A Model-Based Systems Engineering Approach to Space Mission Education of a Geographically Disperse Student Workforce

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Abstract

The Alabama Burst Energetics eXplorer (ABEX) is a 12U CubeSat commissioned by the Alabama Space Grant Consortium; its astrophysics mission is to study the low energy, prompt emission of Gamma-ray Bursts in both gamma and X-ray spectra. The ABEX program is unique in that its workforce is comprised of individuals at seven colleges and universities around the state of Alabama. ABEX management releases Requests for Proposals (RFP) for Senior Design (SD) projects or university research groups to design and build spacecraft subsystems; university faculty with experience and facilities for the development of that subsystem respond to the RFPs to create a team. ABEX supports undergraduate SD students, graduate student mentors, and faculty technical advisors for all spacecraft subsystems in both ground and flight mission segments. Each team has between 5-15 undergraduate students, meaning ABEX teaches spacecraft design to ~85 undergraduate students at any given time; ABEX may be the largest collegiate CubeSat program in the world. The undergraduate labor force turns over, or cycles to new students, every 4-8 months, so ABEX can teach hands-on spacecraft design to over 100 students every year and has taught over 200 to date. Two features of ABEX create a difficult Systems Engineering (SE) environment: the undergraduate labor force turnover rate and the geographically disperse workforce. Most subsystem teams exist within two-semester SD courses, but some teams, like Flight Software, only exist for one semester before the undergraduate team turns over. This means the student onboarding process must be efficient and the material hand-off process effective if any substantive contribution to the spacecraft is to be made in their brief course period. A Model-Based Systems Engineering (MBSE) Integrated System Model (ISM) was created using SysML as a full-program organization of mission requirements, subsystem architectures, verification and validation procedures, and team interaction tracking methodologies for workforce turnover effect mitigation with ISM-exported artifacts as central objects of stage-gate reviews. An ABEX website was created with processes for first-time student onboarding, ISM artifact dissemination, and intercollegiate document transfer in addition to being a public relations arm for the program. With education at the forefront of ABEX, educational requirements and performance measures detailing onboarding efficiency, workforce preparedness, and alumni vocation results are defined within the ISM and used to evaluate program education proficiency. Program organization, ISM structure, and spacecraft design is presented with an emphasis on quantifying student education as a result of program involvement.

Keywords

Space Education, Model-Based Systems Engineering, Workforce Development

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Acronyms

AAMU	*Alabama Agriculture & Mechanical University*
ABEX	*Alabama Burst Energetics eXplorer*
AF	*Architecture Framework*
ASGC	*Alabama Space Grant Consortium*
DAC	*Design Analysis Cycle*
DBSE	*Document-Based SE*
DKM	*Domain Knowledge Map*
DSTC	*J. F. Drake State Community Technical College*
EPM	*Educational Performance Measure*
GRB	*Gamma-ray Bursts*
HBCU	*Historically Black Colleges & Universities*
ISM	*Integrated System Model*
KQ	*Key Question*
MBSE	*Model-Based SE*
NASA	*National Aeronautics and Space Administration*
PF	*Process Framework*
RDP	*Review Data Package*
SE	*Systems Engineering*
SME	*Subject Matter Expert*
SSO	*Sun-Synchronous Orbit*
TPM	*Technical Performance Measure*
UAH	*University of Alabama in Huntsville*
WBS	*Work Breakdown Structure*
WFF	*Wallops Flight Facility*

1. Introduction

The Alabama Burst Energetics eXplorer (ABEX) is a 12U CubeSat that will probe the energy dissipation in astrophysical jets by observing a currently unexplored energy domain in the universe's most energetic phenomena: Gamma-ray Bursts (GRBs). Understanding GRBs is a key element in both the National Aeronautics and Space Administration's (NASA) Astrophysics Roadmap [1] and the 2020 Astrophysics Decadal Survey [2] as a laboratory for high-energy physics, compact object formation, and gravitational waves. ABEX is a coalition effort between 7 universities and Goddard Space Flight Center, which will provide qualification testing and advise the project continually.

1.1. ABEX: A Space Education Program

ABEX is an educational mission uniting 1 NASA center, 7 colleges and universities, 12 faculty, and 19 graduate students with undergraduate teams to create the largest collegiate spacecraft project in the world (M. Swartwout, personal communication, March 7, 2022) and serve as a model for education-centric spacecraft development. Students working in a multidisciplinary and geographically dispersed environment co-lead all aspects of the project and are provided supporting classes with ABEX-specific coursework. ABEX also conducts outreach to underrepresented groups in aerospace through Historically Black Colleges and Universities (HBCUs).

1.2. NASA's Educational Goals

NASA's Strategic Plan and Astrophysics Roadmap both outline a need for engagement within a Science, Technology, Engineering, and Mathematics pipeline to increase diversity in the field [1,3]. ABEX strategically enables 7 academic institutions with faculty, graduate, and undergraduate students in all project domains; faculty members advise graduate students who lead undergraduates in senior-level projects. During major development phases, ABEX provides 19 graduate students with critical leadership roles, such as Project Manager and Chief Engineer, for early career opportunity experience. Academic courses are offered by ABEX faculty to educate students in specific topics relevant to each team. ABEX has a multidisciplinary and geographically disperse work environment, providing realistic working conditions compared to modern collaborative missions with students simultaneously gaining hands-on science and engineering skills and academic credits. Educational risk introduced by student involvement is mitigated by strong onboarding procedures, recorded seminars, process documentation, dedicated classes, faculty oversight, and Subject Matter Expert (SME) mentorship. ABEX provides a training environment to prepare future scientists and engineers to collaborate in managing, conceptualizing, designing, and implementing future NASA and aerospace missions. ABEX responds directly to the 2020 NASA Astrophysics Decadal Survey's recommendation that HBCUs be at the forefront of astrophysical research through its partnerships with J. F. Drake State Community and Technical College (DSTC) and Alabama Agriculture & Mechanical University (AAMU), both institutions proximate to the University of Alabama in Huntsville (UAH) [2]. DSTC will develop a cleanroom for ABEX and lead

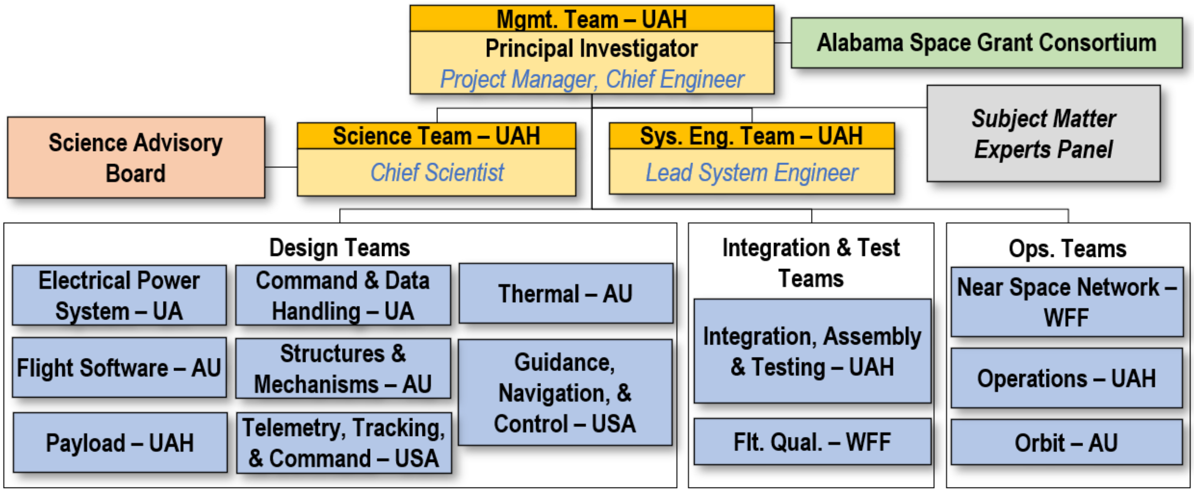

Figure 1. ABEX Management Hierarchy with Auburn University (AU), the University of Alabama (UA), and the University of South Alabama (USA). Blue text indicates management roles for graduate students

spacecraft assembly. Summer research opportunities will be provided to AAMU students to work with UAH science and engineering teams. Since the start of the ABEX collaboration in 2019, over 200 university students have been involved including 8 graduate students.

1.3. ABEX Program Structure

The student involvement in ABEX requires strong management structures and clear lines of authority. ABEX activities are coordinated around a Work Breakdown Structure adapted from NASA/SP-2016-3404 [4]. Undergraduates are managed by graduates overseen by faculty with project leadership from the Principal Investigator through the Project Manager and Chief Engineer. Supporting management roles are the Lead Systems Engineer and Chief Scientist. All teams are technically supported by the Science Advisory Board and SME panel. The Alabama Space Grant Consortium (ASGC) assists with outreach, student activities, and university negotiations to promote ABEX educational goals. The ABEX team hierarchy is shown in Figure 1. Graduate students outside of management roles are allocated to design, operations, and integration & test teams.

2. Astrophysics, Spacecraft, and Mission

GRBs are theorized to originate from powerful jets generated by compact object formation, but debate remains on Key Questions (KQ) concerning the composition of the jet and how energy dissipates forming the bright gamma-ray emission. To resolve KQs, observations must be pushed into a new domain, the low-energy prompt emission, which offers distinctive features able to resolve the tension between emission models. Figure 2 depicts the science mission goals.

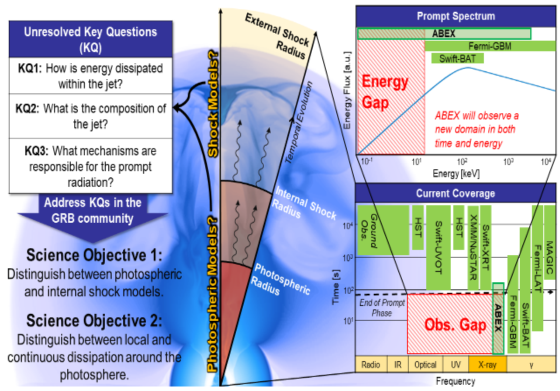

Figure 2. ABEX Science Objectives

To accomplish both education and science goals, the spacecraft bus was custom-designed including the on-board computer, electrical power system, software-defined radio, link antennas, structural chassis, thermal control system, and GRB detection payload. The solar arrays and attitude determination and control systems are vendor-supplied. Like the science mission and spacecraft bus, the mission architecture, shown in Figure 3, was designed and analyzed by students with data products publishing to a student-built website, abexmission.org.

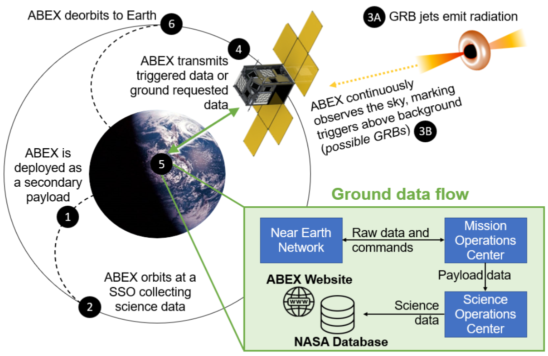

Figure 3. ABEX Mission Architecture

3. MBSE and Space Education

Model-Based Systems Engineering (MBSE) is defined by an Architecture Framework (AF) specifying a taxonomy of work products created throughout the mission, a Process Framework (PF) detailing the maturation of those products, an ontology expressing the properties of and relations between those products, and a modeling language used to create the Integrated Systems Model (ISM) which ties it all together [5]. The AF and PF organize which activities are accomplished in the mission and how they are accomplished, respectively; defining these explicitly affords rigid yet reinforceable structure to a project organization. The ontology aids in student conceptual understanding, product creation, and process execution by defining entity categories for concepts that exist in the program and strong, semantic relationships between those categories; ontologies represent an agreement on relationship usage rather than the usage itself. Graduate systems engineers interact directly with the ISM, not undergraduates. Methods for incorporating MBSE tenets into space education processes are discussed.

3.1. Integration of MBSE & Education

MBSE and space education are integrated in three primary sectors: Work Breakdown Structures (WBS), student onboarding, and review materials, each of which is given dedicated attention subsequently.

3.1.1. Work Breakdown Structures

Program management, in ABEX's case the Project Manager and Chief Engineer, organize engineering, operations, science, and enterprise work in terms of the AF and provide subsets of that work to students in the form of a Design Analysis Cycle (DAC) work package specific to an academic semester. Per the PF, descriptions are included for how the work package should be executed and in what form deliverables should be provided. The PF also dictates which deliverables are shown at which stage-gate reviews, informing the products that should be created for a given DAC. If the AF and PF are defined in mission concept development, all future DAC work is known, ordered, and communicable.

Work products in the AF will also be model-based if possible. ABEX utilizes SysML and UML as modeling languages that students can use to generate DAC work products, such as block definition diagrams for subsystem structure, activity diagrams for subsystem behavior, activity diagrams for integration test chain representation, parametric diagrams for analytical models, and sequence diagrams for software operations. Student-produced, model-based work can be imported directly into the ISM, reducing time required to translate student deliverables into the ISM.

3.1.2. Student Onboarding

Onboarding is the process of educating new members of a workforce in a relevant field and ensuring members can execute provided tasks using a set of provided tools; efficient onboarding provided by faculty and graduate students is paramount for student space programs because student turnover rates are high and knowledge retention is low. Three concepts have aided ABEX in student onboarding: traditional documentation, a centralized repository of onboarding materials, and Domain Knowledge Maps (DKM). Document-Based Systems Engineering (DBSE) is, unfortunately, how students are accustomed to learning. Documents such as analysis plans, development & integration plans, and verification activity plans can be provided as is common of any program, but DBSE material representation should be consistent with the AF, PF, and ontology with figures generated from the ISM. When students provide work products for import into the ISM, the products are polished, connected to other ISM entities such as requirements, structures, or behaviors, and exported back to the DBSE onboarding tools. When students learn subsystem onboarding material, they learn MBSE. Those documents, and any additional onboarding materials, must be available on-demand from a centralized repository for a geographically disperse program. ABEX utilizes a website, abexmission.org, as the first stop in a student's onboarding journey. Students receive onboarding packages specific to their team containing subsystem-specific plans, reports, tool usage guides, and more general spacecraft and SE education.

For analysis products, DKMs facilitate a direct connection between the ontology and the execution of analysis work outlined for a DAC. Ontologies can be created for a specific domain; ABEX subdivides a program-wide ontology into fragments such as the technical analysis domain for hardware and the software development domain for software. A DKM is an application of a domain ontology to a specific problem such as the calculation of a Technical Performance Measure (TPM) or the connection between user-defined software subsystems. If a domain ontology contains concept categories and relationships in that domain, a DKM

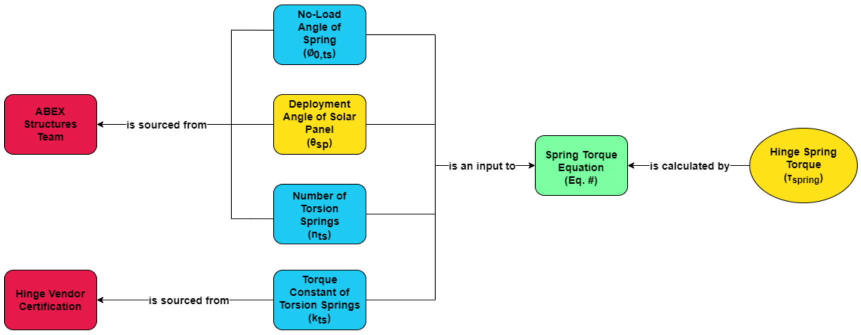

Figure 4. DKM Example. Instances of Source, Scalar Parameter, Array Parameter, and Equation categories are shown in red, blue, yellow, and green, respectively. TPMs are shown as ovals

represents instances of those categories and how they are used. A DKM example detailing instances of predefined categories is provided in Figure 4. The ontological triple, “Number of Torsion Springs is an input to Spring Torque Equation” is an instance of the ontological triple, “Scalar Parameter is an input to Equation.” Strong semantics inherent to DKMs remove ambiguity in concept representation.

3.1.3. Review Materials

Programs with rigorous Systems Engineering (SE) processes feature stage-gate reviews such as a System Requirements Review or Critical Design Review, and SMEs attending reviews need organized review material in the form of Review Data Packages (RDP) prior to reviews. Even at NASA, RDPs are usually created by sourcing materials from various documents, presentations, standards, and verification activity reports – a cumbersome, time-consuming process. A DAC may last only 14 weeks, and time to execute work products may be severely limited if 3 weeks are required for student onboarding and 3 weeks are required to organize RDP materials. Generating some, not all, RDP materials from the ISM is known as a model-based review and affords time-reduction methods when organizing review materials. Using the ISM, a subsystem can depict structural composition, behavior, integration flows, analysis plans via DKMs, test plans, and the satisfaction or verification of requirements as applied to any diagram. The generation of many RDP materials is then accomplished via perfunctory model exports rather than hunt-and-gather documentation.

3.2. Educational Performance Measures

As with TPMs, which are performance measures monitored by comparing current achievement of a parameter with that anticipated at the current time and on future dates [6], the performance of an educational program can be measured by Educational Performance Measures (EPM). Like TPMs, EPMs should be relevant, measurable, tailored for a project, and have a target value to compare performance against. Management should be able to trade cost or schedule to improve EPM performance, and performance should be expected to improve with time. For example, involvement percent of minority and female students is an EPM, and ABEX conducts post-DAC evaluations with anonymous student responses to gather EPM data. For DAC-2 in Fall 2021, 84% of ABEX students asserted that ABEX contributed their skills and knowledge, 68% asserted the learning objectives were clear at the beginning of the DAC, and 74% would recommend ABEX to another student. Target values for these EPMs are not yet justified, but EPM data tracking allows programs to analyze and identify educational improvement areas.

4. Lessons Learned

ABEX management and faculty collaborated on two CubeSat missions prior to ABEX, and various project structures, work vectors, and student activities were pursued before ABEX achieved persistent success.

4.1. To MBSE or not to MBSE

Students have a finite threshold for comprehension of new material and available time; other than the SE team, their efforts should be spent learning technical material specific to a subsystem and not the inner workings of MBSE. When management provides DAC work package material with products, product formats, and due dates, they are decoupling students from the AF and PF. Management knows which products should be presented at which stage-gate reviews; students should be focused on individual tasks in a DAC work package. MBSE is also not a panacea for all life cycle phases. Management should lean heavily into MBSE for student onboarding and RDP preparation, but the utility of MBSE decreases rapidly after test and integration activities are completed [7].

4.2. *Product Formatting is Critical*

If a product is requested of 7 teams and a format is not specified, management will receive 7 products in 7 different formats. It is not sufficient to prevent product formats from being problematic; programs should make the formats work to their benefit. Students should deliver products in a format that is importable to the ISM and consistent with a predefined ontology.

4.3. *Time is Limited for Every DAC*

Two DAC fragments should be reduced as much as possible to maximize product execution time: onboarding and RDP creation. If a program with 20 planned DACs reduces onboarding time by 1 week and RDP creation by 2 weeks, that's 60 weeks of development and execution time gained per student. MBSE can reduce the time required for both.

4.4. *Documentation is Unavoidable*

Students are accustomed to learning by reading, and documentation passed down between student teams is usually the first step in new student onboarding. However, material representation within the documentation such as subsystem structure, behavior, and requirements can be represented using a modeling language. Doing so will prepare students to create MBSE-centric deliverables.

4.5. *Roll the Teams Across DACs*

Not every ABEX team is part of a senior design program, but many are. For those that are senior design teams, a strategy that has significantly improved knowledge retention is to start a new subsystem team every semester. First-semester teams do not produce many valuable deliverables, but they learn from second-semester teams and produce excellent deliverables their second semester in ABEX.

5. Conclusions

The organizational structure of the ABEX program can be emulated to create multi-institution space education programs with geographically disperse workforces. By aligning semesters with DACs and planning DAC operations using AF and PF structures, a program can coordinate mission development activities around SE life cycle phases without spending valuable onboarding time to educate undergraduate students on MBSE tenets. Reducing the time required for onboarding and RDP creation is vital to the long-term success of a program, and advanced MBSE techniques such as ontology definition and DKM utilization can facilitate and standardize spacecraft analysis techniques and report formats. MBSE should be employed heavily in early life cycle phases with DBSE being more useful after integration procedures. Rolling teams across semesters will increase program knowledge retention and onboarding document quality.

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