DEVELOPING AND DISTRIBUTING A CUBESAT MODEL-BASED SYSTEMS ENGINEERING (MBSE) REFERENCE MODEL - STATUS

Primary Author

David Kaslow
Consultant
david.kaslow@gmail.com

Co-authors

Bradley Ayres
The Aerospace Corporation
bradley.ayres.ctr@afit.edu

Michael Jesse Chonoles
Chonoles Consulting
michael@chonolesconsulting.com

Dr. Samuel D. Gasster
TASC, An Engilty Company
sgasster@aol.com

Laura Hart
Lockheed Martin Space System Company
laurahart1@gmail.com

Alejandro G, Levi
USAF Space and Missile Center
alejandro.g.levi@ieee.org

Chris Massa
Draper Laboratory
cmassa@draper.com

Rose Yntema
InterCAX
rose.yntema@intercax.com

Bungo Shiotani
University of Florida
Space Systems Group
bshiota@ufl.edu

ABSTRACT

Model-Based Systems Engineering (MBSE) is a key practice to advance the systems engineering discipline, and the International Council on Systems Engineering (INCOSE) has established the MBSE Initiative to promote, advance, and institutionalize the practice of MBSE. As part of this effort, the INCOSE Space Systems Working Group (SSWG) Challenge Team has been investigating the applicability of MBSE for designing CubeSats since 2011.

At the core of MBSE is the development of the system model that helps integrate other discipline-specific engineering models and simulations. The team has been working to create a system model that captures many of the basic features of a CubeSat project using the Systems Modeling Language (SysML), which is a graphical modeling language for systems engineering. In the past phases of the project, the team has created the initial iteration of the reference model, applied it to the Radio Aurora Explorer (RAX) mission, executed simulations of system behaviors, interfaced with commercial simulation tools, and demonstrated how behaviors and constraint equations can be executed to perform operational trade studies.

This paper reports on our current progress in the development of the CubeSat Reference Model and plans for the future.

INTRODUCTION

Traditional Systems Engineering [1]

Traditional systems engineering has been document-centric. Documents are used to record, store, and convey system and subsystem specification including requirements, concepts of operations, and interfaces. This approach results in creating, updating, reviewing, and managing the configuration of separate documents. Models are created and used on an as-needed basis, most of the time to analyze different aspects of system performance in support of generating requirements.

Model-Based Systems Engineering [1]

Model-based approaches have been in use by various engineering disciplines including electrical, mechanical, and software, and this paradigm is now being adopted by the systems engineering practice as well. INCOSE defines MBSE as follows:

Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. [2]

MBSE is the formalized application of modeling to support key systems engineering tasks for addressing requirements, design, analysis, validation and verification. It is an integration of discipline-specific engineering models and simulations, and it is based on a modeling language and graphical-based modeling tools where requirements and interfaces are not contained in isolated engineering artifacts as done previously but are now integrated within a single system model. This allows for a full exploration of the model, and changes are automatically propagated and reflected in every view of the system. The goal is to generate documentation from the model and not vice versa, and this is only if it necessary in the first place. Moreover, the physical system should be built using the model and not to the documentation.

As illustrated in Figure 1 our application of MBSE utilizes a modeling language, an engineering methodology, a system modeling tool), and interfaces with other models.

Systems Modeling Language [3]

The project's application of MBSE uses the Systems Modeling Language (SysML) and graphical modeling tools from No Magic. SysML is a customization specifically created to address the systems engineering domain based on Unified Modeling Language (UML), a product of the Object Management Group (OMG) [4]. SysML is structured to contain all the design information. Reference [5] has an overview of SysML elements and diagrams.

As shown in Figure 2, the SysML model contains various elements such as blocks, actors, flows, signals, and ports. Structure, behavior, requirement, and parametric diagrams provide views into the model. A block is the fundamental SysML modeling element. A block can define a type of logical or conceptual entity; a physical entity; a hardware, software, or data component; a person; a facility; an entity that flows through the system; or an entity in the natural environment. The block properties used to define a block include structural features, behavioral features, and constraints.

Object-Oriented Systems Engineering Method [3]

SysML is modeling language which can support various system engineering methodologies including the methodology used by this team, Object-Oriented Systems Engineering Method (OOSEM) [6] as presented in the *INCOSE Systems Engineering Handbook* [7] and the *Practical Guide to SysML* [8].

OOSEM includes analyzing stakeholder needs, analyzing system requirements, defining the logical architecture, and synthesizing candidate physical architectures. The logical architecture is a decomposition of the system into logical components that interact to satisfy the system requirements. The logical components are abstractions of the physical components that perform the system functionality without imposing implementation constraints.

The physical architecture defines the physical components that interact to satisfy the system requirements. The physical components of the system include hardware, software, persistent data, and operational procedures.

The CubeSat Reference Model will provide the logical architecture. These logical elements can be reused for specifying a mission specific CubeSat.

The specific methodology used to create the architecture is not critically important to the development of the reference model. It only matters that the model provides the foundation for a user to create a physical architecture. The decomposition of the system into space and ground subsystems is consistent with the *NASA System Engineering Handbook* [9] and *Space Mission Engineering – The New SMAD* [10]. The Cal Poly CubeSat

Design Specification provides the foundation for specifying a CubeSat's physical, mechanical, electrical, testing, and operational requirements [11].

SSWG MBSE CHALLENGE PROJECT EARLY PHASES [1]

The SSWG team consists of students, professors, engineers, and software developers from across government, industry, and academia and modeling and simulation tool providers. Team members are continually recruited from symposiums and workshops. In addition there are interactions with the INCOSE Object-Oriented Systems Engineering Method (OOSEM) and Model-Based Concept Design (MBCD) working groups.

The team has completed four phases (Phase 0 to 3), and Figure 3 shows an overview of these phases. The initial (Phase 0) effort focused on the modeling of a hypothetical FireSat space system. FireSat is a low-Earth orbit spacecraft for detecting, identifying, and monitoring forest fires. This space system is used as an example in the widely used and accepted Space Mission Analysis and Design (SMAD) textbook [10].

Modeling FireSat demonstrated the application of SysML but the hypothetical nature of FireSat precluded anyone from actually building a real space system from the model. Therefore, the practical use of the model could not be demonstrated or verified.

The SSWG MBSE Challenge Project then initiated the MBSE CubeSat Project in April 2011 to demonstrate the application of MBSE to a realistic mission in the space systems domain. A CubeSat is a type of miniature spacecraft with a form factor based on the standardized unit cube, which is 10-centimeters on a side, and it weighs approximately one kilogram per cube. CubeSats typically consist of one to three units with some up to six units.

Phase 1 consisted of developing a SysML model of a CubeSat based on the Radio Aurora Explorer (RAX) mission [12]. RAX is a three-unit CubeSat developed jointly by SRI International and the Michigan Exploration Laboratory at the University of Michigan. The RAX mission was to study the formation of magnetic field-aligned electron density irregularities in the Earth's ionosphere, which are known to disrupt tracking and communication between Earth and orbiting satellites.

The SysML model for the RAX CubeSat demonstrated the basic implementation and utility of MBSE for this type of space mission.

Phase 2 focused on expanding the RAX CubeSat SysML model to include behaviors [13]. Mission activities and states were modeled such as: collection and downlink of mission data as well as collection and storage of solar energy. A model for the power subsystem accounted for solar energy collection and storage and subsystem power consumption. A communication model accounted for data downlink rate, available power, and signal to noise ratio taking into account gains and losses due to communication components, atmosphere, and length of the propagation path.

Phase 3 consisted of two efforts. The first was to develop the beginnings of an enterprise-level model for a generic CubeSat [14]. The second effort was to develop a new model with the capability to time-step through a scenario and to capture the energy collection and usage processes as well as data collection, storage, and downlink [5]. Two trade studies were demonstrated: 1) On-board energy level as a function of solar panel area and maximum battery capacity and 2) quantity of data downlinked as a function of orbital altitude and ground station network.

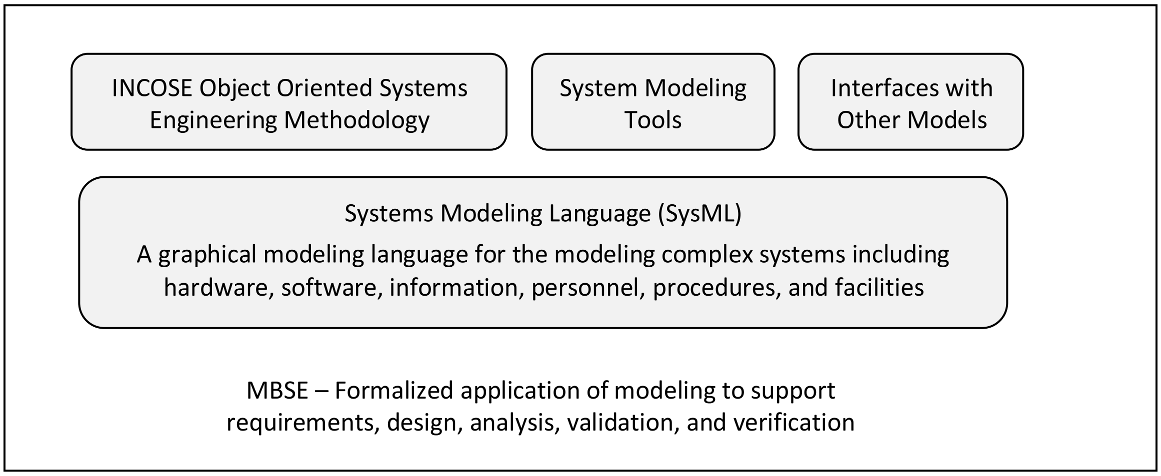

Figure 1– Model-Based Systems Engineering Enablers [3]

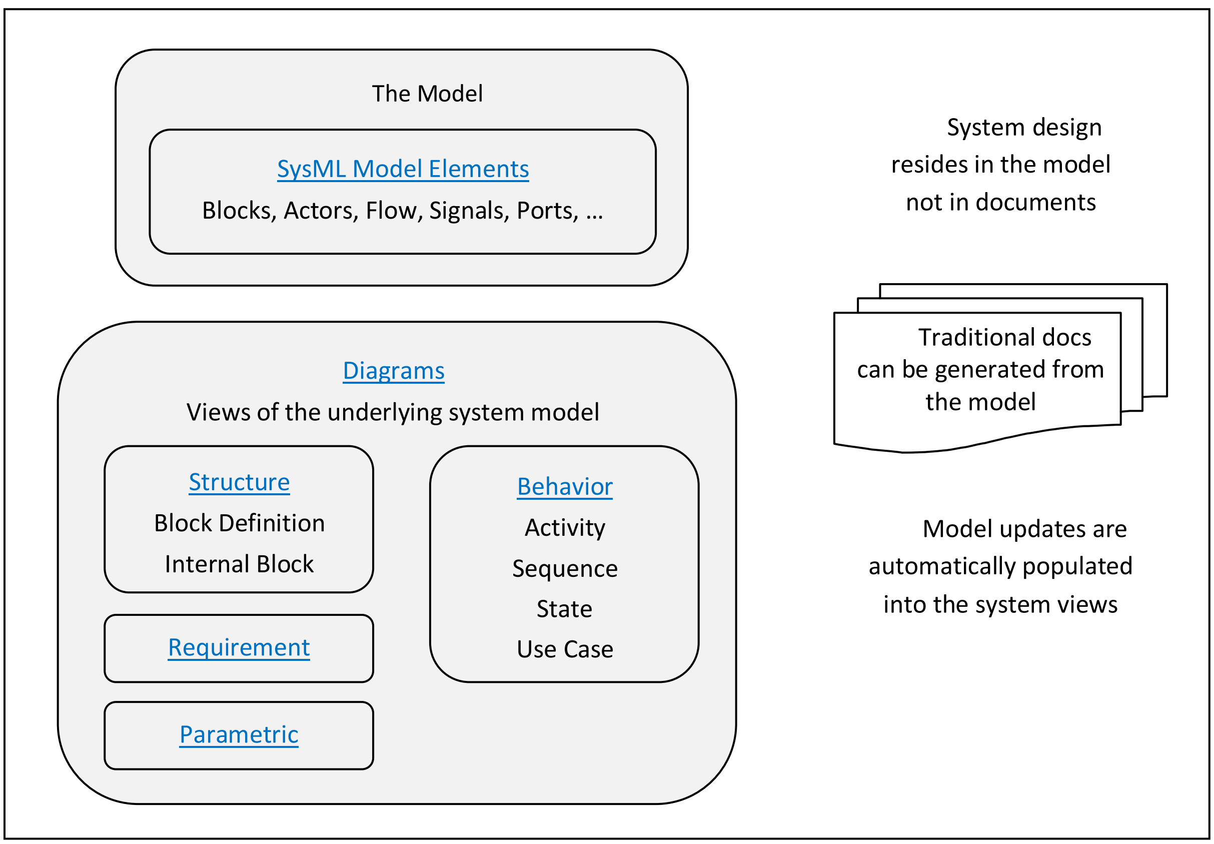

Figure 2. SysML Model Elements and Views into the Model [3]

CURRENT PHASE

Development of the CubeSat Reference Model [1] [3]

The current phase of the project is focused on developing the CubeSat Reference Model. Figure 4 illustrates our approach to the development of the model [1] [3] [15] [16].

The CubeSat Reference Model development began with the identification of the mission stakeholders. A stakeholder is any entity that has an interest in the system including sponsor, end user, procurer, supplier, and regulatory agencies. The stakeholders are shown in Figure 5. Each stakeholder's needs, objectives, constraints, and measures of effectiveness are incorporated in the reference model. Constraints are those items fixed and not subject to trades.

Particular attention must be paid to the regulatory agencies. CubeSat projects are pursued internationally, but the licenses and regulations that cover its activities are administered at the national level. For example, in the United States:

- Federal Communications Commission (FCC) regulates the radio frequencies and spectrum management
- National Aeronautics and Space Administration (NASA) provides orbital debris guidelines.
- National Oceanic and Atmospheric Administration (NOAA) regulates remote sensing. If a satellite has an imaging payload, it must be licensed by NOAA.

The timelines and procedures for requesting and receiving approval must be well understood and part of the model.

One of the stakeholders is the Cal Poly CubeSat Program. One of the recent accomplishments was the translation of the Cal Poly CubeSat Design Specification documentation into a SysML model. This model provides the foundation for specifying a CubeSat's physical, mechanical, electrical, testing, and operational requirements. Figures 6 and 7 are an overview of the Cal Poly model and requirements.

The reference model can support all life cycle stages for a CubeSat mission. For example, for an academic CubeSat project, the likely stages would be concept, development, production, operational, and retirement. The model also supports all phases of operations: pre-launch integration and test, launch, early orbit checkout , and full mission operations.

Figure 8 illustrates the hierarchy of mission needs, objectives, and constraints; technical measures, requirements, and use cases. For example measures of effectiveness trace to mission objectives which refine mission needs. Mission use cases refine mission requirements and system requirements trace to mission use cases. The measures of effectiveness, measures of performance, and technical performance measures are incorporated into the CubeSat Reference Model as block value properties.

CubeSat Domain

Figure 9 shows the CubeSat Domain, which consists of the CubeSat Enterprise, Stakeholders, External Environment, and External Constraints. External Environment consists of the Space Environment and Earth Environment. The External Constraints include such things as Licenses and Regulations.

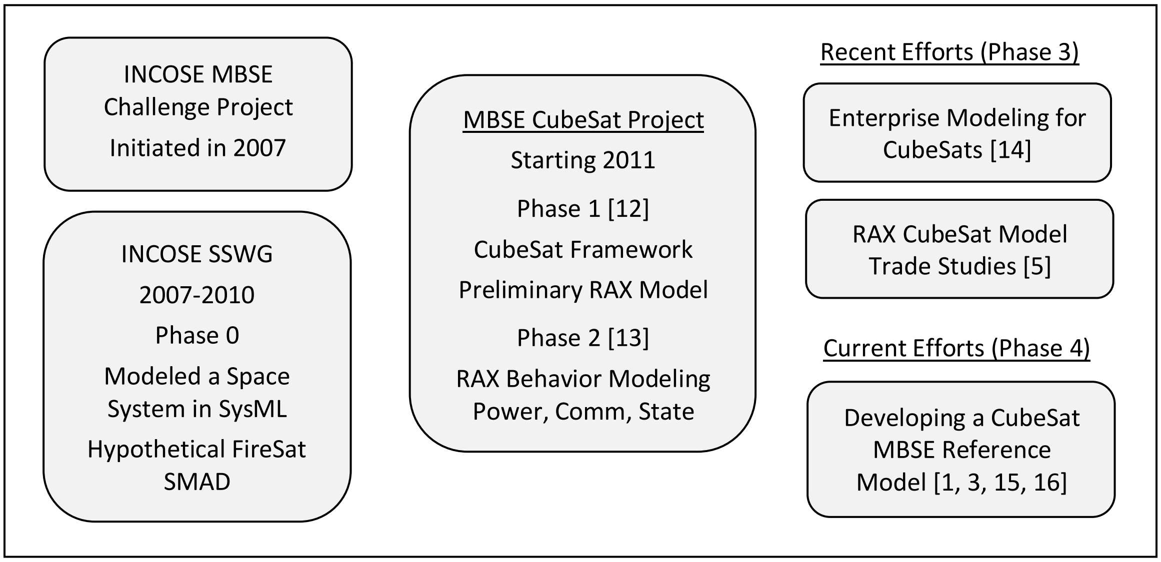

Figure 3 - SSWG MBSE Challenge Project Phases [3]

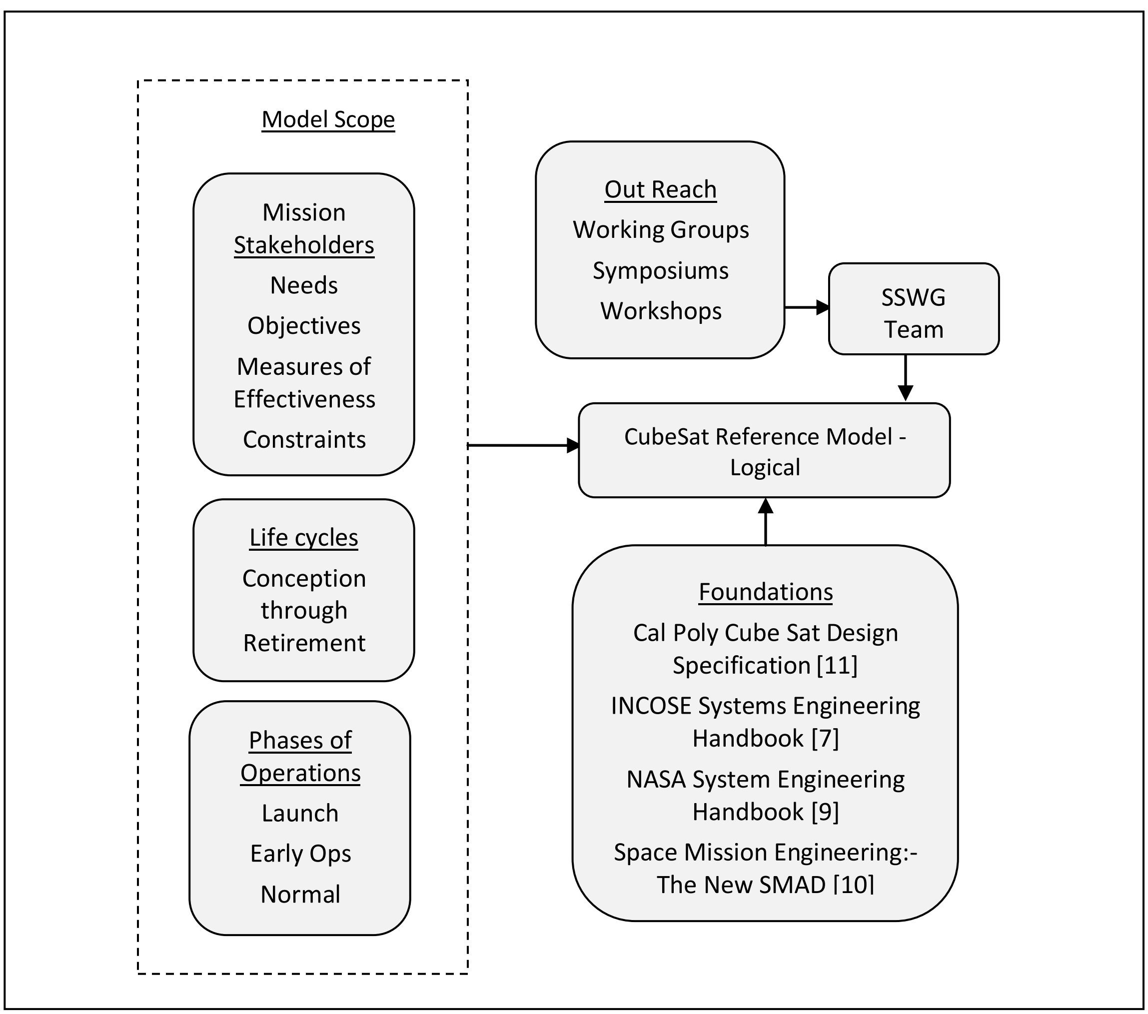

Figure 4 - Development of the CubeSat Reference Model [3]

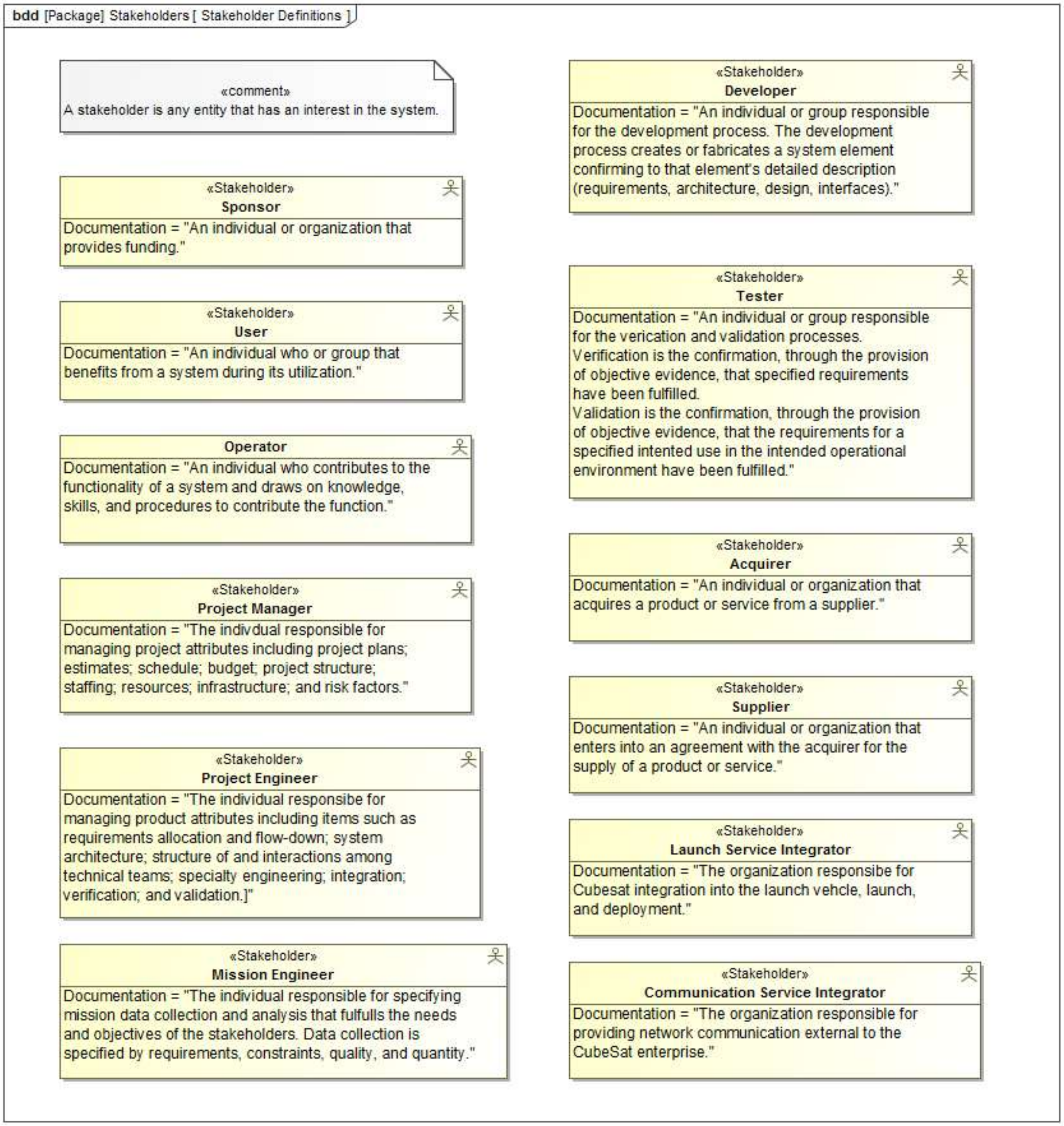

Figure 5. Individual Stakeholders [3]

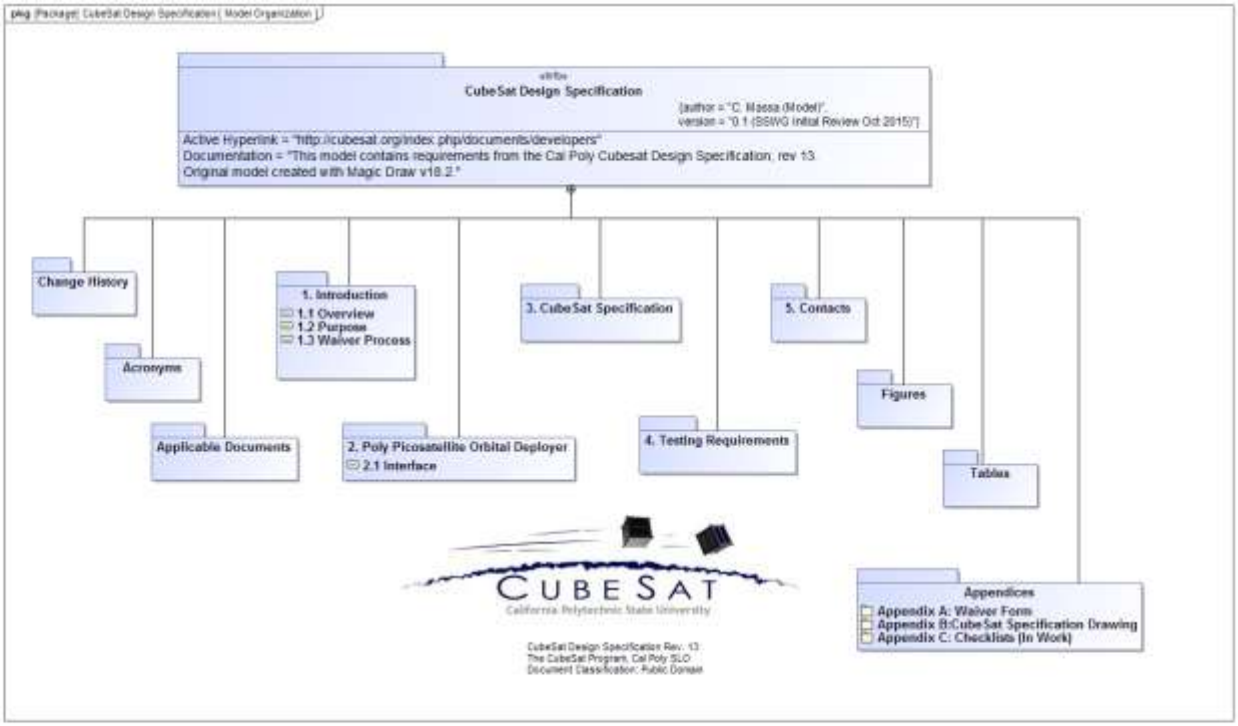

Figure 6. Cal Poly Design Spec Model Organization

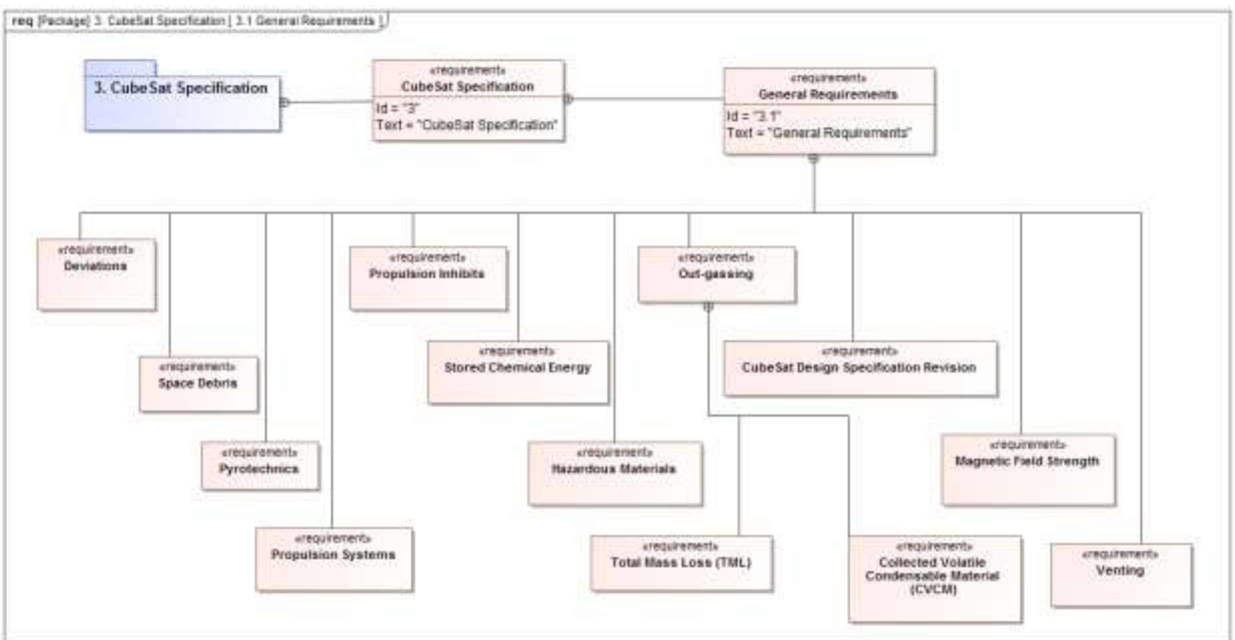

Figure 7. Cal Poly Design Spec Model – Example of Requirements Modeling

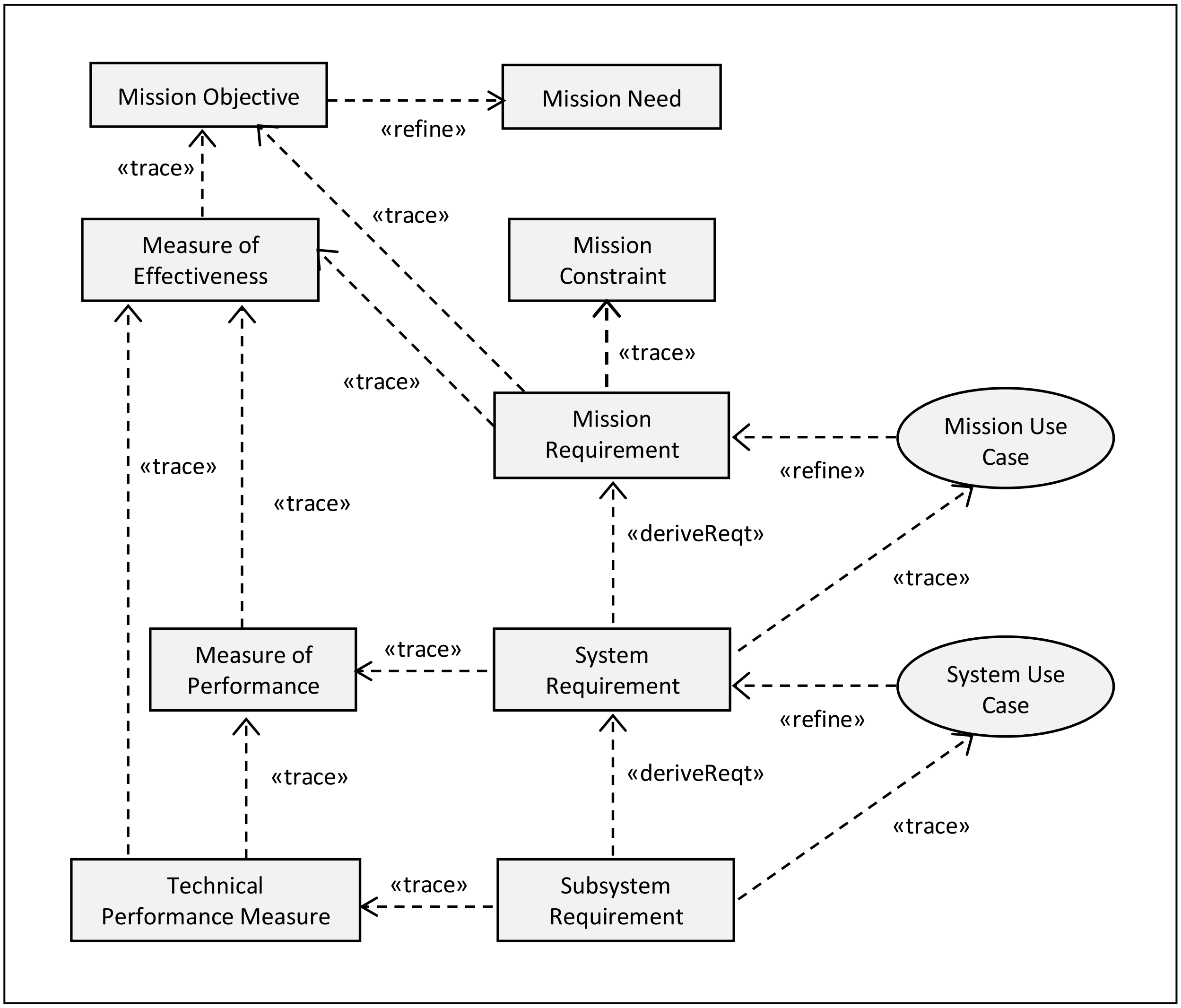

Figure 8. Hierarchy of mission needs, objectives, and constraints; technical measures, requirements, and use cases.

CubeSat Enterprise

At its most basic the CubeSat Enterprise consists of the CubeSat Space System and the CubeSat Ground System. The CubeSat Space System consists of one or more CubeSats with their orbits and subsystems. The CubeSat Ground System consists of it subsystems. The CubeSat Enterprise would include, if needed for CubeSat Mission Operations, GPS satellites and space-ground relay satellites. For example, NASA has considered providing Tracking and Data Relay Satellite System (TDRSS) support to CubeSats. If the CubeSat system develops its own relay satellites, then those satellites would be part of the CubeSat Space System.

For the purposes of the model, the GPS and relay satellites are not considered part of the Space and Ground Systems. But the designs, interfaces, and operations of the Space and Ground Systems would address any necessary interactions with the GPS and relay satellites.

CubeSat Orbits

There are two approaches to specifying and achieving an orbit. CubeSat mission analysis can determine a preferred orbit and a range of satisfactory orbits. If the CubeSat is launched as a secondary payload, the CubeSat project will need to select a launch opportunity that leaves the CubeSat within the range of satisfactory orbit. If the CubeSat has an orbit adjust capability, it can then be moved from the satisfactory orbit to the preferred orbit. If the CubeSat is a primary payload, it can be launched directly to the preferred orbit.

Transport, Launch, and Deploy

CubeSats are transported to a launch site, integrated into a launch vehicle, launched, and deployed. There are many options for transporting, launch, and deployment. Commercial transport services include FedEx® Space Solutions. Launch gets the CubeSat to orbit. Examples are as primary or secondary payload on a launch rocket or on a cargo flight to the space station.

Deployment consists of the activities/processes/mechanisms that separate the CubeSat from the host and make it a free-flyer. Examples are the Poly-PicoSatellite Orbital Deployer (P-POD) and the NanoRacks CubeSat Deployer. Some CubeSats are launched but not deployed as a free-flying CubeSats.

If the CubeSat system has its own transport, launch, deployment capabilities, then they would be part of a Launch System at the same level as CubeSat Space and Ground Systems. Currently the CubeSat community procures these services through external entities as represented by the Ship, Launch, and Deploy Services.

The Space System includes designs, interfaces, and operations to comply with the requirements and constraints of the Transport, Launch, and Deploy Services. For example a launch has a pressure and vibration profile that constrains the design of the CubeSat. The requirements and constraints could be incorporated into a Transport, Launch, and Deploy model unique to the external providers.

CubeSat Ground System

The CubeSat Ground System consists of the CubeSat Mission Operations and one or more Ground Stations. Mission Operations center includes the software, data, procedures, and personnel used to operate the CubeSat mission. Mission Operations activities include mission planning and scheduling, command and control of the CubeSat, control of the ground equipment, mission telemetry processing, and mission data processing and distribution.

The Ground Station consists of the computers, network, communication equipment, and associated control infrastructure hosted in ground facilities. Communication equipment includes the space-ground antennas.

CubeSat Mission Operations are product of the CubeSat project. The CubeSat project could develop its own Ground Station. Or it could co-operate with an existing Ground Station which would be Ground Station Services.

Space and Ground Subsystems

Figures 10 and 11 show the logical architectures for the space and ground systems. The CubeSat Reference Model includes a general system decomposition that users can tailor to suit their particular project needs. Reference [15] provides a description of subsystems.

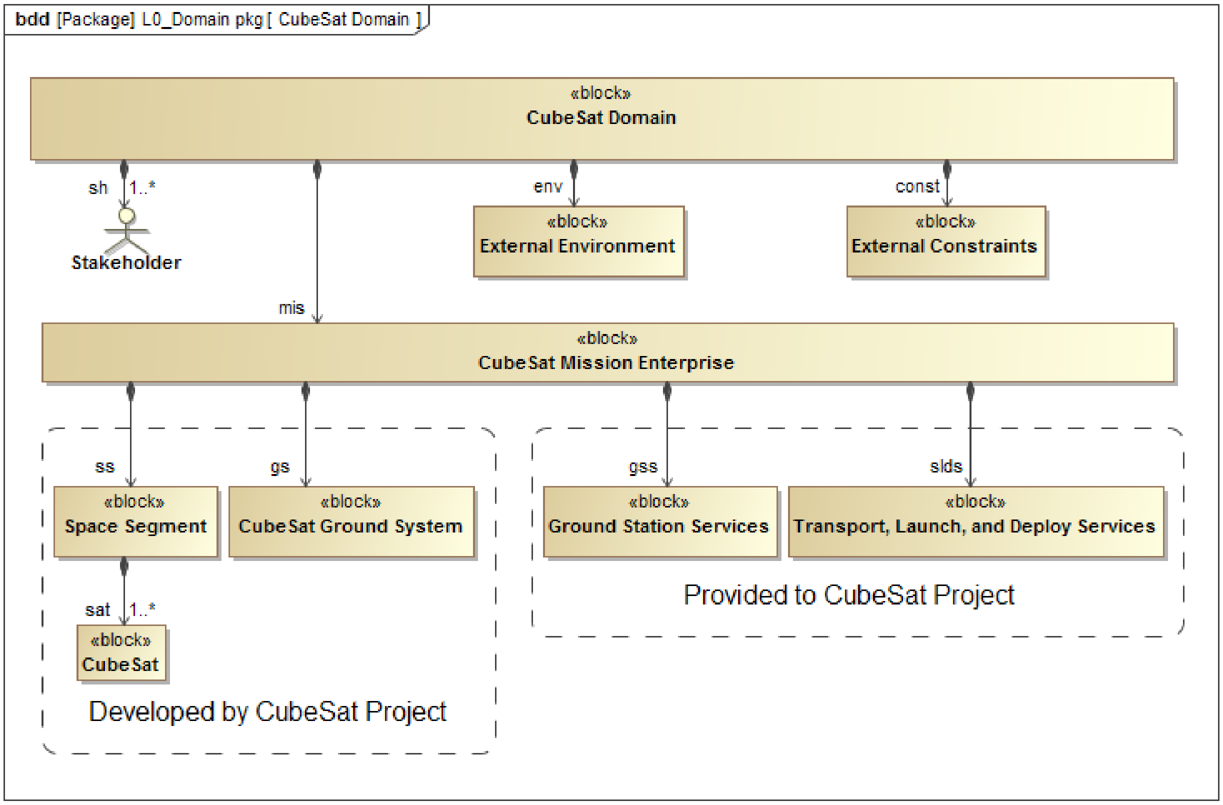

Figure 9. CubeSat Domain and Enterprise

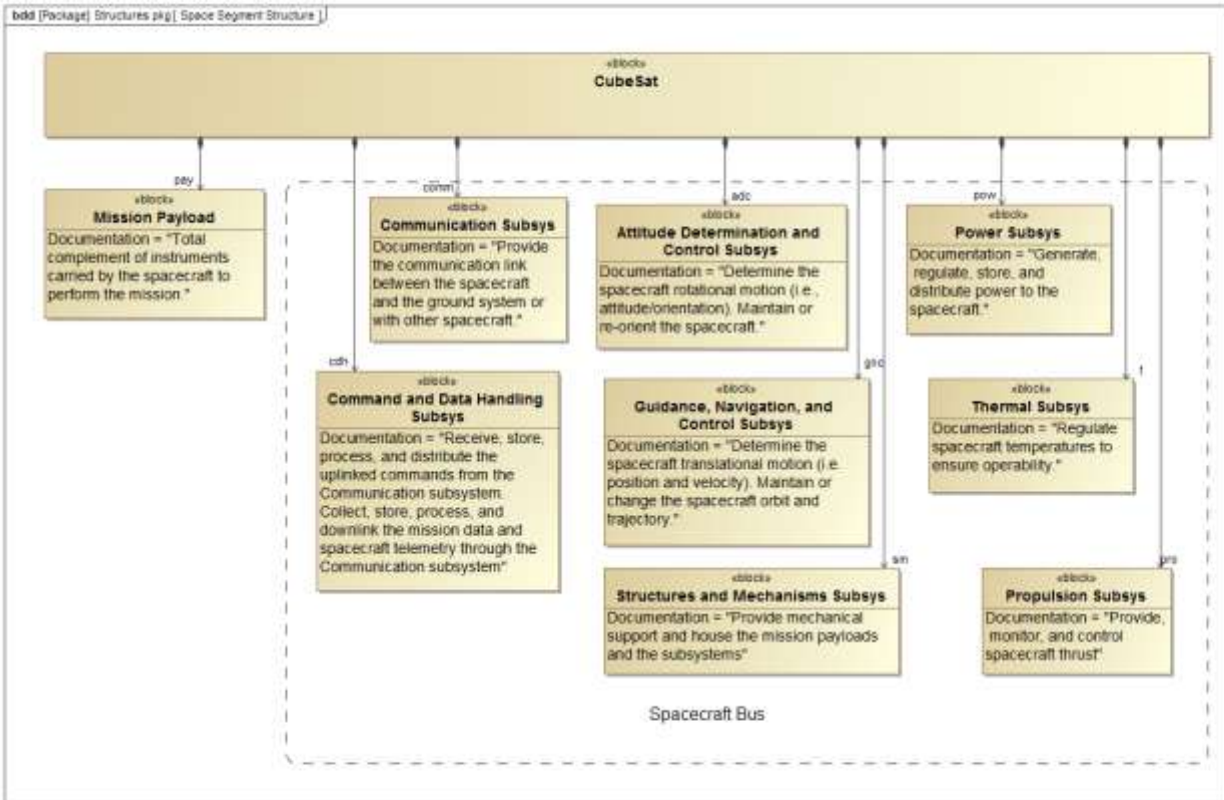

Figure 10. CubeSat – Logical Architecture

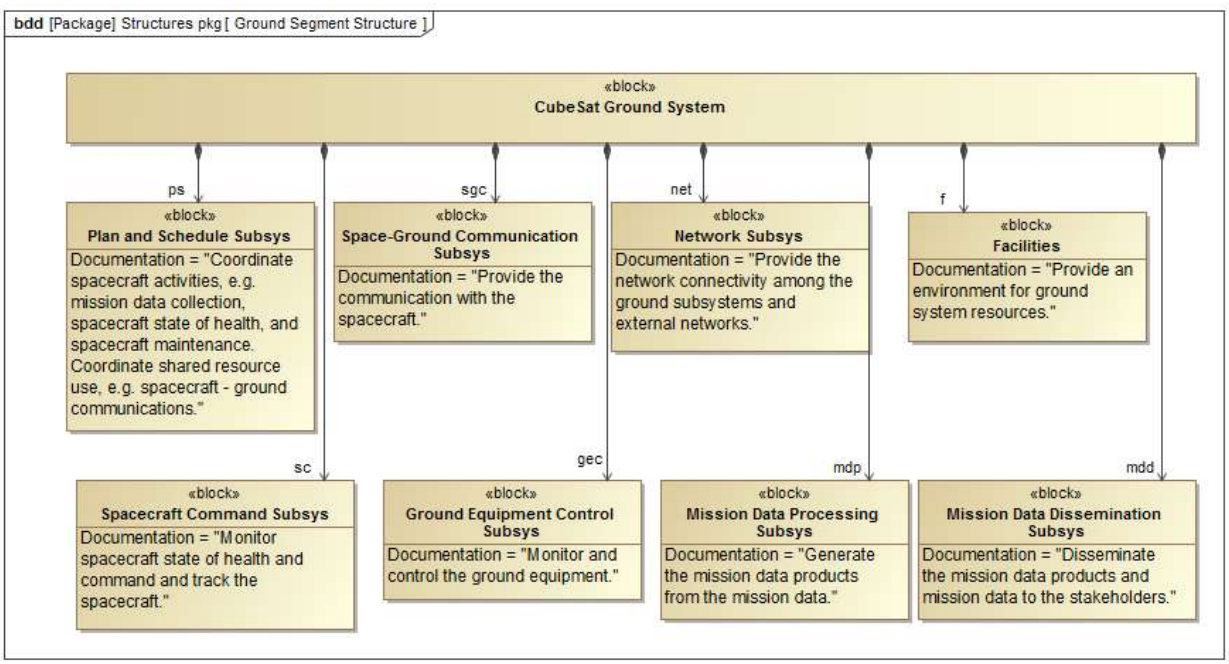

Figure 11. Ground System – Logical Architecture

Distribution of the CubeSat Reference Model [1]

The CubeSat Reference Model is approaching a sufficient level of maturity to begin sharing with the rest of the MBSE community. There have also been requests to use the model for educational purposes and to evaluate it for actual CubeSat projects. In response, the SSWG team is developing a model distribution process to share to external entities, and this is illustrated in Figure 12 In addition to the model file, the distribution will include video recordings that explain and walk through the model and its components.

Since the reference model is being developed by the SSWG team effort, there is an obligation to protect the investment of time and knowledge of each team member. There also needs to be a licensing environment that is conducive to a user organization supporting the development of and use of the model.

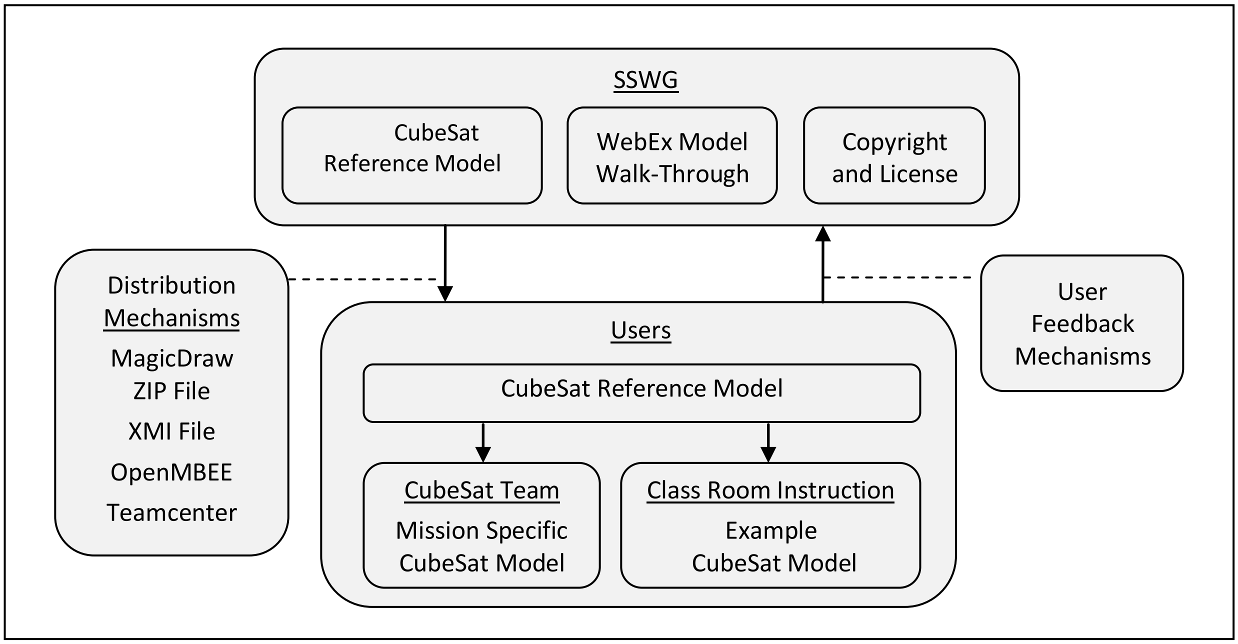

Figure 12 - Distribution and Use of the CubeSat Reference Model [3]

NEXT STEPS

The effort to date has been focused on establishing standard nomenclature and definitions; incorporating the stakeholders and their needs, objectives, and measures of effectiveness; and defining the generic CubeSat architecture down to the logical subsystem level. The future plans include: (i) refining the CubeSat Reference Model to include additional details for each of the model elements, (ii) verifying the correctness of the model, (iii) working with INCOSE on model copyright and licensing and (iv) developing a release plan and process for distributing the model.

CONCLUSION

After several phases of learning and applying MBSE to the CubeSat design process, the SSWG Challenge Team is now focused on developing the CubeSat Reference Model, which is a SysML model that will serve as a framework for future CubeSat developers. MBSE holds the promise of reducing the burden of systems engineering tasks, which is beneficial to small CubeSat teams, and a properly designed reference model can serve as a checklist to these teams and promote uniformity and consistency across future CubeSat models. Several avenues of distribution along with licensing and copyright options are being considered.

REFERENCES

[1] D. Kaslow, L. Anderson, S. Asundi. B. Ayres, C. Iwata, B. Shiotani, R. Thompson, “Developing and Distributing a CubeSat Model-Based System Engineering (MBSE) Reference Model”, *Proceedings of the 31st Space Symposium*, Colorado Springs, CO, April 2015.

[2] Systems Engineering Vision 2020, INCOSE-TP-2004-004-02, ver. 2.03,September 2007. [Online]. Available: http://www.incose.org/ProductsPubs/pdf/SEVision2020_20071003_v2_03.pdf

[3] D. Kaslow, B. Ayres, M. Chonoles, S. Gasster. L. Hart, C. Massa, R. Yntema, “Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status #2”, *Proceedings of the 2016 IEEE Aerospace Conference,* Big Sky, MT, March 2016.

[4] Object Management Group (OMG), OMG Website. [Online]. Available: http://www.omgsysml.org/

[5] D. Kaslow, G. Soremekun, H. Kim, S. Spangelo, “Integrated Model-Based Systems Engineering (MBSE) Applied to the Simulation of a CubeSat Mission”, *Proceedings of the 2014 IEEE Aerospace Conference*, Big Sky, MT, March 2014.

[6] Object Management Group (OMG), OMG Wiki. [Online]. Available: http://www.omgwiki.org/MBSE/doku.php?id=mbse:incoseoosem

[7] *INCOSE Systems Engineering Handbook,* v. 3.2.2, October 2011, INCOSE-TP-2003-002-03.2.2.

[8] S. Friedenthal, A. Moore, R. Steiner, *A Practical Guide to SysML*, 2nd ed., Elsevier, Waltham, MA, 2012.

[9] *NASA Systems Engineering Handbook,* rev. 1, December 2007, NASA/SP-2007-6105 Rev1.

[10] J.R. Wertz, D. Everett, and J. Puschell, Eds., *Space Mission Engineering: The New SMAD*, (Space Technology. Library, Volume 28), Hawthorne, CA, Microcosm Press, 2011.

[11] *CubeSat Design Specification*, rev. 13, The CubeSat Program, Cal Poly SLO, February 2014

[12] S. Spangelo, D. Kaslow, C. Delp, B. Cole, L. Anderson, E. Fosse, B. Gilbert, L. Hartman, T. Kahn, and J. Cutler, “Applying Model Based Systems Engineering (MBSE) to a Standard CubeSat,” in *Proceedings of IEEE Aerospace Conference*, Big Sky, MT, March 2012.

[13] S. Spangelo, L. Anderson, E. Fosse, L Cheng, R. Yntema, M. Bajaj, C. Delp, B. Cole, G. Soremekun, D. Kaslow, and J. Cutler, “Model Based Systems Engineering (MBSE) Applied to Radio Explorer (RAX) CubeSat Mission Operational Scenarios,” *Proceedings of* the 2013 *IEEE Aerospace Conference*, Big Sky, MT, March 2013.

[14] L. Anderson, B. Cole, R. Yntema, M. Bajaj, S. Spangelo, D. Kaslow, C. Lowe, E. Sudano, M. Boghosian, R. Reil, S. Asundi, and S. Friedenthal, "Enterprise Modeling for CubeSats," *Proceedings of* 2014 *IEEE Aerospace Conference*, Big Sky, MT, March 2014.

[15] D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani, R. Thompson, "Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status", *Proceedings of the 2015 IEEE Aerospace Conference,* Big Sky, MT, March 2015.

[16] D. Kaslow, B. Ayres, C. Iwata, and B. Shiotani, "CubeSat Model-Based Systems Engineering (MBSE) Reference Model – Application in the Concept Life Cycle", *Proceedings of the 2015 AIAA Space Forum*, Pasadena, CA, August 2015.