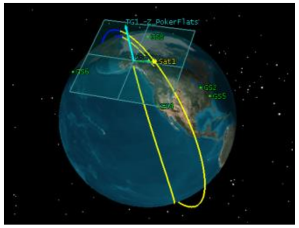
Why MBSE?

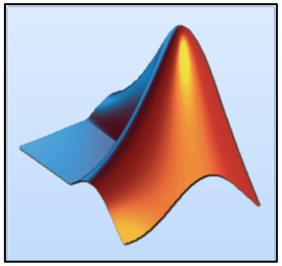
2) Enables integration of models and simulations

- Connect system-level model to analytical tools (STK, Matlab)
- Execute dynamic simulation of end-to-end mission
- Identify failure to satisfy requirements, sub-optimal designs
- Accommodates re-evaluation when design changes occur
- Enables co-simulation: simultaneous vehicle/ mission design

SysML Models





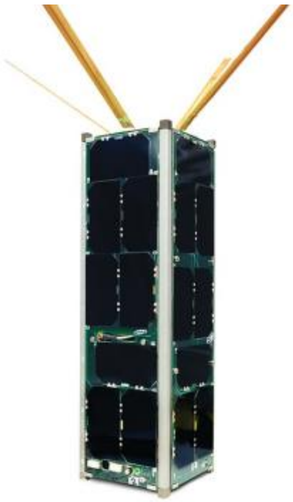


STK, Matlab Simulation Tools

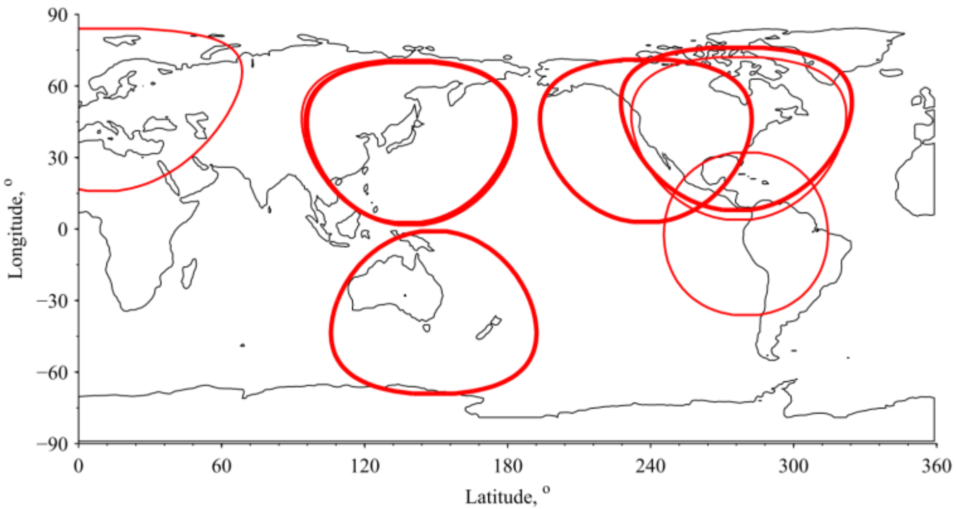
Image Credit: STK?/Matlab Websites

Motivating Mission Example

- Radio Aurora Explorer (RAX) CubeSat mission
- Science target: plasma irregularities in ionosphere
- Experimental zone in Poker Flat, Alaska
- Global ground station network
- Vehicle constraints: solar panels, battery, data buffer



RAX 3U CubeSat



RAX Ground Network footprints

RAX Image Credit: RAX CubeSat Website

Motivating Mission Example

Systems engineering questions:

- How do satellite states evolve throughout mission?
- Does the vehicle design/operations meet all mission requirements?
- How do changes in spacecraft mission parameters impact performance and requirements satisfaction?

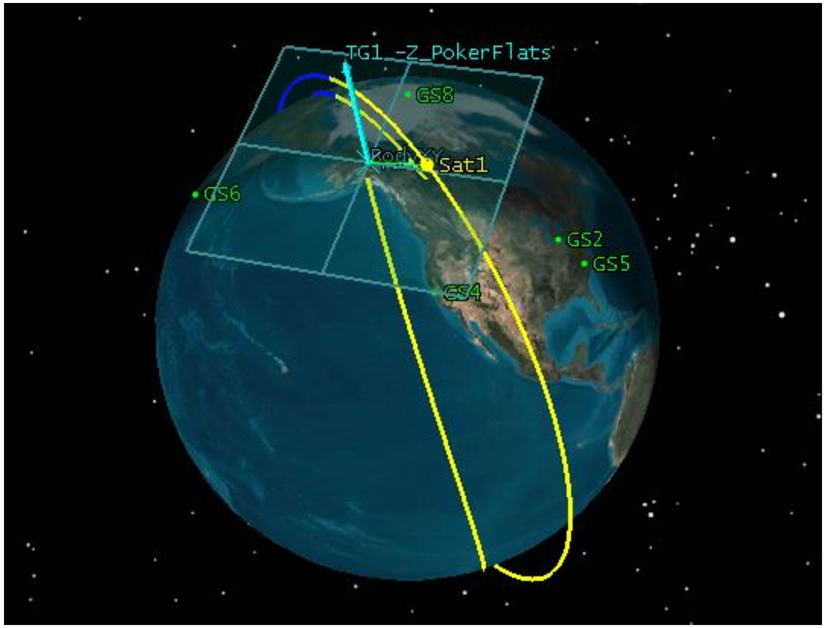


Image Generated with STK

Project: "Model" Operational CubeSat

Mission goals….

Goal #1: Develop fundamental systems model of CubeSat mission

Capture structure, function, relationships, requirements, traceability.

Pretty clear-cut if you know what you're modeling. Accomplished by SSWG[1,2].

Goal #2: Execute realistic behavioral CubeSat scenarios

Capture operational opportunities, state evolution, mission performance.

No clear way to do this in March 2013.

Potential tools: MagicDraw? Simulation Tool Kit (STK)? Matlab? Phoenix ModelCenter? Cameo Simulation Toolkit?

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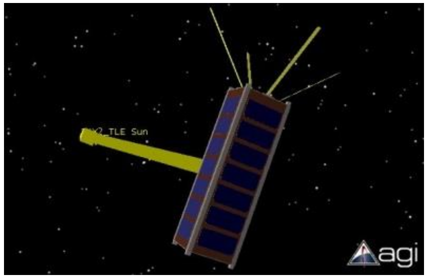
[1] S. Spangelo, D. Kaslow, C. Delp, L. Anderson, B. Cole, E. Foyse, L. Cheng, R. Yntema, M. Bajaj, G. Soremekum, and J. Cutler, "Model Based Systems Engineering (MBSE) Applied to Radio Aurora Explorer (RAX) CubeSat Mission Operational Scenarios", Accepted for IEEE Aerospace Conference, 2013, Big Sky, MT, March 2013.

[1] S. Spangelo, D. Kaslow, C. Delp, B. Cole, L. Anderson, E. Fosse, L. Hartman, B. Gilbert, and J. Cutler, "Applying Model Based Systems Engineering (MBSE) to a Standard CubeSat", IEEE Aerospace Conference, 2012, Big Sky, MT, March 2012.

Project: "Model" Operational CubeSat

Mission accomplished…



Project Deliverables:

- Systems-level SysML model (in MagicDraw)
  - Structure of mission architecture and vehicle
  - Requirements definition and traceability
  - Parametric diagrams to capture analytical relationships
    - Evaluated using MBSE Analyzer
  - Behavioral diagrams to capture dynamic operations
    - Executed using Cameo Simulation Toolkit and MBSE Analyzer[1]
- Analytical models for describing behavior
  - STK, Matlab, Java
  - ModelCenter enabled integration with SysML and automated execution of dynamic scenarios

[1] A prototype capability was developed for this work that allows CST to execute parametric diagrams via MBSE Analyzer

Image Generated with STK

Modeling Philosophies

For usability/ extensibility:

- ***Modularity*****:** re-usable libraries of parts
  e.g. constraint block modules are re-used in many parametric diagrams

- ***Patterning*****:** re-use of modeling patterns
  e.g. common pattern in Power and Data Management subsystems

- ***Nomenclature*****:** simple and sufficiently descriptive
  e.g. subsystem naming codes used for data rate and power values

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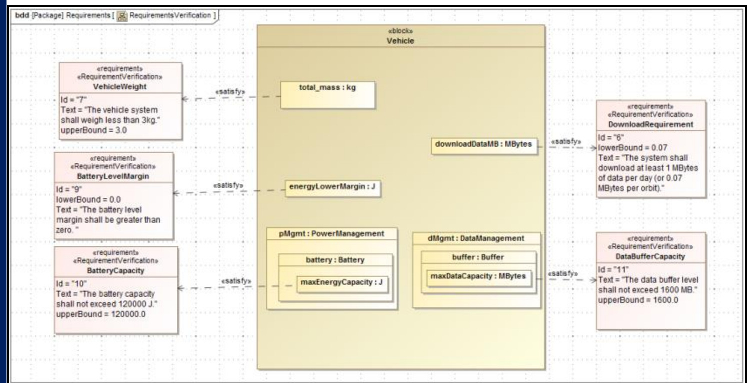
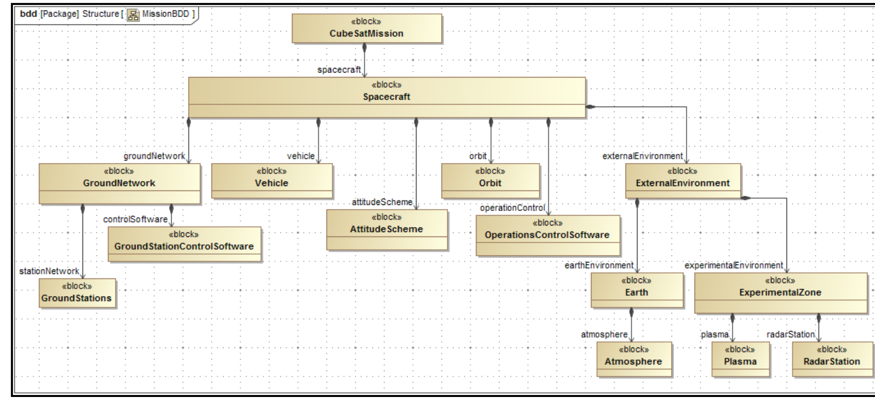
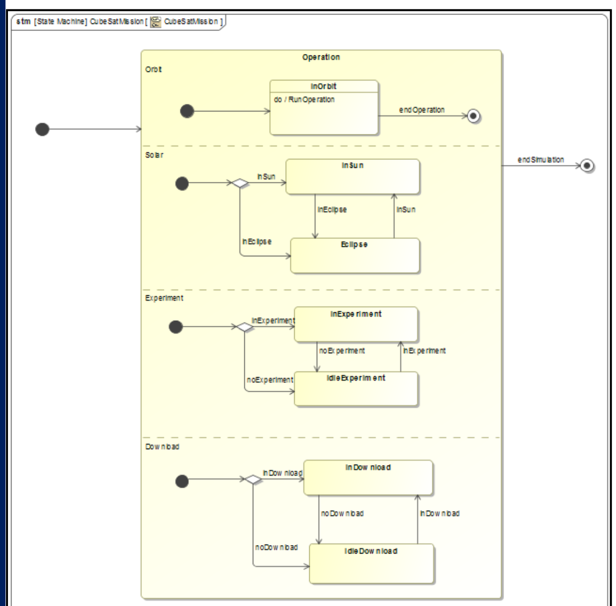
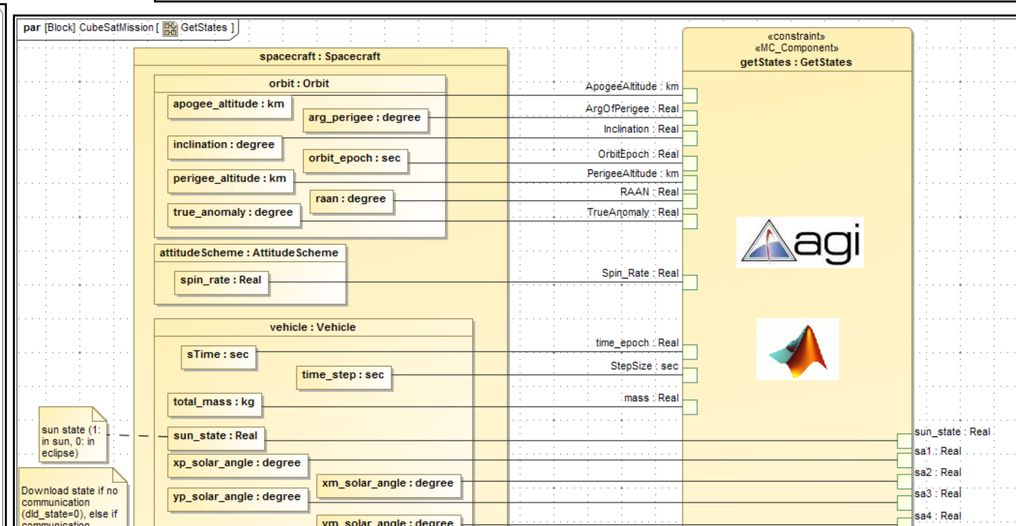
CubeSat System Model Architecture

- Motivation
- Overview
- Modeling
- Simulating
- Design Trades
- Reflections
- Future Work



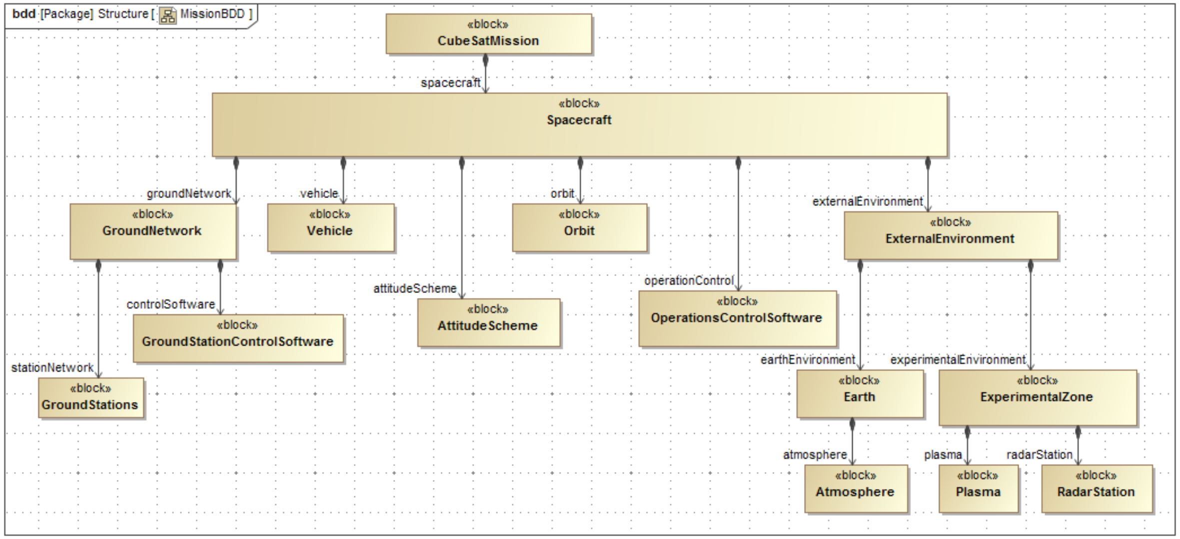




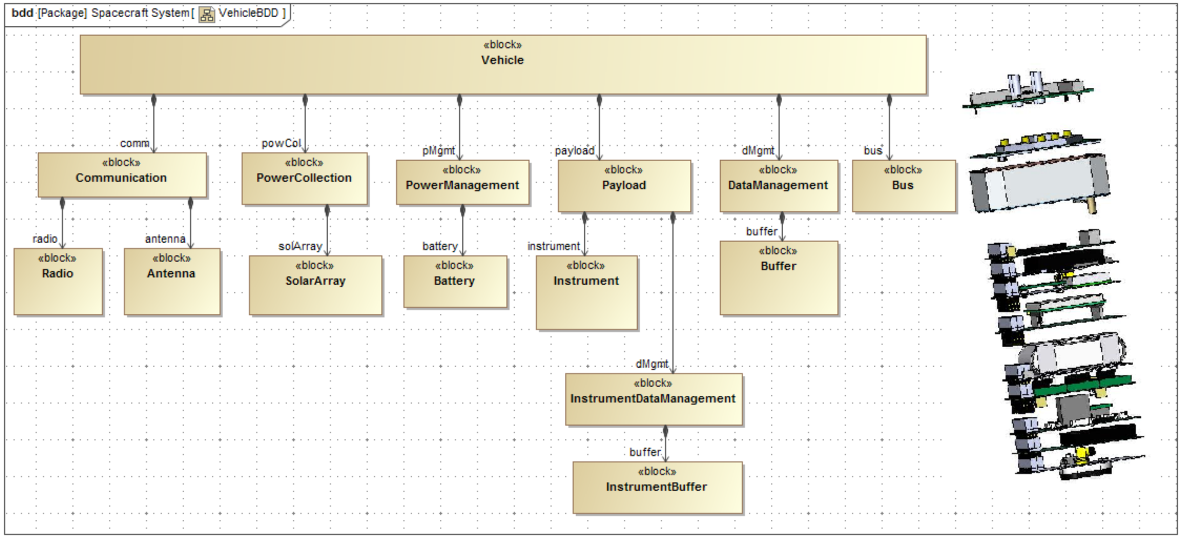


The system model captures requirements, structure, behavior, and parametrics.

Structural Diagrams



Mission Level



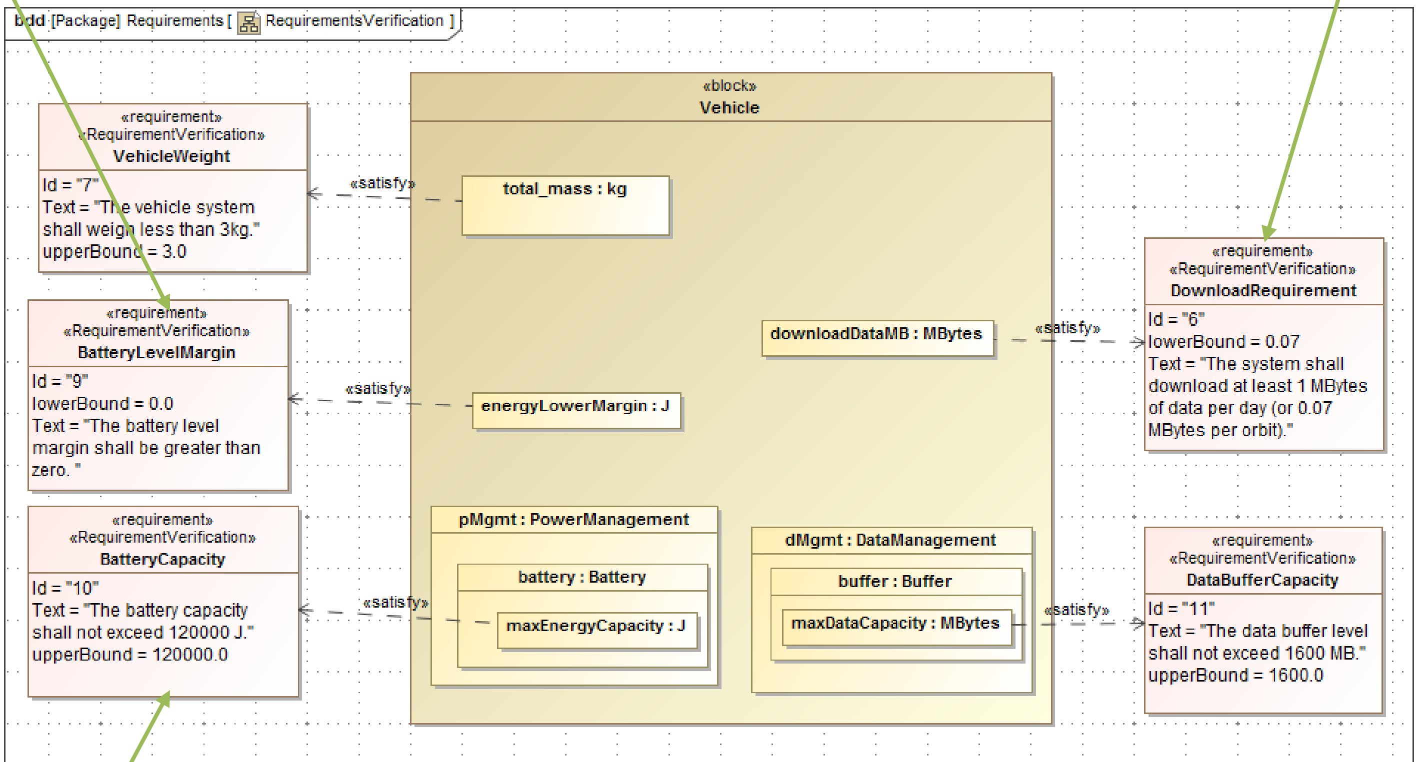
Vehicle Level

Mission Requirements

Drive systems design

Defines constraint on lowest battery level throughout mission

Defines constraint on minimum download



Defines constraint on lowest data storage level throughout mission

- Motivation
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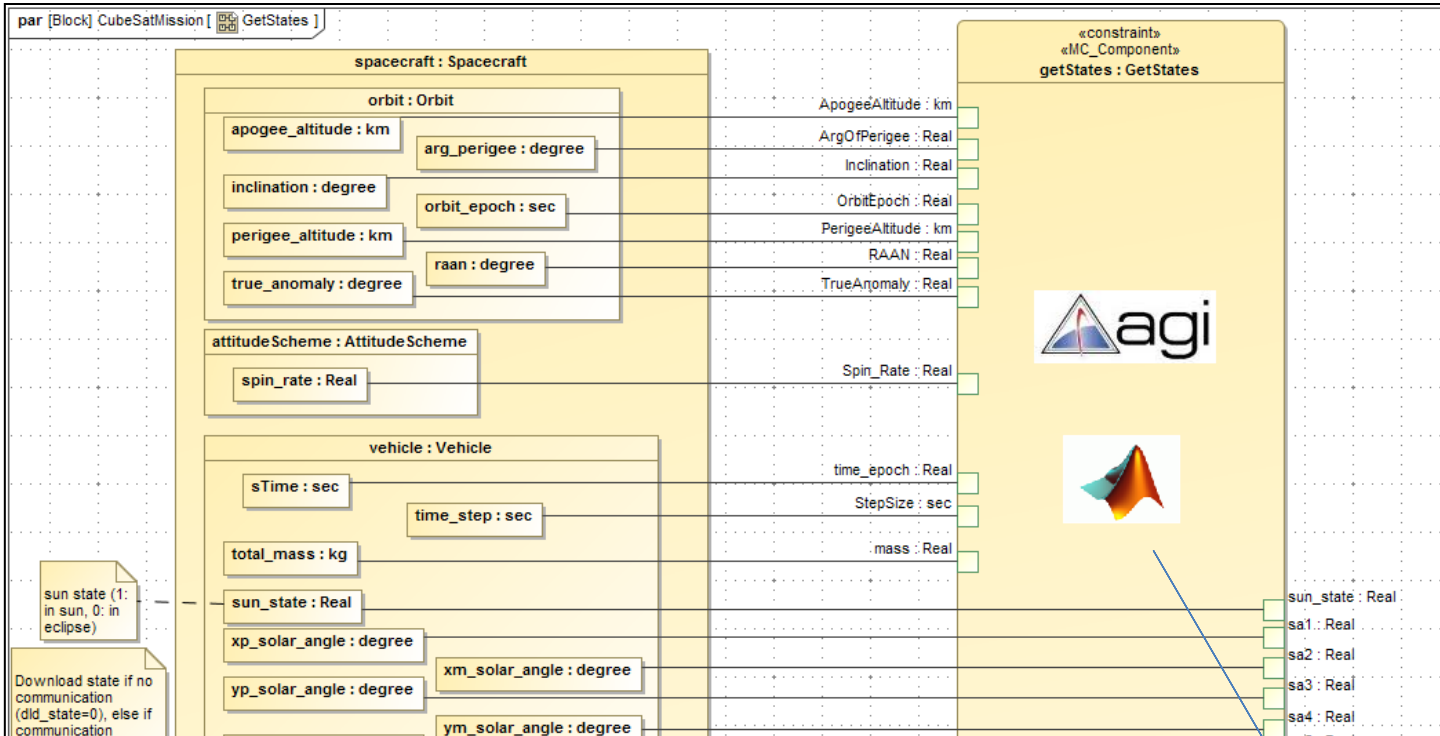
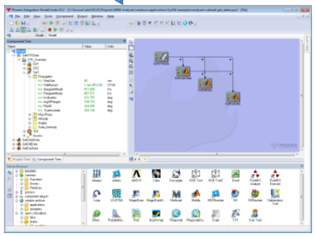
Parametric Diagram

Constraint blocks defines opportunities

- Motivation
- Overview
- **Modeling**
- Simulating
- Design Trades
- Reflections
- Future Work

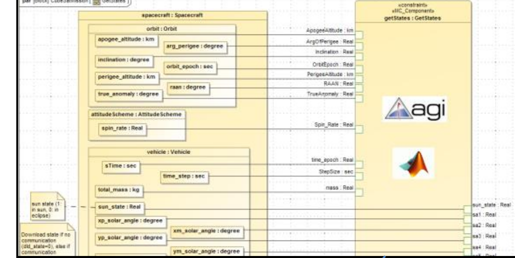


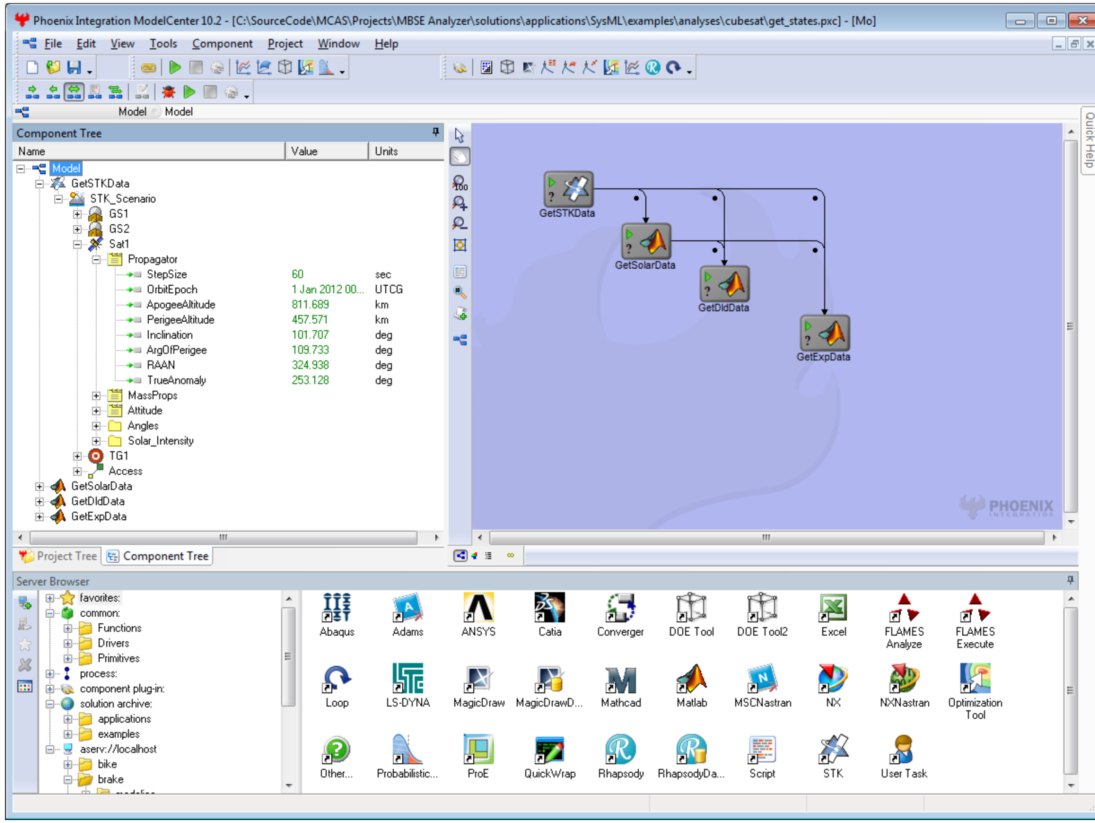
Pointing to a ModelCenter model with STK and Matlab



ModelCenter Model

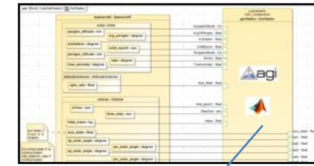
STK and Matlab Plug-Ins





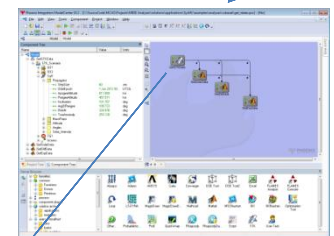
- Analysis models (STK, Matlab) wrapped and integrated with ModelCenter
- ModelCenter models imported into SysML model constraint blocks with MBSE Analyzer

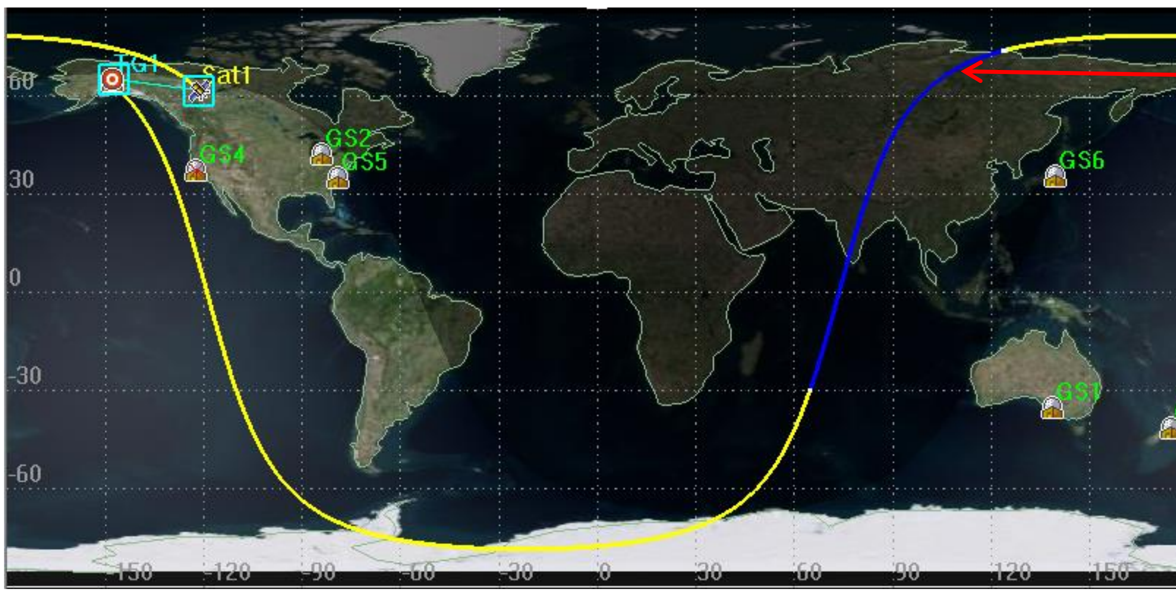
Systems Tool Kit (STK)



Analytic simulation tool used to propagate obit & compute:

- Solar state: sun/eclipse, solar panel angles
- Access to experimental zone
- Access to ground stations





Sun State/
Eclipse State

Image Generated with STK

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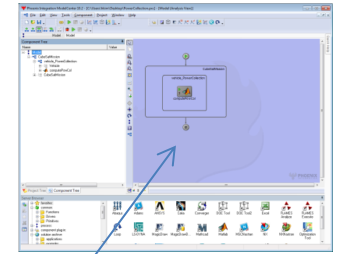
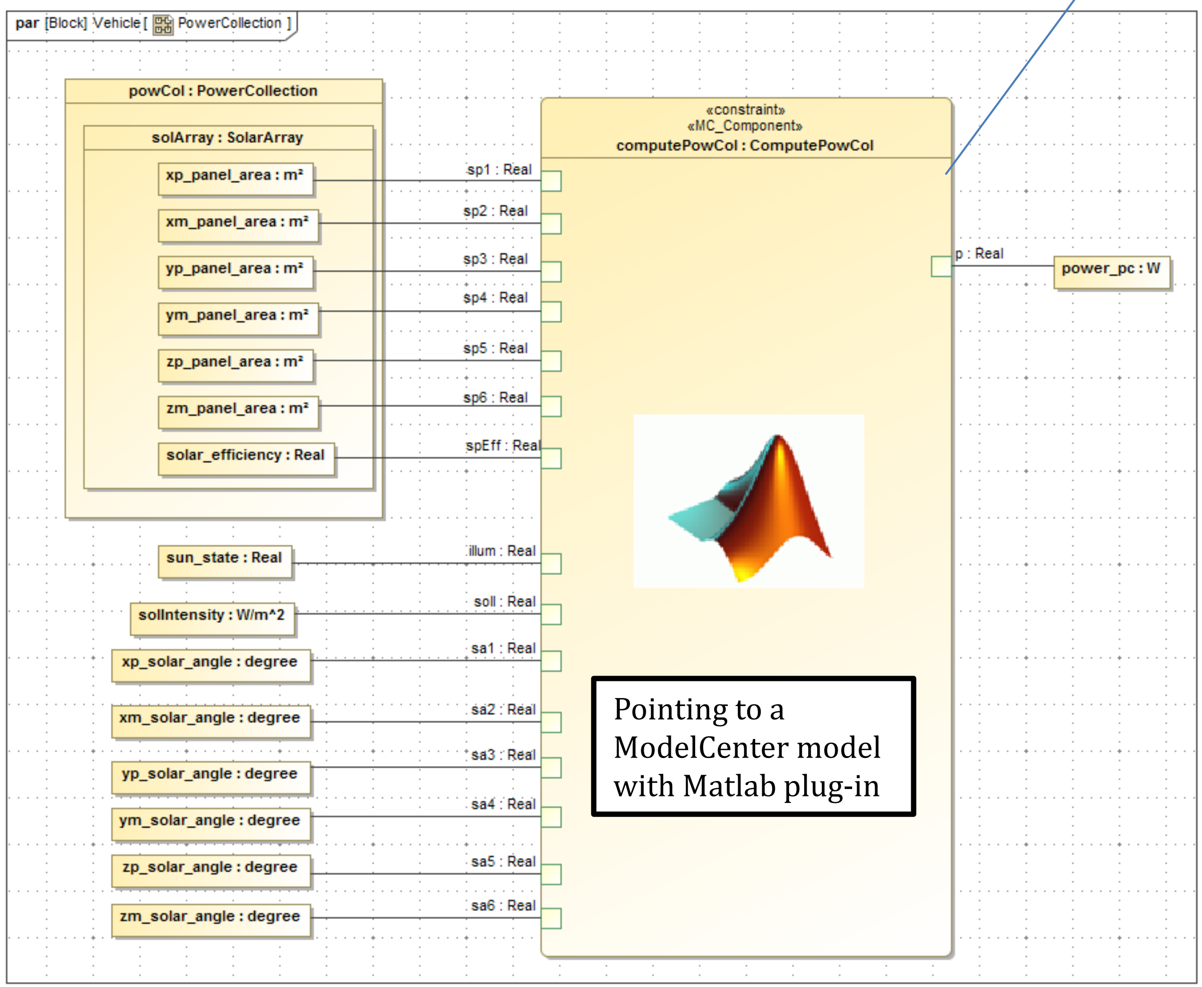
Parametric Diagrams

Constraint blocks computes total power

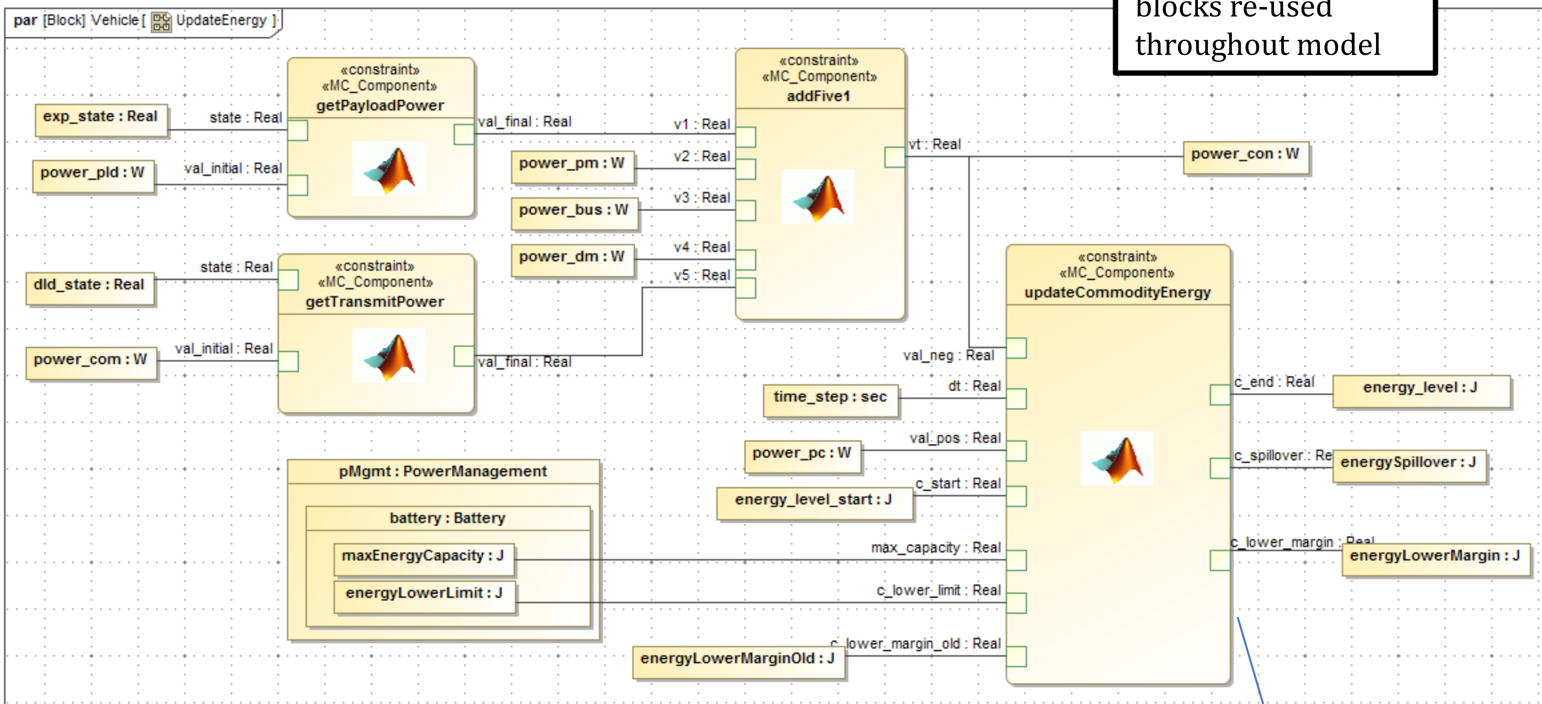




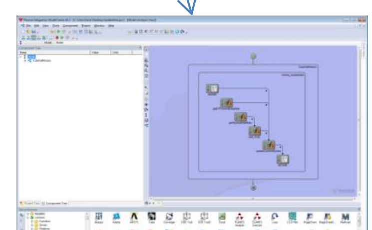
Parametric Diagrams

Constraint blocks update satellite states

Several constraint blocks re-used throughout model



- Compute energy level at the next time step
- Similar parametric diagrams for experiment data and data download



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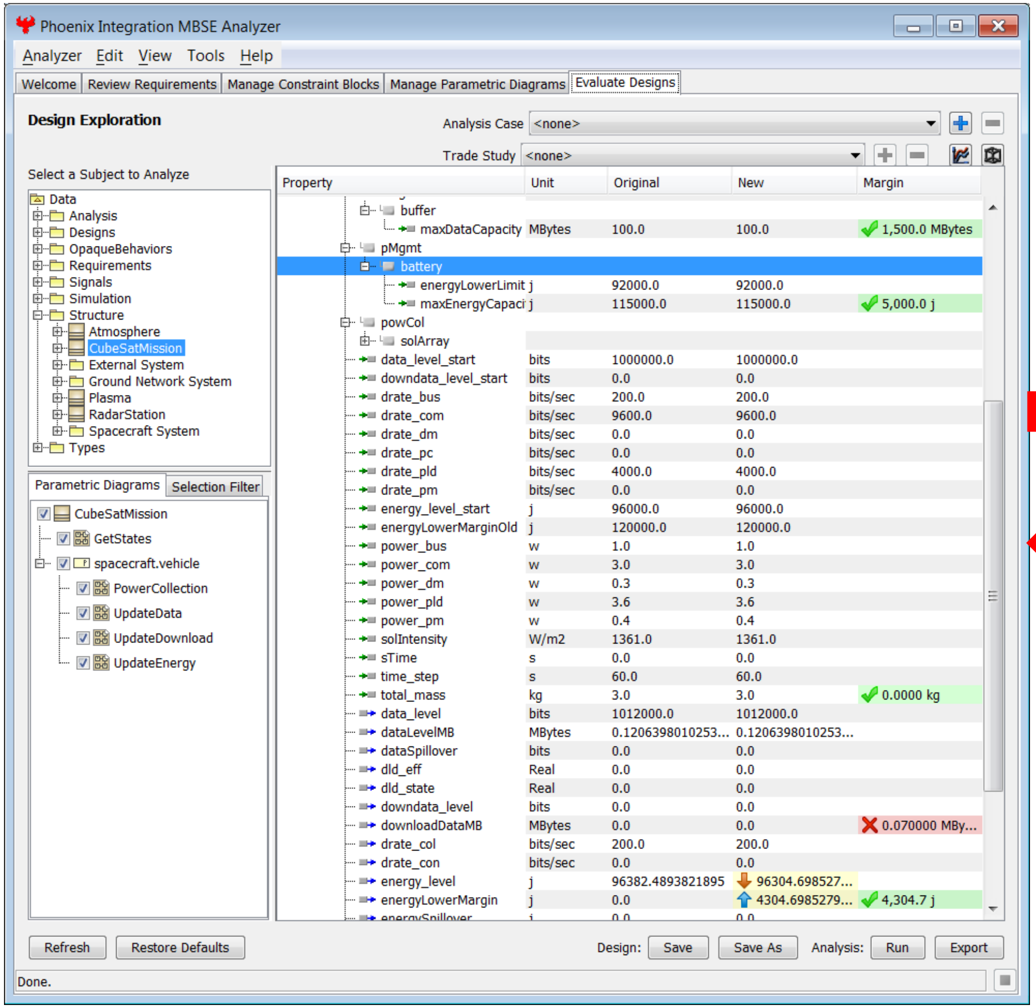
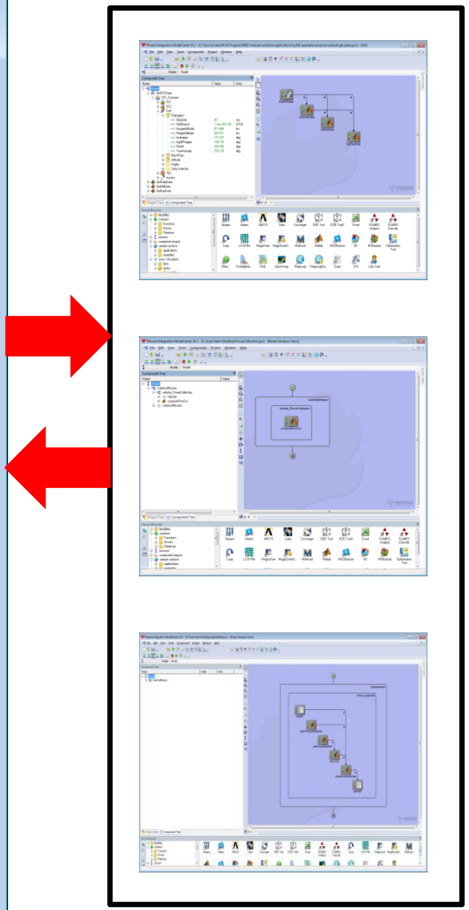
MBSE Analyzer: Parametric Diagram Solver

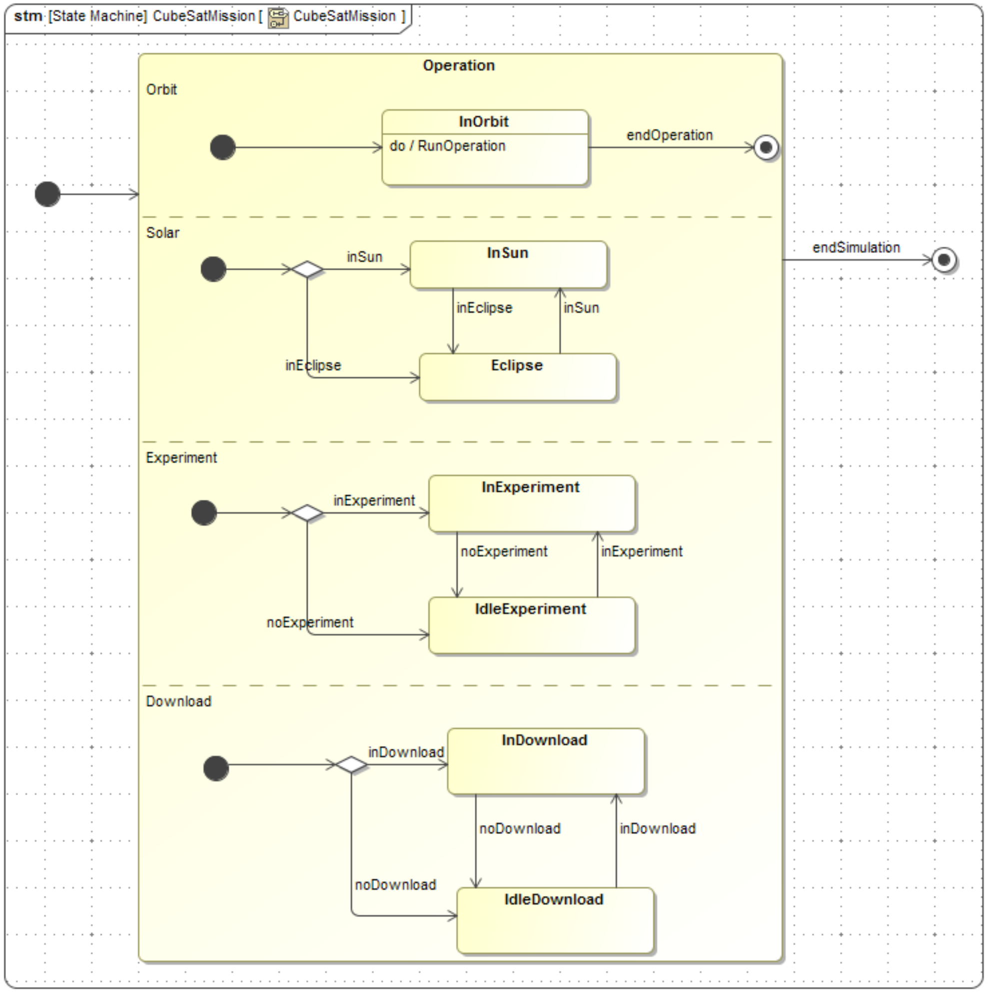




- Solves linked parametric diagrams (all 3) simultaneously
- Automated requirements verification (green: pass, red: fail)

Bringing the Model to Life

Main State Machine Diagram



- Entry point of Cameo Simulation Toolkit (CST) behavioral simulation
- Starts "RunOperation" activity diagram that steps through mission simulation
- Updates solar, experiment, and download states according to signals

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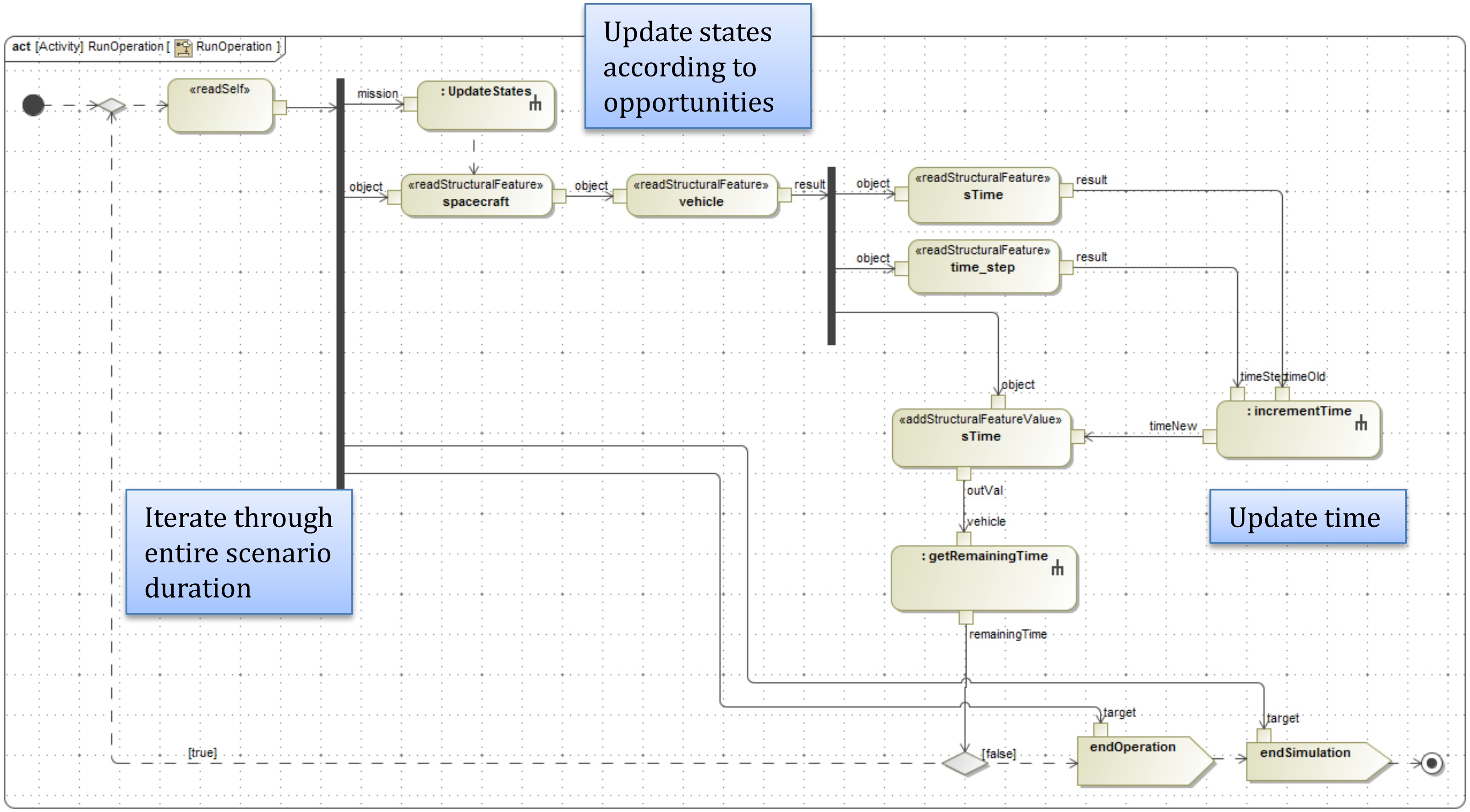
Main Simulation Loop



State Update Activity Diagram

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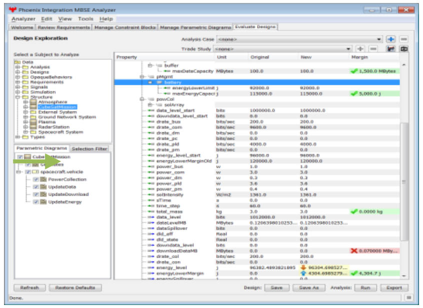
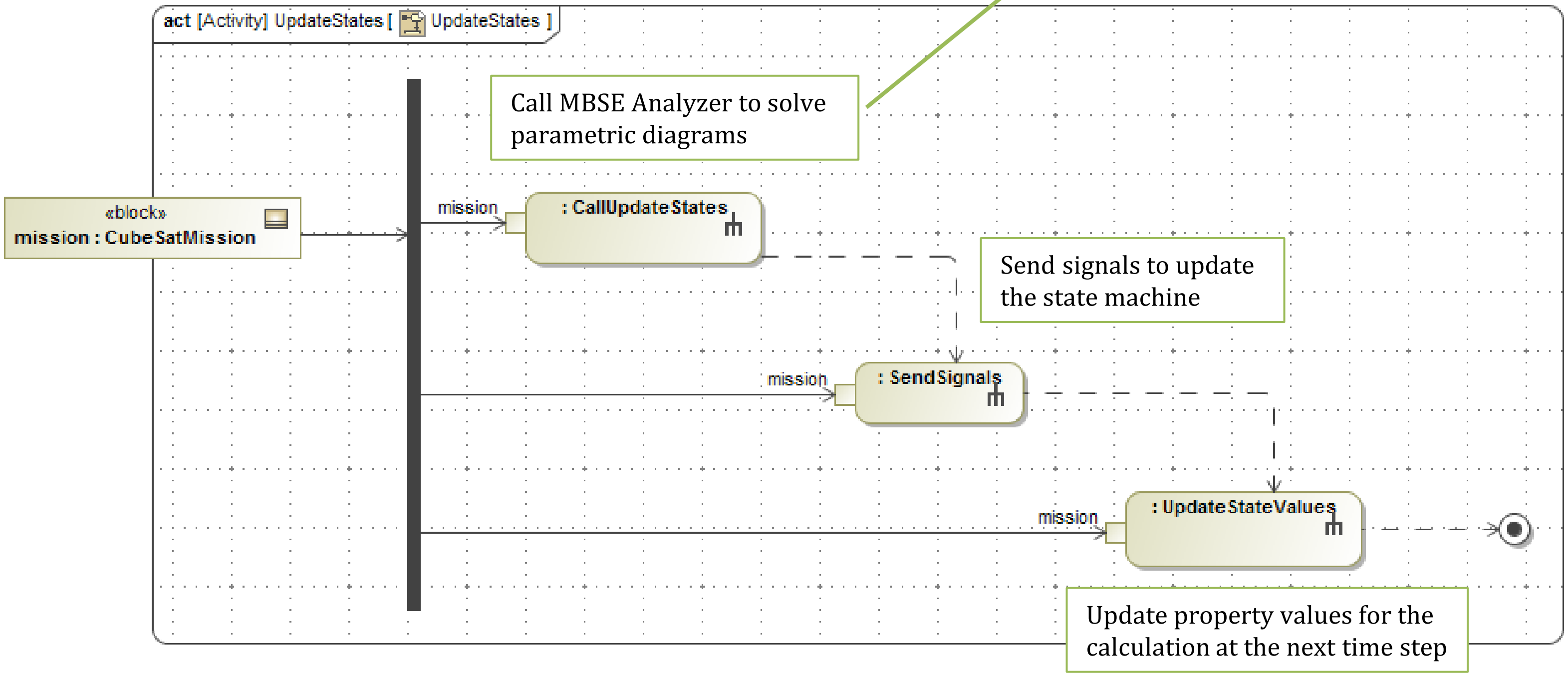
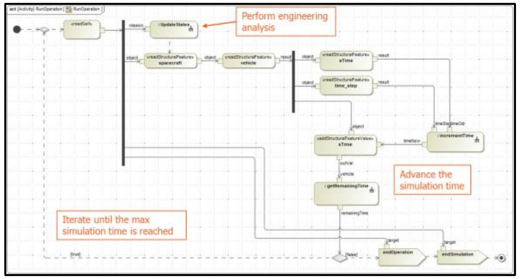
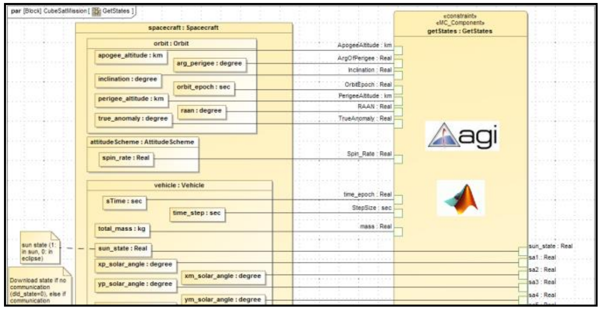


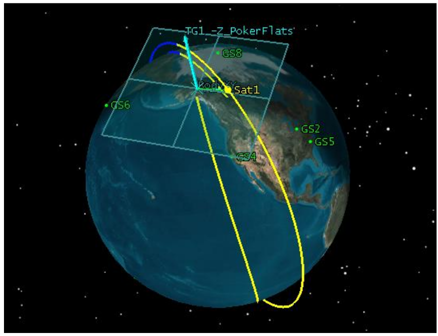


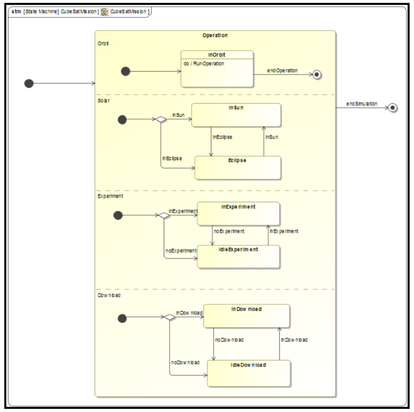
[1] A prototype capability was developed for this work that allows CST to execute parametric diagrams via MBSE Analyzer

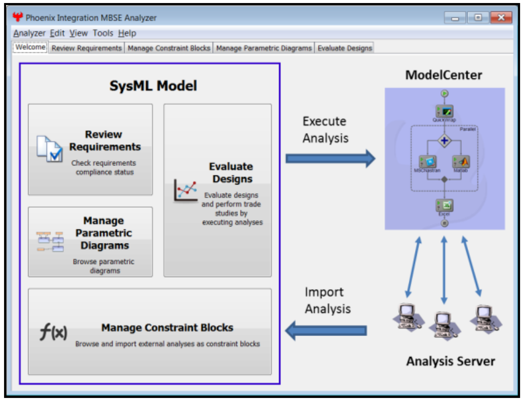
How are Mission Simulations Performed?

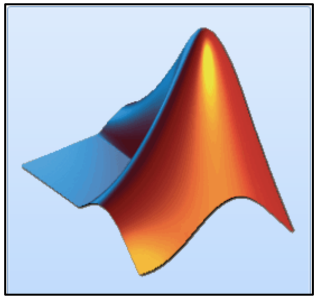












MagicDraw CST
(Behavioral diagrams)

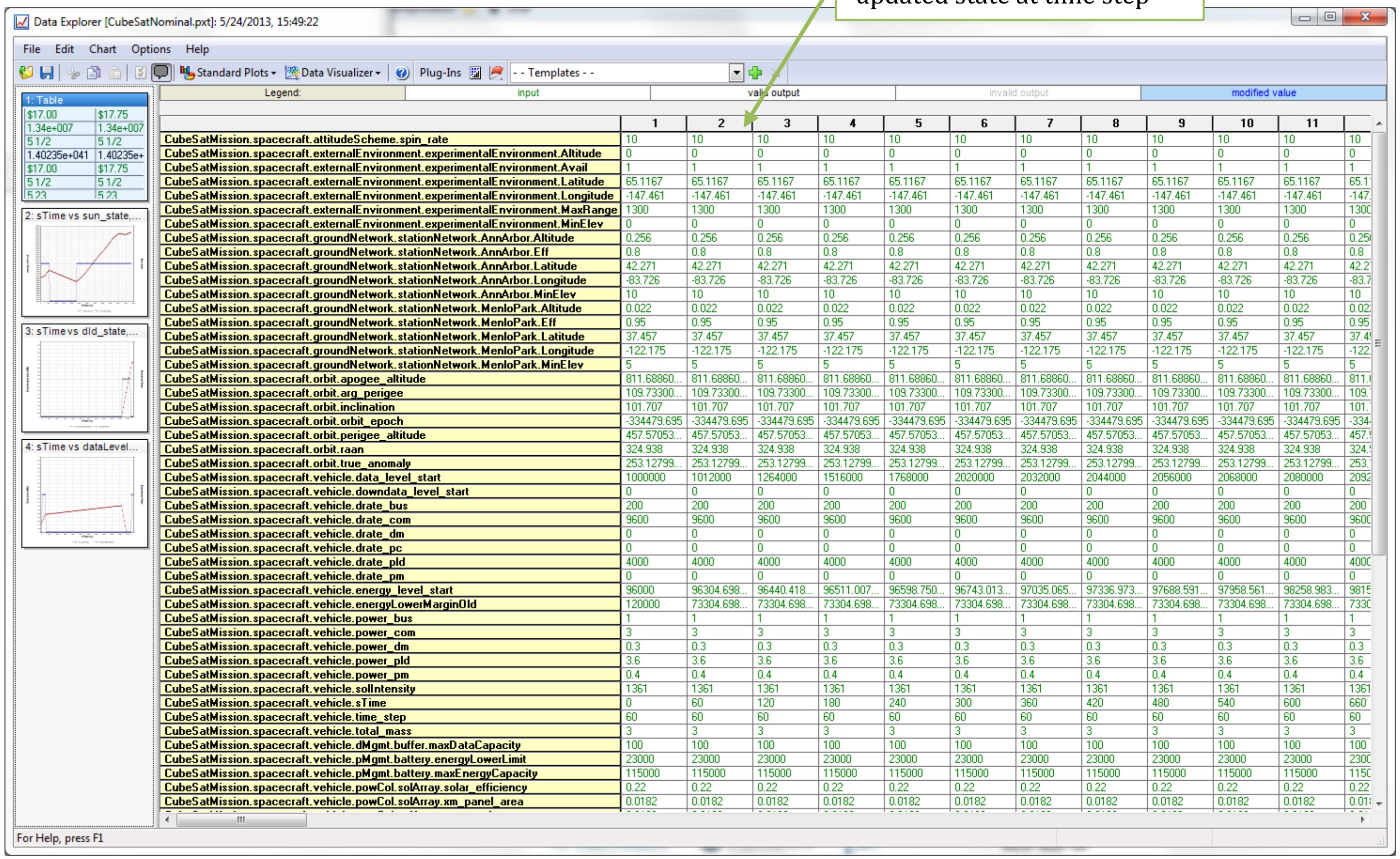
MBSE Analyzer/ModelCenter
(Parametric diagrams)

STK, Matlab, etc.
(Analytical models)

Matlab Symbol Image Credit: Matlab Websites

Mission Simulation Results

Each column contains updated state at time step

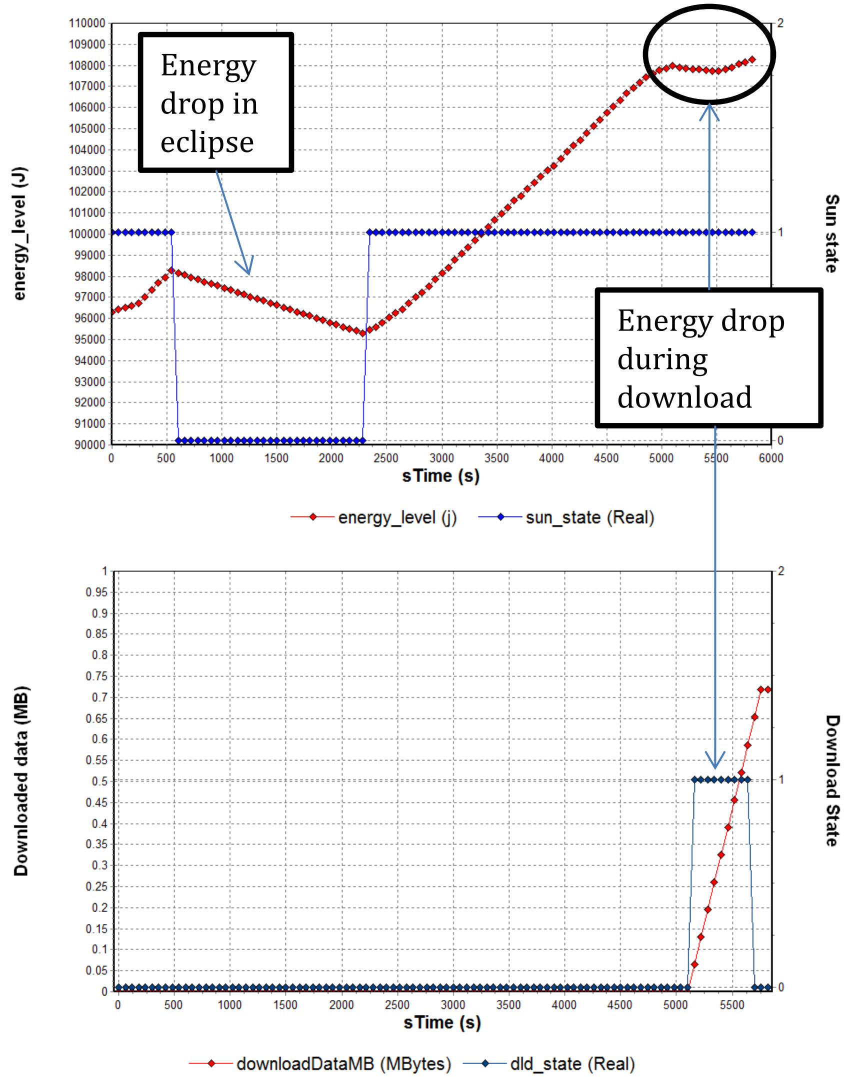


	1	2	3	4	5	6	7	8	9	10	11	
CubeSatMission.spacecraft.attitudeScheme.spin_rate	10	10	10	10	10	10	10	10	10	10	10	10
CubeSatMission.spacecraft.externalEnvironment.experimentalEnvironment.Altitude	0	0	0	0	0	0	0	0	0	0	0	0
CubeSatMission.spacecraft.externalEnvironment.experimentalEnvironment.Avail	1	1	1	1	1	1	1	1	1	1	1	1
CubeSatMission.spacecraft.externalEnvironment.experimentalEnvironment.Latitude	65.1167	65.1167	65.1167	65.1167	65.1167	65.1167	65.1167	65.1167	65.1167	65.1167	65.1167	65.1
CubeSatMission.spacecraft.externalEnvironment.experimentalEnvironment.Longitude	-147.461	-147.461	-147.461	-147.461	-147.461	-147.461	-147.461	-147.461	-147.461	-147.461	-147.461	-147.
CubeSatMission.spacecraft.externalEnvironment.experimentalEnvironment.MaxRange	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300	130
CubeSatMission.spacecraft.externalEnvironment.experimentalEnvironment.MinElev	0	0	0	0	0	0	0	0	0	0	0	0
CubeSatMission.spacecraft.groundNetwork.stationNetwork.AnnArbor.Altitude	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.25
CubeSatMission.spacecraft.groundNetwork.stationNetwork.AnnArbor.Eff	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
CubeSatMission.spacecraft.groundNetwork.stationNetwork.AnnArbor.Latitude	42.271	42.271	42.271	42.271	42.271	42.271	42.271	42.271	42.271	42.271	42.271	42.2
CubeSatMission.spacecraft.groundNetwork.stationNetwork.AnnArbor.Longitude	-83.726	-83.726	-83.726	-83.726	-83.726	-83.726	-83.726	-83.726	-83.726	-83.726	-83.726	-83.7
CubeSatMission.spacecraft.groundNetwork.stationNetwork.AnnArbor.MinElev	10	10	10	10	10	10	10	10	10	10	10	10
CubeSatMission.spacecraft.groundNetwork.stationNetwork.MenloPark.Altitude	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.02
CubeSatMission.spacecraft.groundNetwork.stationNetwork.MenloPark.Eff	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
CubeSatMission.spacecraft.groundNetwork.stationNetwork.MenloPark.Latitude	37.457	37.457	37.457	37.457	37.457	37.457	37.457	37.457	37.457	37.457	37.457	37.4
CubeSatMission.spacecraft.groundNetwork.stationNetwork.MenloPark.Longitude	-122.175	-122.175	-122.175	-122.175	-122.175	-122.175	-122.175	-122.175	-122.175	-122.175	-122.175	-122.
CubeSatMission.spacecraft.groundNetwork.stationNetwork.MenloPark.MinElev	5	5	5	5	5	5	5	5	5	5	5	5
CubeSatMission.spacecraft.orbit.apogee_altitude	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.68860...	811.
CubeSatMission.spacecraft.orbit.arg_perigee	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.73300...	109.
CubeSatMission.spacecraft.orbit.inclination	101.707	101.707	101.707	101.707	101.707	101.707	101.707	101.707	101.707	101.707	101.707	101.
CubeSatMission.spacecraft.orbit.orbit_epoch	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334479.695	-334
CubeSatMission.spacecraft.orbit.perigee_altitude	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.57053...	457.
CubeSatMission.spacecraft.orbit.raan	324.938	324.938	324.938	324.938	324.938	324.938	324.938	324.938	324.938	324.938	324.938	324.
CubeSatMission.spacecraft.orbit.true_anomaly	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.12799...	253.
CubeSatMission.spacecraft.vehicle.data_level_start	1000000	1012000	1264000	1516000	1768000	2020000	2032000	2044000	2056000	2068000	2080000	2092
CubeSatMission.spacecraft.vehicle.downdata_level_start	0	0	0	0	0	0	0	0	0	0	0	0
CubeSatMission.spacecraft.vehicle.drate_bus	200	200	200	200	200	200	200	200	200	200	200	200
CubeSatMission.spacecraft.vehicle.drate_com	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	9600	960
CubeSatMission.spacecraft.vehicle.drate_dm	0	0	0	0	0	0	0	0	0	0	0	0
CubeSatMission.spacecraft.vehicle.drate_pc	0	0	0	0	0	0	0	0	0	0	0	0
CubeSatMission.spacecraft.vehicle.drate_pld	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	400
CubeSatMission.spacecraft.vehicle.drate_pm	0	0	0	0	0	0	0	0	0	0	0	0
CubeSatMission.spacecraft.vehicle.energy_level_start	96000	96304.698...	96440.418...	96511.007...	96598.750...	96743.013...	97035.065...	97336.973...	97688.591...	97958.561...	98258.983...	9815
CubeSatMission.spacecraft.vehicle.energyLowerMarginOld	120000	73304.698...	73304.698...	73304.698...	73304.698...	73304.698...	73304.698...	73304.698...	73304.698...	73304.698...	73304.698...	733
CubeSatMission.spacecraft.vehicle.power_bus	1	1	1	1	1	1	1	1	1	1	1	1
CubeSatMission.spacecraft.vehicle.power_com	3	3	3	3	3	3	3	3	3	3	3	3
CubeSatMission.spacecraft.vehicle.power_dm	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
CubeSatMission.spacecraft.vehicle.power_pld	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
CubeSatMission.spacecraft.vehicle.power_pm	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
CubeSatMission.spacecraft.vehicle.solIntensity	1361	1361	1361	1361	1361	1361	1361	1361	1361	1361	1361	1361
CubeSatMission.spacecraft.vehicle.sTime	0	60	120	180	240	300	360	420	480	540	600	660
CubeSatMission.spacecraft.vehicle.time_step	60	60	60	60	60	60	60	60	60	60	60	60
CubeSatMission.spacecraft.vehicle.total_mass	3	3	3	3	3	3	3	3	3	3	3	3
CubeSatMission.spacecraft.vehicle.dMgmt.buffer.maxDataCapacity	100	100	100	100	100	100	100	100	100	100	100	100
CubeSatMission.spacecraft.vehicle.pMgmt.battery.energyLowerLimit	23000	23000	23000	23000	23000	23000	23000	23000	23000	23000	23000	230
CubeSatMission.spacecraft.vehicle.pMgmt.battery.maxEnergyCapacity	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115
CubeSatMission.spacecraft.vehicle.powCol.solArray.solar_efficiency	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
CubeSatMission.spacecraft.vehicle.powCol.solArray.xm_panel_area	0.0182	0.0182	0.0182	0.0182	0.0182	0.0182	0.0182	0.0182	0.0182	0.0182	0.0182	0.01

- During CST simulation, MBSE Analyzer is called at each time step
- Data Explorer automatically stores time history of the simulation data

Mission Simulation Results

Motivation
Overview
Modeling
Simulating
Design Trades
Reflections
Future Work



- Combined simulation SysML behavioral diagrams to STK, Matlab using MBSE Analyzer
- MBSE Analyzer is called at each time step during CST simulation
- Time history of energy level, experiments, and data download is stored

Final Step: Requirements Verification

Full end-to-end (dynamic) scenario

Motivation
Overview
Modeling
Simulating
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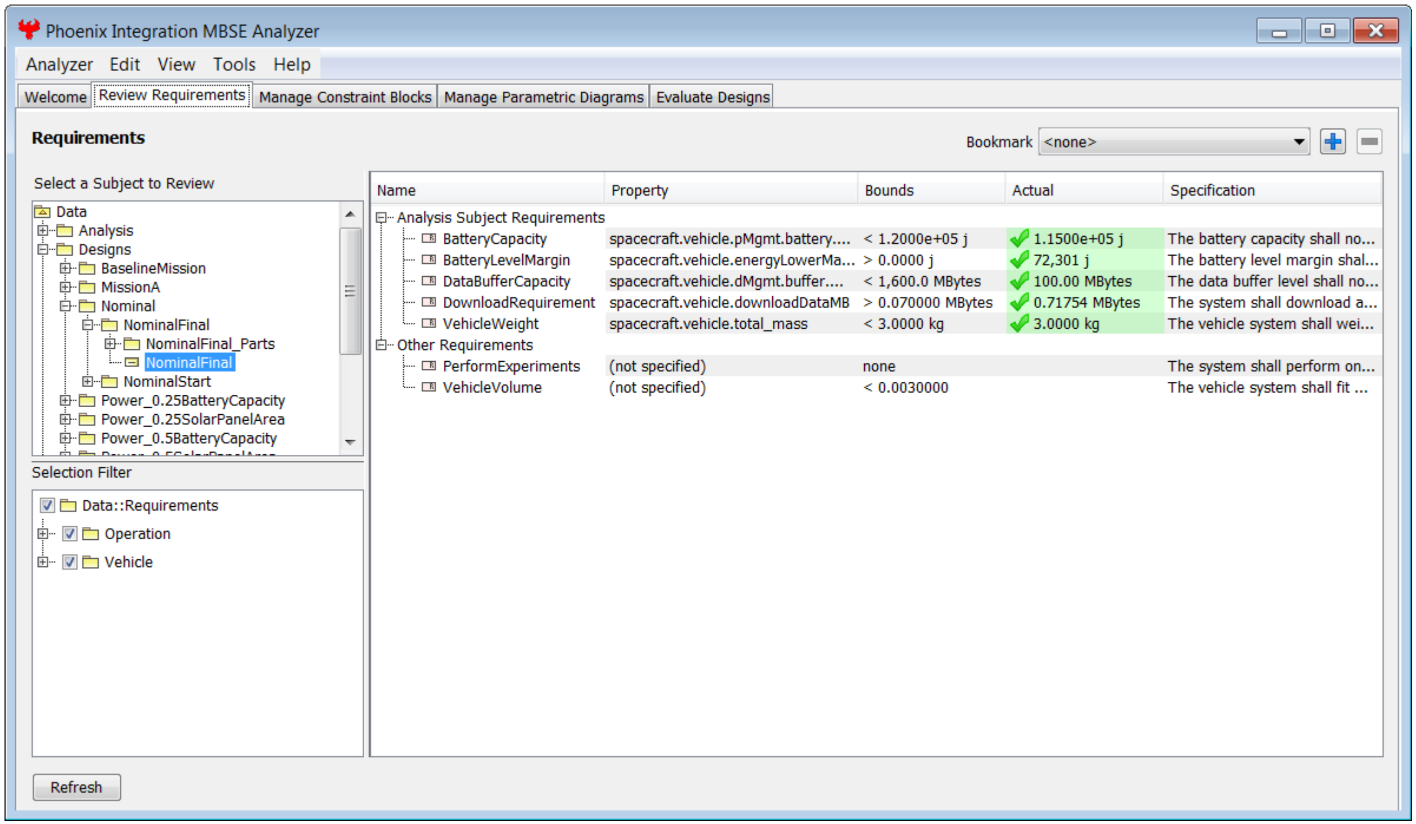
Future Work



- Post-CST simulation: final state stored in an instance specification
- Use MBSE Analyzer to verify requirements with visual tool!

Mission and Design Trade-Offs

Battery Capacity

Motivation
Overview
Modeling
Simulating
Design Trades
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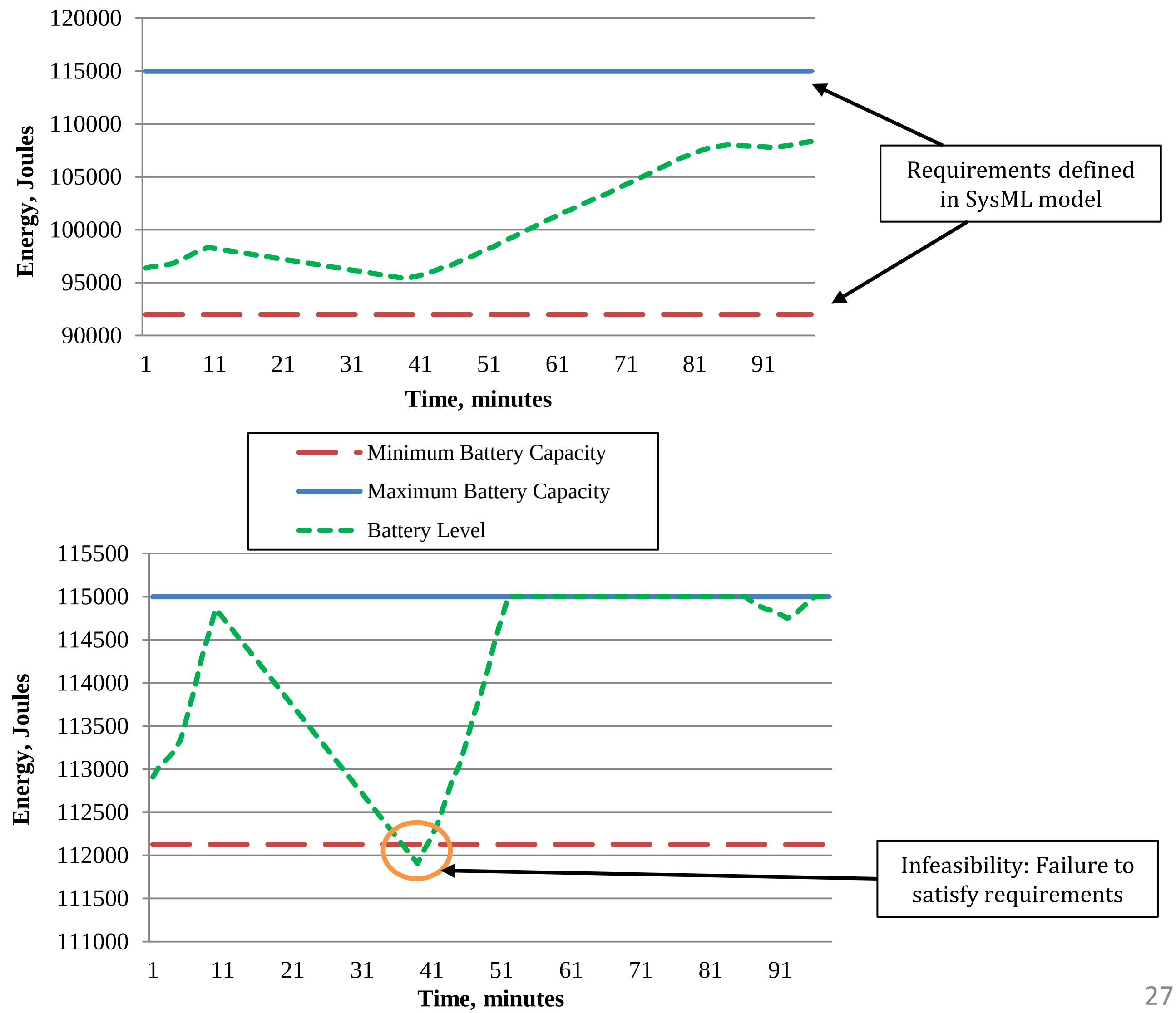
Future Work

Nominal Battery Capacity

1/8 Battery Capacity



Mission and Design Trade-Offs

Orbit Altitudes

Motivation

Overview

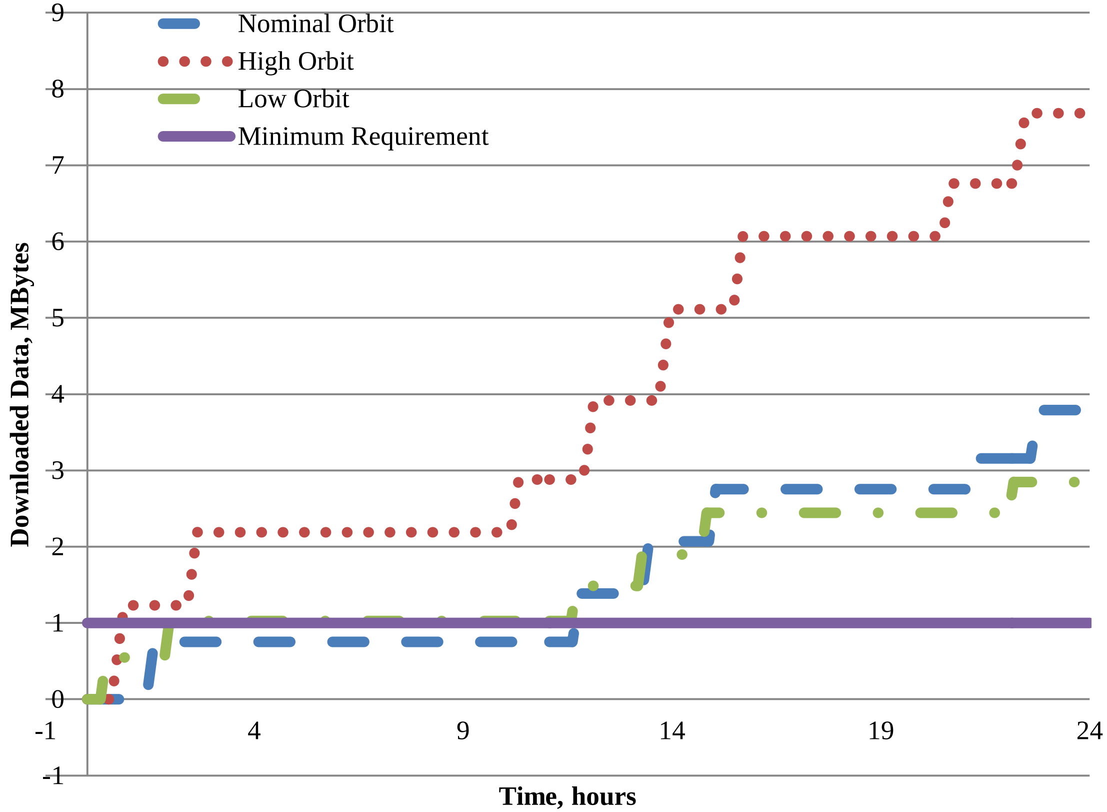
Modeling

Simulating

Design Trades

Reflections

Future Work

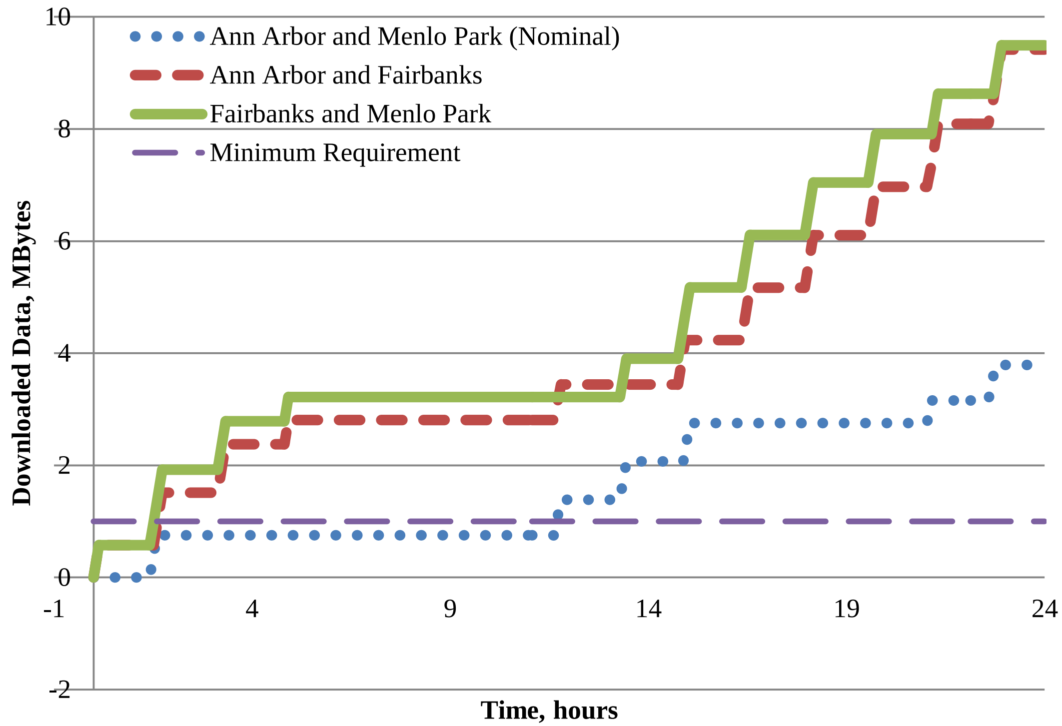


Nominal: semi-major axis = 7012km, apogee altitude = 811.69 km, perigee altitude=457.57 km
High: semi-major axis = 7500 km, apogee altitude = 1311.22 km, perigee altitude = 932.50 km
Low: semi-major axis = 6800 km, apogee altitude =593.55 km, perigee altitude=250.18 km

Mission and Design Trade-Offs

Ground Station Locations

- Motivation
- Overview
- Modeling
- Simulating
- Design Trades
- Reflections
- Future Work



Location And Description Of Ground Stations In Network

Name	State	Latitude (degrees)	Longitude (degrees)	Altitude (km)	Minimum Elevation (degrees)	Efficiency
AnnArbor	MI	42.271	-83.73	0.256	5	0.8
Fairbanks	AK	64.88	-147.5	0	0	1
MenloPark	CA	37.457	-122.2	0.022	0	0.95

Reflecting on Project Experience

How did MBSE enable us to overcome challenges?

- Coupled analytic models with simulation capabilities
- Demonstrated dynamic behavioral modeling
- Achieved requirements verification for full end-to-end missions
- Extensible by use of standards, libraries, patterns, etc.

Lessons Learned

- Working with many tools is challenging (license, versions, etc.)
- STK has a lot of flexibility: exploit use vectors/ angles
- Best to automate repeated tasks
- Working with vendors is necessary/advantageous
- Always ask: “Am I using the right modeling/simulation tool?”

Software for Space, Defense & Intelligence

Future Work

- Extend the system-level model
  - Higher fidelity models of the spacecraft subsystems
  - Include communication and experimental link budgets
- Extend and refine the behavioral and analysis models
  - Add spacecraft scheduling for optimal use of resources
  - Improve approach for data extraction at specific time (e.g. from STK)
- Automate system and mission parameters trade-offs
  - Extend MBSE Analyzer to drive simulations by CST
  - Enable sensitivity analysis and design optimization
- Generalize the model for applicability to a variety of mission concepts

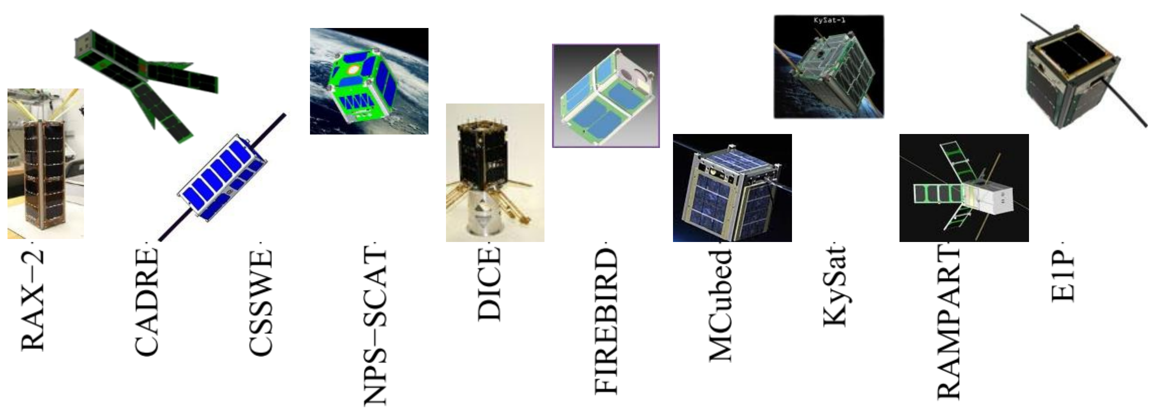


Image Credit: CubeSat Mission Team Websites

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