ABEX
Alabama Burst Energetics eXplorer

Structures and Mechanisms Development and Integration Plan

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No.	Section	Description	Date

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1 Introduction

1.1 Document Description

The Structures & Mechanisms Development and Integration Plan (DIP) will establish the technology development approach and integration flow to mature this subsystem to a Technology Readiness Level (TRL) of 5.

1.2 Scope of Applicability

The document will establish the necessary efforts for technology development efforts up to TRL 5, which will include descriptions of the testing demonstrations and the flight unit integration as applicable. The TRL 6 effort will be covered by the Subsystem Qualification Plan and the flight unit's acceptance testing prior to spacecraft assembly is covered in the Subsystem Acceptance Plan. The system wide integration will be covered in the ABEX Integration Plan. The application of this plan, such as the specific analysis and testing described within, will be published in separate analysis and test reports as needed during the project design analysis cycles.

1.3 Reference Documents

The following project and subsystem documents should be referenced as needed.

Table 1: Relevant project documents.

Project Document Name	Description of Document
Project Summary	An overview of the ABEX mission and major elements.
Requirements Document	List of project requirements with V&V allocations.
Structural Qualification Plan (SQP)	Document that entails methodologies to validate the structure bus of the S/C

2 Structures & Mechanisms Technical Summary

2.1 System Description

The Structures and Mechanisms subsystem is focused on the structural design of the CubeSat. To verify the design of the structure bus, the Structures and Mechanisms Team have identified Technical Performance Measures that will quantify the performance of the structure. The calculations and simulations involved with these Technical Performance Measures (TPMs) are outlined in Domain Knowledge Maps (DKMs).

In addition to the structural design of the spacecraft, the Structures and Mechanisms subsystem explores the different tests used in validating its structural integrity. The team has created Integration Flow Diagrams that specifically address how specific components of the system are tested and integrated with the rest of the system.

2.2 Product Breakdown Structure

The Product Breakdown Structure (PBS) is shown below, in x**Error! Reference source not found.**. s pecifically identifies each component that comprises the structure. Each component in the Structures and Mechanisms subsystem is defined with a corresponding Product Breakdown Structure Identification number (PBS ID). A description of the component is also listed.

For general guidance on making and updating the PBS, see 7.

Table 2: Product breakdown structure for the subsystem.

PBS ID	Product Name	Product Description
1.1	**S&M Flight Hardware**	
1.1.1	Structural Chassis	
1.1.1.1	+X Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 347x220.3 mm
1.1.1.2	-X Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 347x220.3 mm
1.1.1.3	+Y-Frame	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 226.3x364 mm
1.1.1.4	-Y-Frame	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 226.3x364 mm
1.1.1.5	+Z-Frame	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 209.3x209.3 mm
1.1.1.6	-Z-Frame	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 209.3x209.3 mm
1.1.1.7	Chassis Fasteners	44 M4x12mm Fasteners that will hold the chassis together
1.1.2	Payload Harnessing	
1.1.2.1	+X Angled Gamma Ray Detector Harness 1	Harness that will hold the +X Angled GRD in place
1.1.2.2	-X Angled Gamma Ray	Harness that will hold the -X Angled GRD in place

	Detector Harness 2	
1.1.2.3	-Z Angled Gamma Ray Detector Harness 3	Harness that will hold the -Z Angled GRD in place
1.1.2.4	+X Angled X-Ray Detector Harness	Harness that will hold the + X Angled XRD in place
1.1.2.5	-X Angled X-Ray Detector Harness	Harness that will hold the -X Angled XRD in place
1.1.2.6	-Z Angled X-Ray Detector Harness	Harness that will hold the -Z Angled XRD in place
1.1.2.7	Cable Harness 1	Harness that will hold the Cables in place
1.1.2.8	Harness Fasteners	M4x12mm Fasteners that will hold the Harnesses in place
1.1.3	Avionics Box	
1.1.3.1	AB +X-Face	+X Face for Avionics Box, Aluminum 7075-T73 118x168x3 mm
1.1.3.2	AB -X-Face	-X Face for Avionics Box , Aluminum 7075-T73 118x168x3 mm
1.1.3.3	AB +Y-Face	+Y Face for Avionics Box, Aluminum 7075-T73 118x187.3x2.5 mm
1.1.3.4	AB -Y-Face	-Y Face for Avionics Box, Aluminum 7075-T73 118x187.3x2.5 mm
1.1.3.5	AB +Z-Face	+Z Face for Avionics Box, Aluminum 7075-T73 187.3x168x3.5 mm
1.1.3.6	AB -Z-Face	-Z Face for Avionics Box, Aluminum 7075-T73 187.3x168x3.5 mm
1.1.3.7	AB Fasteners	21 A286 stainless steel torx/9.2x12mm and 32 flat head Phillips Machine/2.39x3.18mm Fasteners that will keep the AB in place
1.1.3.8	AB Brackets	
1.1.3.9	AB Flanges	
1.1.4	Mechanisms	
1.1.4.1	Hold and Release Mechanism 1	A mechanism that holds and releases the solar panels
1.1.4.2	Hold and Release Mechanism 2	A mechanism that holds and releases the solar panels
1.1.4.3	Deployment Switch 1	A switch that deploys the solar panels
1.1.4.4	Deployment Switch 2	A switch that deploys the solar panels
1.1.4.5	Mechanical Fasteners	16 #4 binding hex screws, 18 M4x16mm, and 18 stainless steel/M3x18mm Fasteners that will keep the mechanisms in place
1.1.5	Periphereal Cabling	
1.1.5.1	-Z XRD Cable	Cable for the -Z XRD

1.1.5.2	-Z GRD Cable	Cable for the -Z GRD
1.1.5.3	-X GRD Cable	Cable for the -X GRD
1.1.5.4	+X GRD Cable	Cable for the +X GRD
1.1.5.5	-X XRD Cable	Cable for the -X XRD
1.1.5.6	+X XRD Cable	Cable for the +X XRD
1.1.5.7	-X Angled XRD Cable	Cable for the angled -X XRD
1.1.5.8	+X Angled XRD Cable	Cable for the angled +X XRD
1.1.5.9	-Z Angled XRD Cable	Cable for the angled -Z XRD
1.1.5.10	GPS Receiver Cable	Cable for the GPS Reciever
1.1.5.11	XACT-100 Cable	Cable for the XACT-100
1.1.5.12	X-Band Antenna Cable	Cable for the X-Band Antenna
1.1.5.13	S-Band Antenna Cable	Cable for the S-Band Antenna
1.2	**S&M Prototype Hardware**	
1.2.1	Structural Chassis Prototype	12.5 mm thick Aluminum 7075-T73 plate milled and modified
1.2.1.1	+X Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 347x220.3 mm
1.2.1.2	-X Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 347x220.3 mm
1.2.1.3	+Y Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 226.3x364 mm
1.2.1.4	-Y Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 226.3x364 mm
1.2.1.5	+Z Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 209.3x209.3 mm
1.2.1.6	-Z Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 209.3x209.3 mm
1.2.1.7	Fasteners	44 M4x12mm Fasteners that will hold the chassis together
1.2.2	Payload Harnessing Prototype	
1.2.2.1	+X Angled Gamma Ray Detector Harness 1	Harness that will hold the +X Angled GRD in place
1.2.2.2	-X Angled Gamma Ray Detector Harness 2	Harness that will hold the -X Angled GRD in place
1.2.2.3	-Z Angled Gamma Ray Detector Harness 3	Harness that will hold the -Z Angled GRD in place
1.2.2.4	+X Angled X-Ray Detector Harness	Harness that will hold the + X Angled XRD in place
1.2.2.5	-X Angled X-Ray Detector Harness	Harness that will hold the -X Angled XRD in place
1.2.2.6	-Z Angled X-Ray Detector	Harness that will hold the -Z Angled XRD in place

	Harness	
1.2.2.7	Harness Fasteners	M4x12mm Fasteners that will hold the Harnesses in place
1.2.3	Avionics Box Prototype	
1.2.3.1	AB +X Face	+X Face for Avionics Box Prototype, Aluminum 7075-T73 118x168x3 mm
1.2.3.2	AB -X Face	-X Face for Avionics Box Prototype, Aluminum 7075-T73 118x168x3 mm
1.2.3.3	AB +Y Face	+Y Face for Avionics Box Prototype, Aluminum 7075-T73 118x187.3x2.5 mm
1.2.3.4	AB -Y Face	-Y Face for Avionics Box Prototype, Aluminum 7075-T73 118x187.3x2.5 mm
1.2.3.5	AB +Z Face	+Z Face for Avionics Box Prototype, Aluminum 7075-T73 187.3x168x3.5 mm
1.2.3.6	AB -Z Face	-Z Face for Avionics Box Prototype, Aluminum 7075-T73 187.3x168x3.5 mm
1.2.3.7	AB Fasteners	21 A286 stainless steel torx/9.2x12mm and 32 flat head Phillips Machine/2.39x3.18mm Fasteners that will keep the AB in place
1.2.3.8	AB Brackets	
1.2.3.8	AB Flanges	
1.2.4	Mechanisms Prototype	
1.2.4.1	Hold and Release Mechanisms 1 EM	A mechanism that holds and releases the solar panels
1.2.4.2	H&RM 2 EM	A mechanism that holds and releases the solar panels
1.2.4.3	Deployment Switch 1	A switch that deploys the solar panels
1.2.4.4	Deployment Switch 2	A switch that deploys the solar panels
1.2.4.5	Mechanical Fasteners	16 #4 binding hex screws, 18 M4x16mm, and 18 stainless steel/M3x18mm Fasteners that will keep the mechanisms in place
1.2.5	Dispenser Prototype	
1.2.6	Periphereal Cabling	
1.2.6.1	-Z XRD Cable	Cable for the -Z XRD
1.2.6.2	-Z GRD Cable	Cable for the -Z GRD
1.2.6.3	-X GRD Cable	Cable for the -X GRD
1.2.6.4	+X GRD Cable	Cable for the +X GRD
1.2.6.5	-X XRD Cable	Cable for the -X XRD
1.2.6.6	+X XRD Cable	Cable for the +X XRD
1.2.6.7	-X Angled XRD Cable	Cable for the angled -X XRD
1.2.6.8	+X Angled XRD Cable	Cable for the angled +X XRD
1.2.6.9	-Z Angled XRD Cable	Cable for the angled -Z XRD

1.2.6.10	GPS Reciever Cable	Cable for the GPS Reciever
1.2.6.11	XACT-100 Cable	Cable for the XACT-100
1.2.6.12	X-Band Antenna Cable	Cable for the X-Band Antenna
1.2.6.13	S-Band Antenna Cable	Cable for the S-Band Antenna
1.3	**S&M Development Hardware**	
1.3.1	Structural Chassis Development Hardware	
1.3.1.1	+X Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 347x220.3 mm
1.3.1.2	-X Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 347x220.3 mm
1.3.1.3	+Y Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 226.3x364 mm
1.3.1.4	-Y Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 226.3x364 mm
1.3.1.5	+Z Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 209.3x209.3 mm
1.3.1.6	-Z Face	12.5 mm thick Aluminum 7075-T73 plate milled and modified, 209.3x209.3 mm
1.3.1.7	Fasteners	44 M4x12mm Fasteners that will hold the chassis together
1.3.2	Payload Harnessing Development Hardware	
1.3.2.1	+X Angled Gamma Ray Detector Harness 1	Harness that will hold the +X Angled GRD in place
1.3.2.2	-X Angled Gamma Ray Detector Harness 2	Harness that will hold the -X Angled GRD in place
1.3.2.3	-Z Angled Gamma Ray Detector Harness 3	Harness that will hold the -Z Angled GRD in place
1.3.2.4	+X Angled X-Ray Detector Harness	Harness that will hold the + X Angled XRD in place
1.3.2.5	-X Angled X-Ray Detector Harness	Harness that will hold the -X Angled XRD in place
1.3.2.6	-Z Angled X-Ray Detector Harness	Harness that will hold the -Z Angled XRD in place
1.3.2.7	Harness Fasteners	M4x12mm Fasteners that will hold the Harnesses in place
1.3.3	Avionics Box Development Hardware	
1.3.3.1	AB +X Face	+X Face for Avionics Box Devleopment Hardware, Aluminum 7075-T73 118x168x3 mm
1.3.3.2	AB -X Face	-X Face for Avionics Box Development Hardware,

		Aluminum 7075-T73 118x168x3 mm
1.3.3.3	AB +Y Face	+Y Face for Avionics Box Development Hardware, Aluminum 7075-T73 118x187.3x2.5 mm
1.3.3.4	AB -Y Face	-Y Face for Avionics Box Development Hardware, Aluminum 7075-T73 118x187.3x2.5 mm
1.3.3.5	AB +Z Face	+Z Face for Avionics Box Development Hardware, Aluminum 7075-T73 187.3x168x3.5 mm
1.3.3.6	AB -Z Face	-Z Face for Avionics Box Development Hardware, Aluminum 7075-T73 187.3x168x3.5 mm
1.3.3.7	AB Fasteners	21 A286 stainless steel torx/9.2x12mm and 32 flat head Phillips Machine/2.39x3.18mm Fasteners that will keep the AB in place
1.3.3.8	AB Brackets	
1.3.3.9	AB Flanges	
1.3.4	Mechanisms Development Hardware	
1.3.4.1	Hold and Release Mechanism 1 EM	A mechanism that holds and releases the solar panels
1.3.4.2	Hold and Release Mechanisms2 EM	A mechanism that holds and releases the solar panels
1.3.4.3	Deployment Switch 1	A switch that deploys the solar panels
1.3.4.4	Deployment Switch 2	A switch that deploys the solar panels
1.3.4.5	Mechanical Fasteners	16 #4 binding hex screws, 18 M4x16mm, and 18 stainless steel/M3x18mm Fasteners that will keep the mechanisms in place
1.3.5	Periphereal Cabling	
1.3.5.1	-Z XRD Cable	Cable for the -Z XRD
1.3.5.2	-Z GRD Cable	Cable for the -Z GRD
1.3.5.3	-X GRD Cable	Cable for the -X GRD
1.3.5.4	+X GRD Cable	Cable for the +X GRD
1.3.5.5	-X XRD Cable	Cable for the -X XRD
1.3.5.6	+X XRD Cable	Cable for the +X XRD
1.3.5.7	-X Angled XRD Cable	Cable for the angled -X XRD
1.3.5.8	+X Angled XRD Cable	Cable for the angled +X XRD
1.3.5.9	-Z Angled XRD Cable	Cable for the angled -Z XRD
1.3.5.10	GPS Reciever Cable	Cable for the GPS Reciever
1.3.5.11	XACT-100 Cable	Cable for the XACT-100
1.3.5.12	X-Band Antenna Cable	Cable for the X-Band Antenna
1.3.5.13	S-Band Antenna Cable	Cable for the S-Band Antenna

3 Technology Development Plan

3.1 Overview

The subsystem integration and testing plan is intended to mature the subsystem from its current TRL of 3 to a TRL of 5. This process will involve the development of hardware that demonstrates the system in both its function and its function in the relevant environment, including the flight system to a level ready for qualification testing or acceptance testing, which is in the subsystem Qualification Plan and Acceptance Plan respectively.

3.2 Technology Advancement Plan

The following table provides context for each test in validating the spacecraft design. Each step in raising the TRL is documented along with the needed test. Functional tests prove that individual components can survive sufficient stresses. Integration tests prove the survivability of integrated components. Lastly, Environmental Tests prove that component(s) survivability in anticipated environmental conditions.

For guidance on testing types and TRL levels see 6.

Table 3: Description of remaining technology steps and testing goals to be accomplished.

TRL Step	Development (Type I) Testing Goals		
	Functional Tests	Integration Tests	Environmental Test
3 – 4	N/A	N/A	• Compressive Stress Test
4 – 5	• Shock Test	• Shaker sine Vibration Test	• Modal Survey Test • TVAC Cycling Test
5 – 6	• Shaker Random Vibration Test • Acoustic Test	• Centrifuge Test	N/A

4 Defining TPMs

4.1 Purpose

TPMs are methods of tracking the technical performance of a system over time. They help decision making in the design through capturing the impact to the project into helpful parameters. TPMs can be defined for components, subsystems, and systems. System-level TPMs are considered Key Performance Parameters (KPP). TPMs can also be defined for capabilities, which are functions with a specified level of performance. Project will specify a certain level of performance through capability requirements, and that level of performance can be described using a TPM.

4.2 Structure

ABEX defines three types of TPMs: Technical Performance Parameters (TPP), Technical Environmental Parameters (TEP), and KPPs.

Table 4: TPM type definitions with an example.

TPM Type	Description	Example
Technical Performance Parameter	Those capabilities or characteristics (typically engineering-based or related to health and safety or operational performance) considered relevant to operational performance, supportability, and interoperability at any level. TPPs are elevated to KPPs if they are relevant to the entire system	Subsystem Mass
Technical Environmental Parameter	Those capabilities or characteristics relevant to the definition of system interactions with the Operational Environment. TEPs are never elevated to KPPs	Surface Heat Flux
Key Performance Parameter	Those capabilities or characteristics (typically engineering-based or related to health and safety or operational performance) considered most essential for successful mission accomplishment. They characterize the major drivers of operational performance, supportability, and interoperability [1]	Spacecraft Mass Margin

TPPs, TEPs, and KPPs are all TPMs. They're used to calculate relevant aspects of a design and communicate the value of that design to project stakeholders. TPMs must be tracked and reported each DAC. A basic visualization of this is shown in Figure 2. Well-defined TPMs have defining features:

- Should be important and relevant to the subsystem design
- Should be relatively easy to measure for reporting
- The performance or knowledge of performance should be expected to improve with time
- A target, threshold, or expectation of uncertainty should be known and if the measure crosses its threshold, corrective action should be known
- The measured parameter should be controllable by the design decisions
- Should be tracked and documented
- Should be tailored for the project

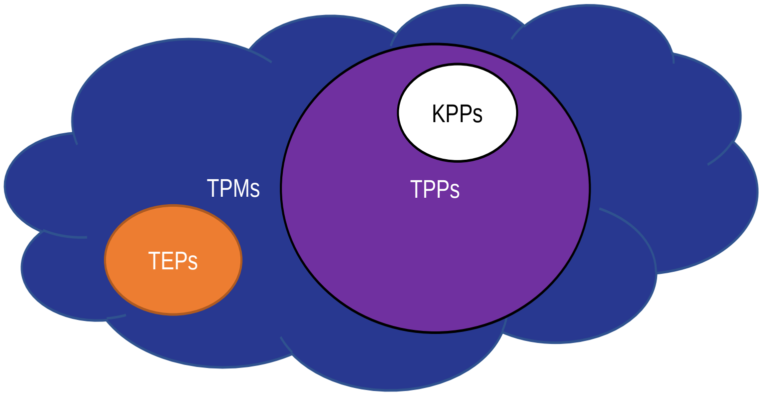


Figure 1: ABEX TPM strategy visualization

5 Integration Plan

5.1 Development Integration Flow

The Visual Parts Breakdown is shown below, in Figure 3. This diagram displays how the components from the Product Breakdown Structure (listed in **Error! Reference source not found.** in Section 2.2 integrated with one another.

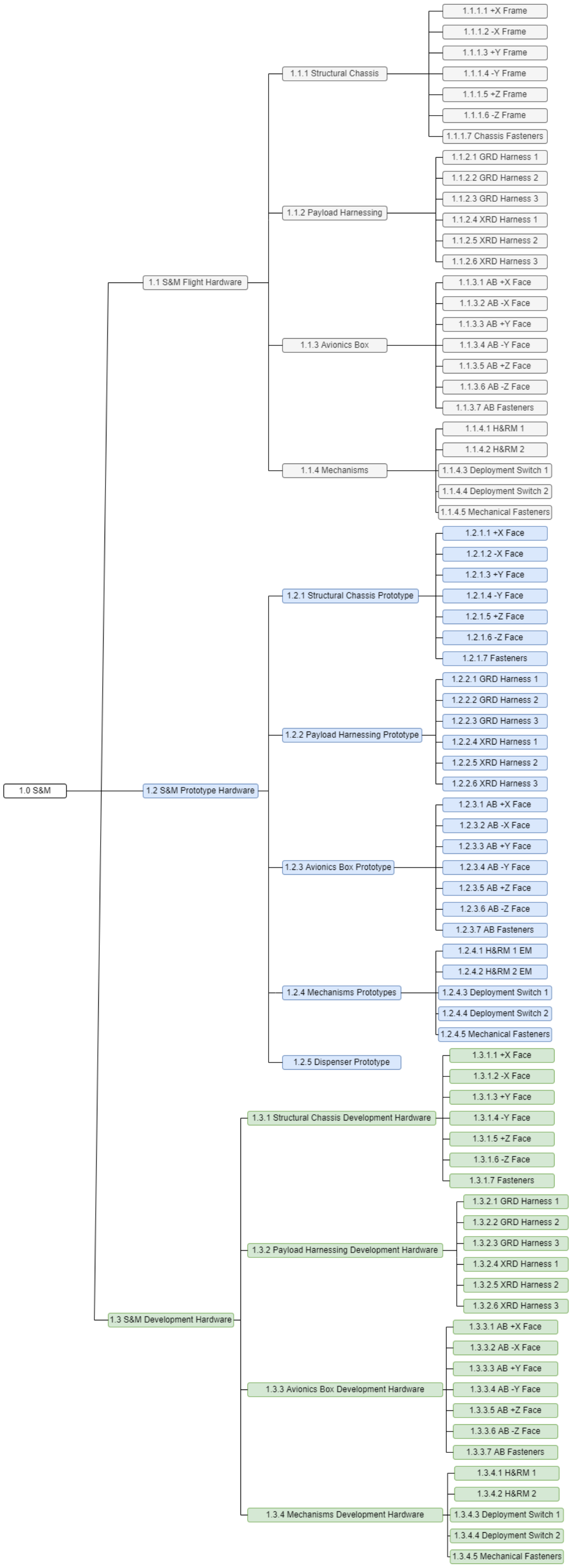


Figure 3: Visual Parts Breakdown

The Integration Flow Diagrams document the process of integrating components and subsystems together. They show the sequential order that the spacecraft is constructed along with the tests used in validation. Each Integration Flow Diagram appears on this document in a series of several images due to the size of the diagrams with the limitations of page dimensions. The spacecraft enters the S&M Development Hardware Integration Flow at a TRL of 3. The structural components are not functionally tested individually rather only when fully integrated. The components of the Structural Chassis (1.2.1 in Table 2 are integrated and tested with an integration test and environmental test. The components of the Payload Harnessing (1.2.2 in Table *2*), Avionics Box (1.2.3 in Table *2*), and Mechanisms (1.2.4 in Table *2*) are integrated and tested using the same process that was utilized for the Structural Chassis. Upon each of those subsystems being integrated and tested (integration and environmental), the entirety of the Prototype Hardware is integrated and tested beginning with an integration test. Following that, the hardware will progress from TRL 3 to TRL 4 by passing a functional test. Then, it will progress from TRL 4 to TRL 5 by passing an environmental test. Technology Readiness Levels of 6 or higher are addressed in the Qualification Plan and not covered in this document.

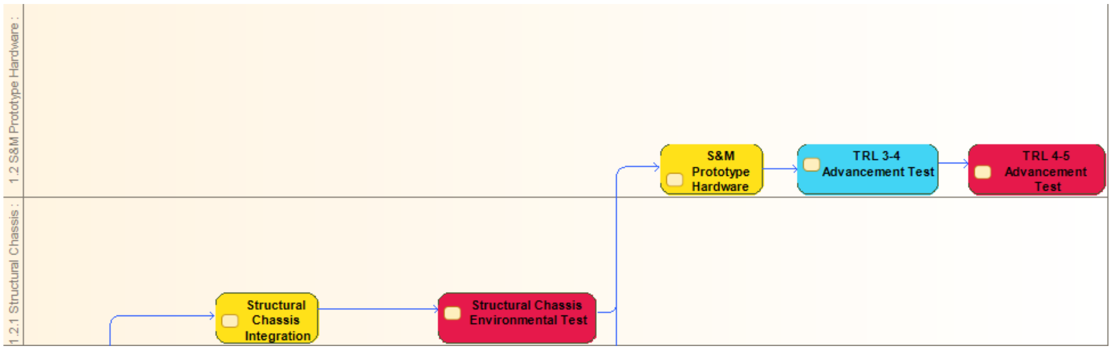


Figure 4: S&M Development Hardware Integration Flow (Image 1)

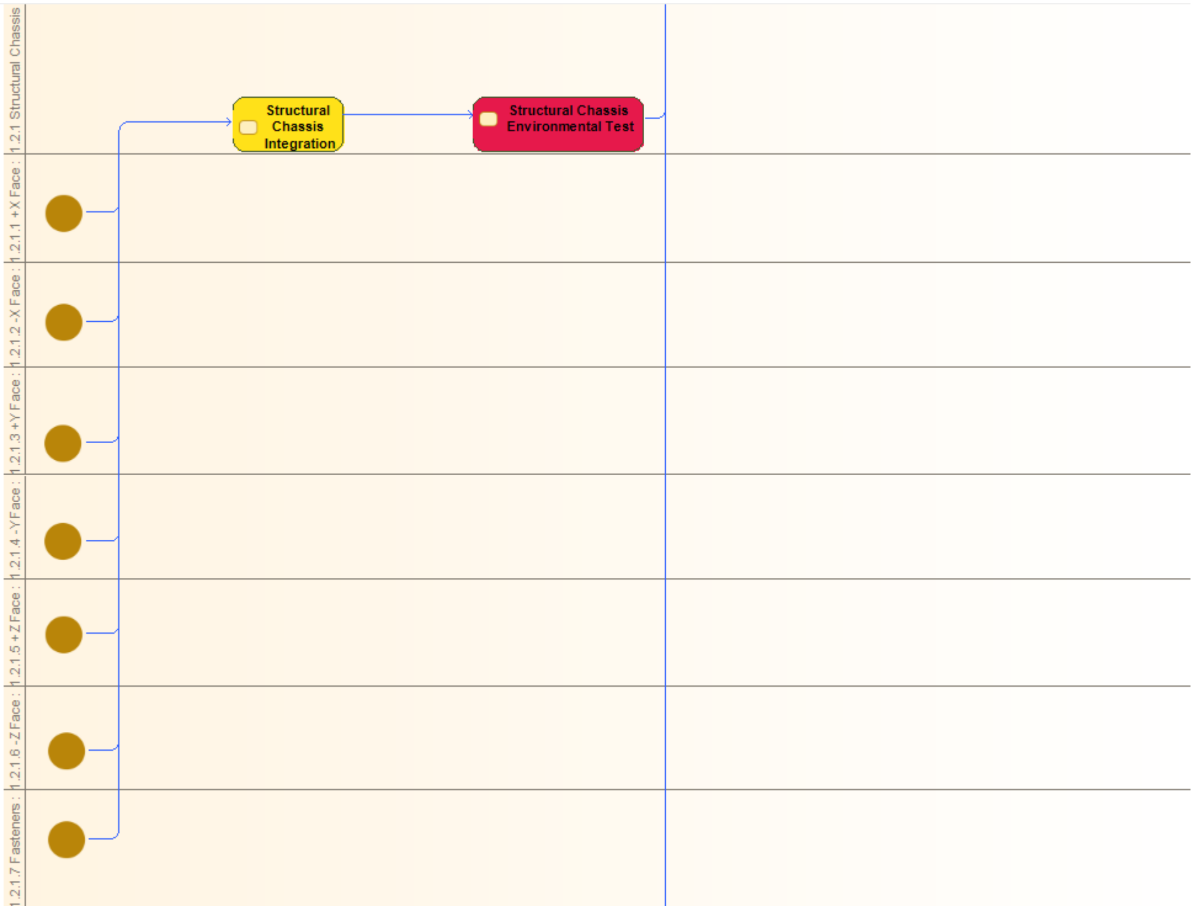


Figure 5: S&M Prototype Hardware Integration Flow (Image 2)

Figure 6: S&M Prototype Hardware Integration Flow (Image 3)

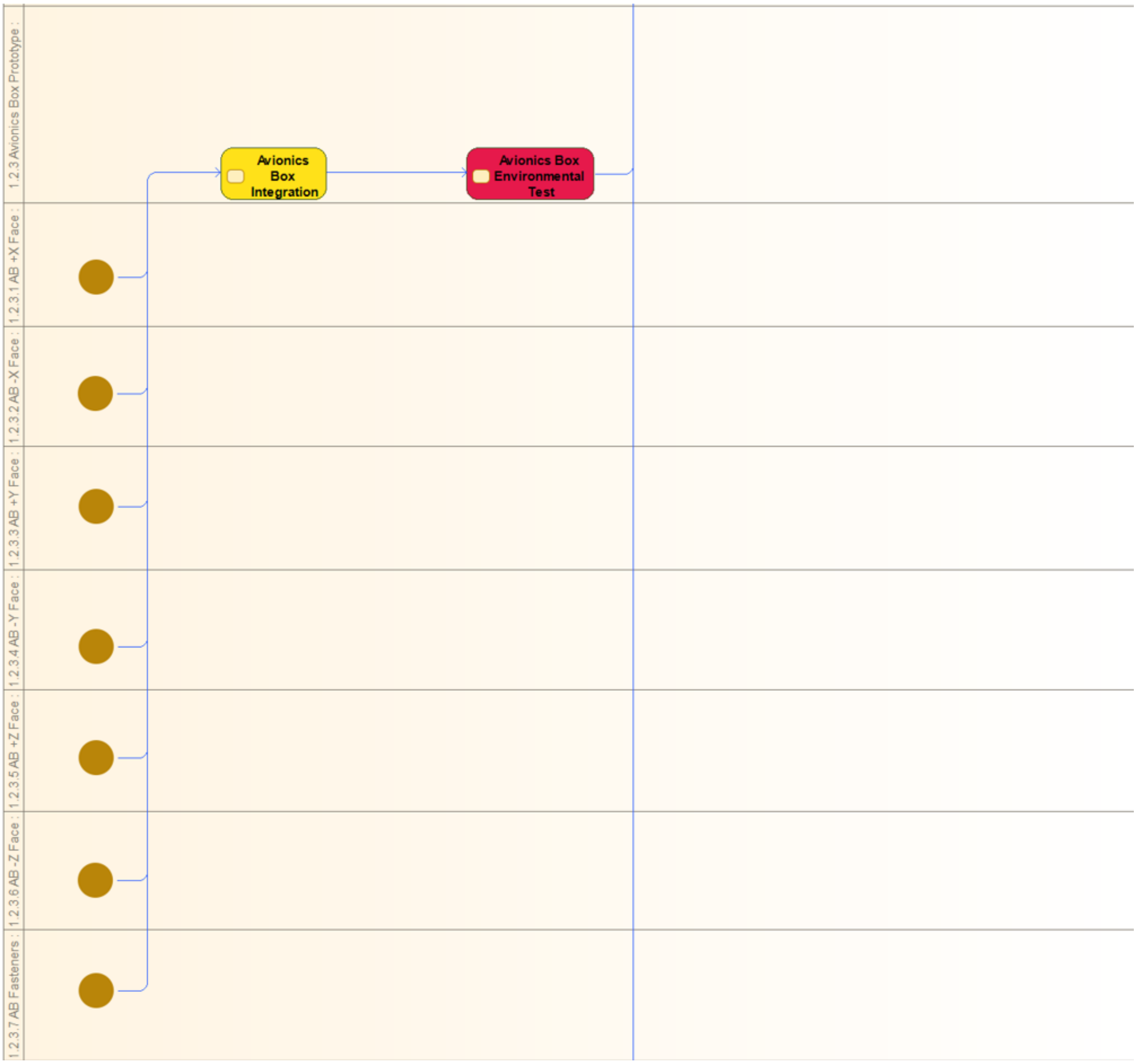


Figure 7: S&M Prototype Hardware Integration Flow (Image 4)

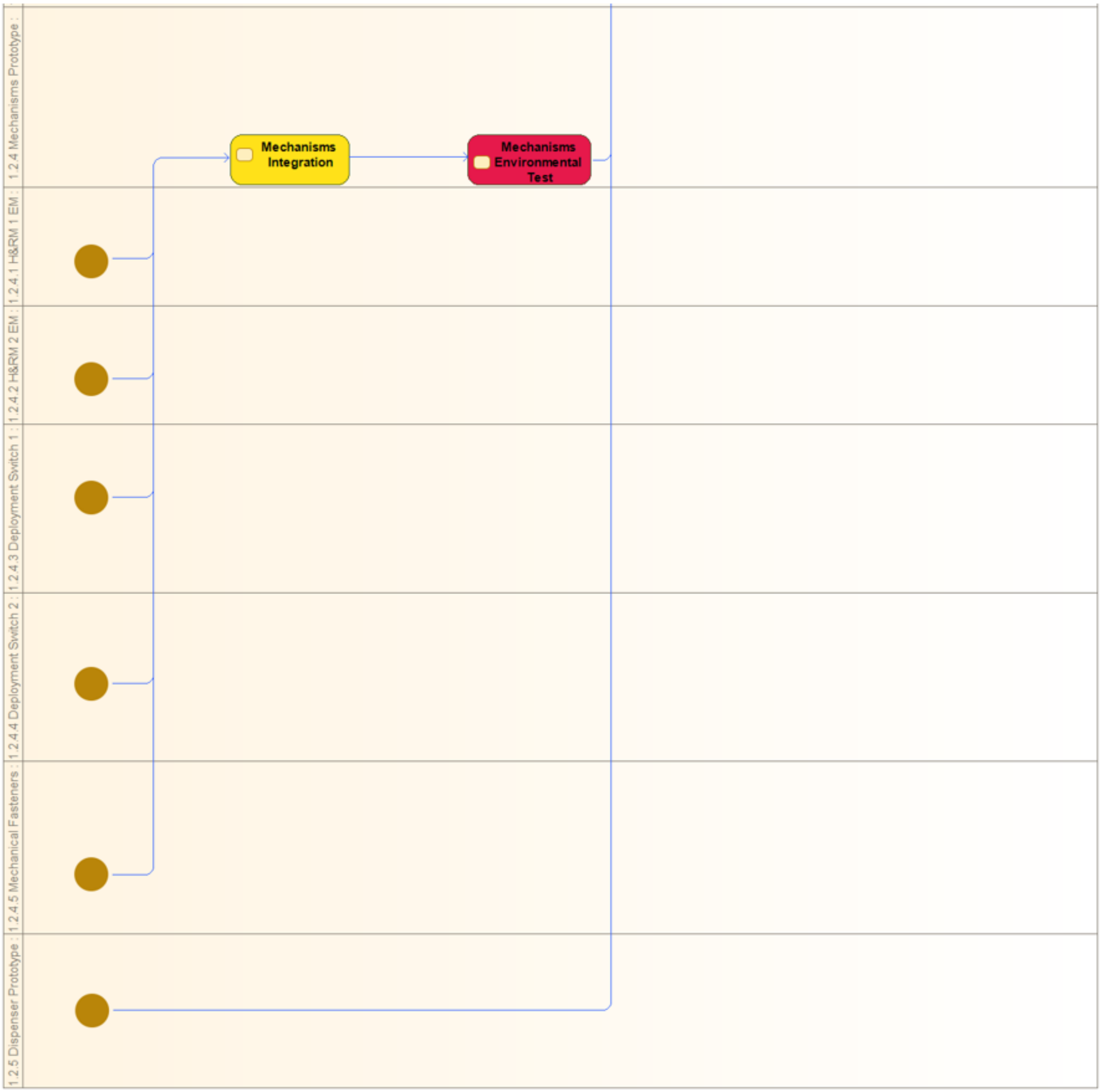
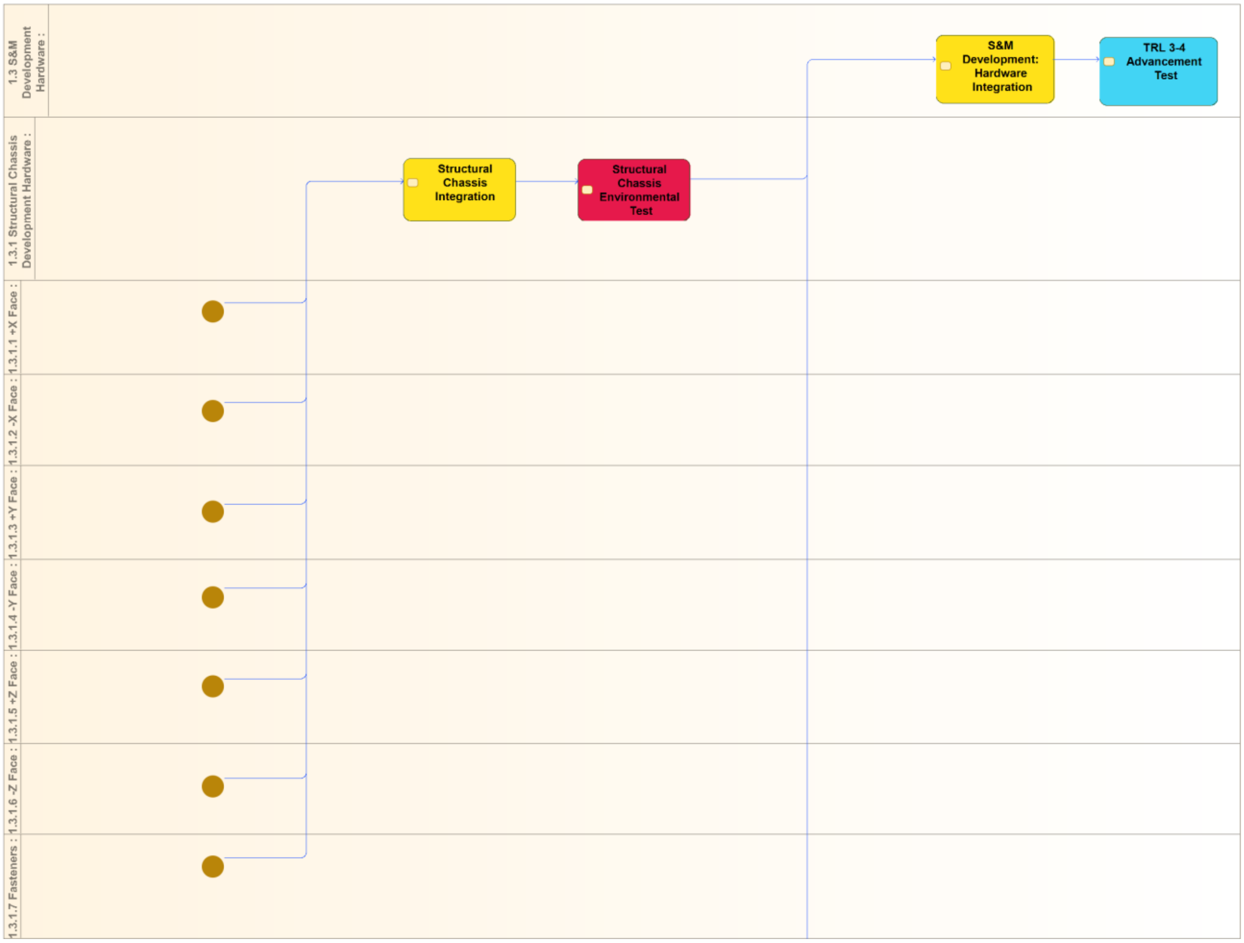


Figure 8: S&M Prototype Hardware Integration Flow (Image 5)



1.3 S&M Development Hardware :
1.3.1 Structural Chassis Development Hardware :
1.3.1.1 +X Face :
1.3.1.2 -X Face :
1.3.1.3 +Y Face :
1.3.1.4 -Y Face :
1.3.1.5 +Z Face :
1.3.1.6 -Z Face :
1.3.1.7 Fasteners :
Structural Chassis Integration
Structural Chassis Environmental Test
S&M Development: Hardware Integration
TRL 3-4 Advancement Test

1.3.2 Payload Harnessing Development Hardware : 1
Payload Harnessing Integration
Payload Harnessing Environmental Test
1.3.2.1 GRD Harness 1 : 1
GRD Harness 1 Environmental Test
1.3.2.2 GRD Harness 2 : 1
GRD Harness 2 Environmental Test
1.3.2.3 GRD Harness 3 : 1
GRD Harness 3 Environmental Test
1.3.2.4 XRD Harness 1 : 1
XRD Harness 1 Environmental Test
1.3.2.5 XRD Harness 2 : 1
XRD Harness 2 Environmental Test
1.3.2.6 XRD Harness 3 : 1
XRD Harness 3 Environmental Test

1.3.3 Avionics Box Development Hardware :
Avionics Box Integration
Avionics Box Environmental Test
1.3.3.1 AB +X Face :
1.3.3.2 AB -X Face :
1.3.3.3 AB +Y Face :
1.3.3.4 AB -Y Face :
1.3.3.5 AB +Z Face :
1.3.3.6 AB -Z Face :
1.3.3.7 AB Fasteners :

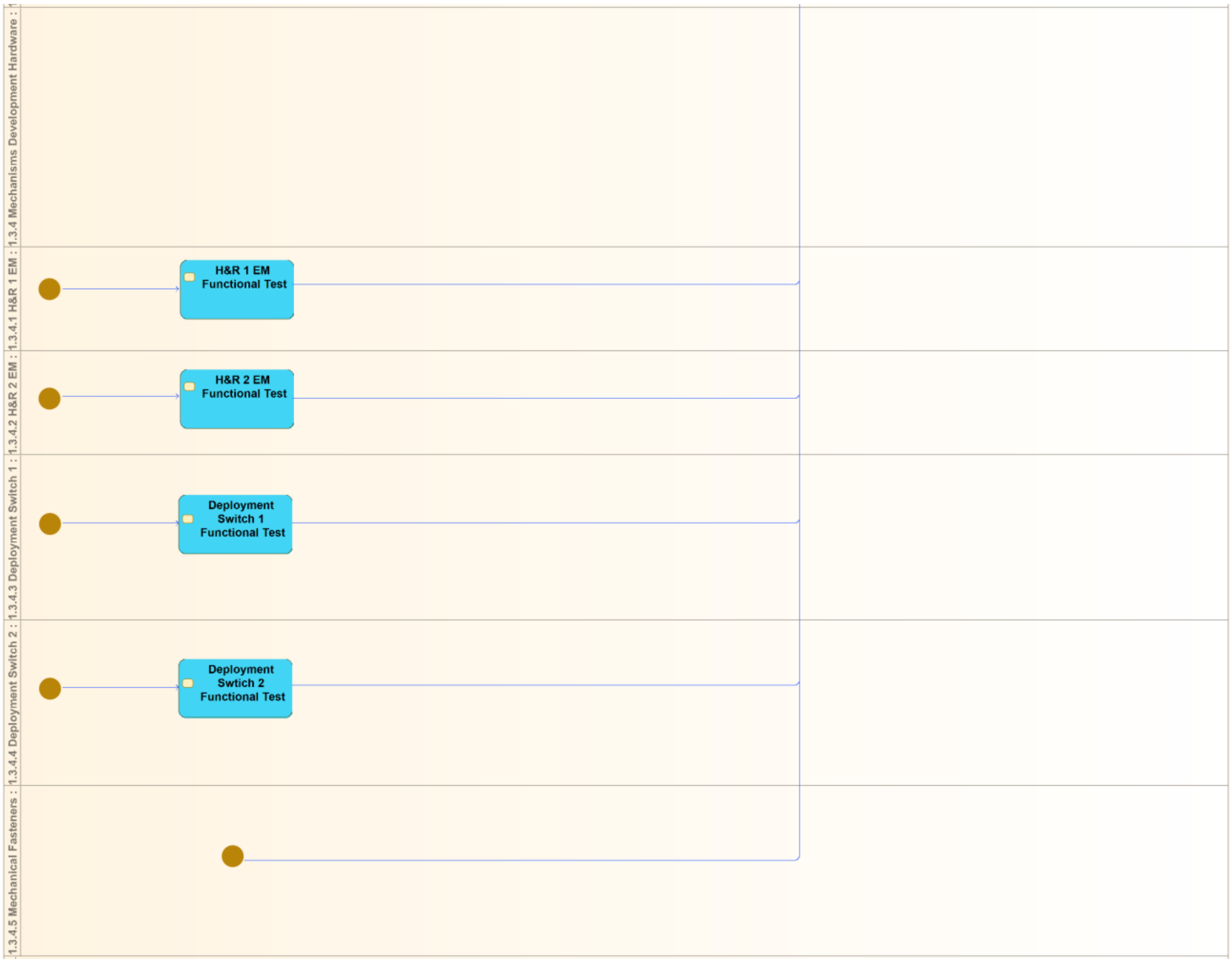


Figure 9: S&M Development Hardware Integration Flow

5.1.1 Integration Points Descriptions

The configuration of the spacecraft parts has a total of 15 integration points where the parts come together. The final integration point 1.0 S&M is the configuration point of all the other configuration points in the spacecraft. These configuration points are 1.1 S&M Flight Hardware, 1.2 S&M Prototype Hardware, and 1.3 S&M Development Hardware. The 1.1 S&M Flight Hardware is the integration point for the 1.1.1 Structural Chassis, 1.1.2 Payload Harnessing, 1.1.3 Avionics Box, and 1.1.4Mechanisms. The 1.2 S&M Prototype Hardware is the integration point for X.2.1 Structural Chassis Prototype, 1.2.2 Payload Harnessing Prototype, 1.2.3 Avionics Box Prototype, and 1.2.4 Mechanisms Prototypes. 1.3 The S&M Development Prototype is the integration point for the 1.3.1 Structural Chassis Development Hardware, 1.3.2 Payload Harnessing Development Hardware, 1.3.3 Avionics Box Development Hardware and 1.3.4 Mechanisms Development Hardware.

The 1.1.1 Structural Chassis is the integration point for 1.1.1.1 +X Frame, 1.1.1.2 -X Frame, 1.1.1.3 +Y Frame, 1.1.1.4 -Y Frame, 1.1.1.5 +Z Frame, 1.1.1.6 -Z Frame, and 1.1.1.7 Chassis Fasteners. The 1.1.2 Payload Harnessing is the integration point for X.1.2.1 GRD Harness 1, X.1.2.2 GRD Harness 2, 1.1.2.3 GRD Harness 3, 1.1.2.4 XRD Harness 1, 1.1.2.5 XRD Harness 2, and 1.1.2.1 XRD Harness 3. The 1.1.3 Avionics Box is the integration point for 1.1.3.1 +X Face, 1.1.3.2 -X Face, 1.1.3.3 +Y Face, 1.1.3.4 -Y Face, 1.1.3.5 +Z Face, 1.1.3.6 -Z Face, and 1.1.3.7 AB Fasteners. The 1.1.4 Mechanisms is the integration point for 1.1.4.1 H&RM 1, 1.1.4.2 H&RM 2, 1.1.4.3 Deployment Switch 1, 1.1.4.4, Deployment Switch 2, and 1.1.4.5 Mechanical Fasteners.

The 1.2.1 Structural Chassis Prototype is the integration point for 1.2.1.1 +X Frame, 1.2.1.2 -X Frame, 1.2.1.3 +Y Frame, 1.2.1.4 -Y Frame, 1.2.1.5 +Z Frame, 1.2.1.6 -Z Frame, and 1.2.1.7 Chassis Fasteners. The 1.2.2 Payload Harnessing Prototype is the integration point for 1.2.2.1 GRD Harness 1, 1.2.2.2 GRD Harness 2, 1.2.2.3 GRD Harness 3, 1.2.2.4 XRD Harness 1, 1.2.2.5 XRD Harness 2, and 1.2.2.1 XRD Harness 3. The 1.2.3 Avionics Box Prototype is the integration point for 1.2.3.1 +X Face, 1.2.3.2 -X Face, 1.2.3.3 +Y Face, 1.2.3.4 -Y Face, 1.2.3.5 +Z Face, 1.2.3.6 -Z Face, and 1.2.3.7 AB Fasteners. The 1.2.4 Mechanisms Prototype is the integration point for 1.2.4.1 H&RM 1, 1.2.4.2 H&RM 2, 1.2.4.3 Deployment Switch 1, 1.2.4.4, Deployment Switch 2, and 1.2.4.5 Mechanical Fasteners.

The 1.3.1 Structural Chassis Development Hardware is the integration point for 1.3.1.1 +X Frame, 1.3.1.2 -X Frame, 1.3.1.3 +Y Frame, 1.3.1.4 -Y Frame, 1.3.1.5 +Z Frame, 1.3.1.6 -Z Frame, and 1.3.1.7 Chassis Fasteners. The 1.3.2 Payload Harnessing Development Hardware is the integration point for 1.3.2.1 GRD Harness 1, 1.3.2.2 GRD Harness 2, 1.3.2.3 GRD Harness 3, 1.3.2.4 XRD Harness 1, 1.3.2.5 XRD Harness 2, and 1.3.2.1 XRD Harness 3. The 1.3.3 Avionics Box Development Hardware is the integration point for 1.3.3.1 +X Face, 1.3.3.2 -X Face, 1.3.3.3 +Y Face, 1.3.3.4 -Y Face, 1.3.3.5 +Z Face, 1.1.3.6 -Z Face, and 1.1.3.7 AB Fasteners. The 1.3.4 Mechanisms Development Hardware is the integration point for 1.3.4.1 H&RM 1, 1.3.4.2 H&RM 2, 1.3.4.3 Deployment Switch 1, 1.3.4.4, Deployment Switch 2, and 1.3.4.5 Mechanical Fasteners.

Another 8 integration points are to represent the tests that will take place on the spacecraft. The Compressive Stress Test, Shock Test, Shaker Sine Vibration Test, Modal Survey Test, TVAC Cycling Test, Shaker Random Vibration Test, Acoustic Test, and the Centrifuge test will take place at different integration points in the spacecraft.

Table 5: Descriptions of integration points from the integration flow diagram.

Integration Point Name	Description
1.1.1 Structural Chassis	Integration point for X, Y, Z frames, and Chassis Fasteners
1.1.2 Payload Harnessing	Integration point for GRD and XRD Harnessing
1.1.3 Avionics Box	Integration point for AB X, Y, Z Faces and AB Fasteners
1.1.4 Mechanisms	Integration point for H&RMs, deployment switches, and mechanical fasteners.
1.2.1 Structural Chassis Prototype	Integration point for prototype X, Y, Z frames, and Chassis Fasteners
1.2.2 Payload Harnessing Prototype	Integration point for prototype GRD and XRD Harnessing
1.2.3 Avionics Box Prototype	Integration point for prototype AB X, Y, Z Faces and AB Fasteners
1.2.4 Mechanisms Prototypes	Integration point for prototype H&RMs, deployment switches, and mechanical fasteners.
1.3.1 Structural Chassis Development Hardware	Integration point for development hardware X, Y, Z frames, and Chassis Fasteners
1.3.2 Payload Harnessing Development Hardware	Integration point development hardware for GRD and XRD Harnessing
1.3.3 Avionics Box Development Hardware	Integration point for development hardware AB X, Y, Z Faces and AB Fasteners

1.3.4 Mechanisms Development Hardware	Integration point for development hardware H&RMs, deployment switches, and mechanical fasteners.
1.1 S&M Flight Hardware	Integration point for Structural Chassis, Payload Harnessing, Avionics Box, and Mechanisms
1.2 S&M Prototype Hardware	Integration point for Structural Chassis Prototype, Payload Harnessing Prototype, Avionics Box Prototype, and Mechanisms Prototype
1.3 S&M Development Hardware	Integration point for Structural Chassis Development Hardware, Payload Harnessing Development Hardware, Avionics Box Development Hardware, and Development Hardware Prototype
1.0 S&M	Integration point for S&M Flight Hardware, S&M Prototype Hardware, S&M Development Hardware
Compressive Stress Test	Integration point for the compressive shock test
Shock Test	Integration point for the shock test
Shaker Sine Vibration Test	Integration point for the shaker sine vibration test
Modal Survey Test	Integration point for the modal survey test
TVAC Cycling Test	Integration point for the TVAC cycling test
Shaker Random Vibration Test	Integration point for the random vibration test
Acoustic Test	Integration point for the acoustic test
Centrifuge Test	Integration point for the centrifuge test

5.1.2 Test Event Descriptions

The Test Events are listed in the table below. The subsystems must undergo a variety of tests to provide proof of survivability. The Compressive Stress Test validates that the structure bus will survive sufficient stress conditions. The component is loaded into a universal testing machine and undergoes increasing compressive forces. The upper limit of the force is determined by static analysis. The test is run 3 separate times at different orientations. The Shock Test measures the mechanical and electrical response to an electrical shock. The components will be put into mechanical or electrical modes depending on which phase of the mission when the shock occurs. The components response to the shock is measured and the components are tested until failure. The Shaker sine and random Vibration Tests subject the components to waves (including sine waves) at various frequencies using a vibration testing machine. For the Shaker Sine Test, a sine sweep will be used to expose the components to a single tone with a varying frequency across a specified range. The resonant frequencies can be determined. The components will be tested until failure. For the Shaker Random Vibration test, the components will get loaded onto the vibration testing machine and will be subjected to random multiple frequencies at the same time. The component passes the test if the component survives, and the component will be tested to failure. The Modal Survey Test measures the payload response to excitations at anticipated loads. The excitation of the components is performed by an electro-dynamic shaker that is loaded to anticipated environmental conditions to predict the payload responses. Accelerometers will read the excitation leading to the development of the dynamic structural characteristics of the components. The components pass if FEM predictions are verified. The TVAC Cycling Test subjects the components to environmental conditions anticipated in the mission. The components will be placed into a thermal vacuum chamber and subjected to the anticipated temperature. The anticipated temperatures will be found from previous analysis. The component passes the test if the component survives. The Acoustic Test exposes the payload to various vibrations via sound. For the Acoustic Test, the payload will be placed in a test chamber isolated from all energy inputs on a soft suspension system. The minimum test should take place at 138 dB. The payload will be examined after the test. If the payload survives, it passes the test. The Centrifuge Test subjects the assembly to centrifugal forces to anticipated loading conditions. The assembly will be placed in a centrifuge and the centrifugal force will pull on any attached devices. The assembly will be tested at anticipated loading conditions. If the assembly survives the test, then it passes the test. **Invalid source specified.**

Table 6: Descriptions of test events from the integration flow diagram.

Test Event Name	Type	Description
Compressive Stress Test	Functional Environmental	Component will be loaded under increasing compressive forces with the upper limit being determined to simulate anticipated loading conditions.
Shock Test	Environmental	Assembly will be shocked while electrically and mechanically operating.
Shaker sine Vibration Test	Integration	The assembly will be exposed to a sine tone that is varied across a specified range of frequencies on a vibration testing machine.
Modal Survey Test	Environmental	Component is excited by electro-dynamic shaker. Accelerometers read the payload responses being tested to anticipated loading conditions.
TVAC Cycling Test	Environmental	Component will be placed into thermal vacuum chamber and subjected to anticipated environmental temperature.
Shaker Random Vibration Test	Functional	The component will be subjected to random frequencies on a vibration testing machine.
Acoustic Test	Functional	The payload will be subjected to various vibrations due to a change in frequency in the sound.
Centrifuge Test	Integration	Assembly is placed into spinning test chamber (centrifuge). Centrifugal forces will pull on the assembly being test too anticipated loading conditions.
Deployment Test	Functional	Assembly’s H&RMs and Deployment switches are tested to ensure its capability

6 Technology Readiness Levels

6.1 Purpose

Technology readiness is used to determine how ready a technology is to operate as a part of a system, based on its demonstrated functional ability within the target environment and how ready it is to be integrated within the flight system. Levels are defined within this to act as milestones during technology development, integration, and testing.

6.2 Level Classifications

NASA defines 9 levels of technology readiness. These are described in Table 7 including the descriptions for what this means for the hardware and software elements of a technology with exit criteria expectation.

Table 7: TRL definitions adapted from NASA NPR 7123.1C.

Lvl	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.

Lvl	Definition	Hardware Description	Software Description	Exit Criteria
6	System/sub-system model or prototype demonstration in an operational environment.	A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high-fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment	Documented mission operational results.

6.3 Raising TRL

In general, you can conceptualize the process of raising a TRL (from a subsystem perspective) in the following manner:

1. Define the requirements for a subsystem. For ABEX, these are provided by Management.
2. Define an architecture (what) that characterizes the functions described in the requirements.
3. Determine the TPMs that a design can provide to meet the specification requirements.
4. Define a design (how) that specifically details what components or subsystems are providing the functionality described in the requirements. Characterize the entire design space to meet the problem space before selecting the design.

5. Break the subsystem design into constituent components, organized into a PBS. For ABEX we include both the development hardware elements and flight hardware.
6. Establish the current TRL level of the subsystem based on the concept design.
7. Determine the entry and exit criteria for each TRL level from its current point to TRL 6. Determine the test categories required to verify compliance of the subsystem design to its requirements as they relate to each TRL level. Define the development hardware we need and include that into the PBS.
8. Determine the configuration items that could exist and associated integration chains for each TRL advancement. This might include several TRL steps at once.
9. Once the subsystem has demonstrated TRL 6 from tests done independently to it, the flight unit is ready to be built and tested to the operational environment with the whole spacecraft together to achieve TRL 8.
10. After flight the subsystem is at TRL 9.

7 Product Breakdown Structure

7.1 Purpose

The Product Breakdown Structure (PBS) is designed to organize the system elements into a hierarchy to organize work, planning, documentation, and requirements around the physical things that a project needs to make. The PBS for ABEX will capture both the flight elements and the development products needed to mature the systems technology. The PBS will also establish a common terminology for the system for the team and for the project's system engineering effort. Flight units are the things which we need for the final mission. Development products are the things that we need to raise the subsystem TRL, but that will not end up in the final mission.

7.2 Guidance

When creating the PBS, the following points should be kept in-mind:

- Products are organized around a tree structure that represents how products fit within (or integrate) into each other in the final implementation.
- The leveling approach should go as far as needed to capture the major elements of the project but does not need to recreate a full parts list (such as each capacitor and resistor).
- PBS is used to organize the project, so the hierarchy should also group elements together based on how we interact with the system, such as showing categories with sub elements for connectors and cables for interfacing.
- Development is to be included in the ABEX PBS and should be organized around major technology advancement hardware units/setups.
- Each PBS should use an ID system, this numbering can be relative to the system (with the ability to map/integrate into the projects PBS).

An example of this is shown below in Table 8 for a fictional system.

Table 8: Example product breakdown structure.

PBS ID	Product Name	Product Description
1	System Name	System example name
1.1	Flight Products	Flight system elements
1.1.1	Power Conversion Board	Power conversion system
1.1.2	Data Acquisition Unit	Data logging and conversion unit
1.2	Development Products	All the technology development hardware
1.2.1	Tech Demo	Demonstration hardware setup for TRL 4/5.
1.2.1.1	Power System Test Unit	This is a flight-like power system unit with test interfaces
1.2.1.2	Data Acquisition Breadboard	Scale data acquisition breadboard with main processing FPGA.
1.2.2	Concept Demo	FPGA development demo with data interfaces for TRL 3.

References

[1] "NASA Systems Engineering Handbook," p. 297, 2016.

[2] E. Author, "IEEE Paper Example," *IEEE,* vol. 1, no. 1, p. 1, 2020.

[3] W. J. Larson, D. Kirkpatrick, J. J. Sellers, L. D. Thomas and D. Verma, Applied Space Systems Engineering, McGraw Hill, 2018.

Appendix A Acronyms, Terminology, & Nomenclature

A.1 Acronyms

Acronym	Definition
ABEX	Alabama Burst Energetics Explorer
APRA	Astrophysics Research & Analysis
ASGC	Alabama Space Grant Consortium
CAD	Computer-Aided Design
C&DH	Command & Data Handling
CDR	Critical Design Review
CE	Chief Engineer
CLB	Configurable Logic Block
COTS	Commercial Off The Shelf
CS	Chief Scientist
CSLI	CubeSat Launch Initiative
DAC	Design Analysis Cycle
EAR	Export Administration Regulations
EPMs	Educational Performance Measures
EPS	Electrical Power System
FPGA	Field Programmable Gate Array
FSW	Flight Software
GN&C	Guidance, Navigation, & Control
GPS	Global Positioning System
GRB	Gamma-ray Burst
GRD	Gamma-ray Detector
HV	High Voltage
ICP	Instrument Calibration Plan
IMS	Integrated Master Schedule
IMU	Inertial Measurement Unit
ISM	Integrated Systems Model
ITAR	International Traffic in Arms Regulations
IV&T	Integration, Verification, & Test
KDP	Key Decision Point
KPPs	Key Performance Parameters
LSE	Lead System Engineer
MBSE	Models Based System Engineering
MCR	Mission Concept Review
NDA	Non-Disclosure Agreement
NIST	National Institute of Standards and Technology
PC	Program Coordinator
PDR	Preliminary Design Review

Acronym	Definition
PIU	Payload Interface Unit
PM	Project Manager
POP	Period of Performance
QP	Qualification Plan
QR	Qualification Report
QPSK	Quadrature Phase Shift Keying
SE	Systems Engineering
SEMP	System Engineering Management Plan
SIS	Software Interface Specification
SME	Subject Matter Expert
SMP	Software Management Plan
SQP	Structural Qualification Plan
SQR	Structural Qualification Report
SRD	System Requirements Document
SRR	System Requirements Review
STDP	Subsystem Technology Development Plan
STP	Subsystem Testing Plan
TCP	Technology Control Plan
TID	Total Ionizing Dose
TPM	Technical Performance Measure
TQP	Thermal Qualification Plan
TQR	Thermal Qualification Report
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, & Command
V&V	Verification and Validation
WBS	Work Breakdown Structure
XRD	X-ray Detector

A.2 Terminology

Term	Description
Acceptance	A type of verification procedure specifically for testing and analysis. Acceptance test/analysis criteria show that the manufacturing/workmanship of the unit conforms to the design that was previously verified/qualified. Acceptance activities are performed on each of the flight units as they are manufactured and readied for flight/use (NASA Systems Engineering Handbook, 2016)
Analysis	Verification by analysis is a predicted compliance to requirements. The use of mathematical modeling and analytical techniques to predict the suitability of a design to stakeholder expectations based on calculated data or data derived from lower system structure end product verifications. Analysis is generally used when a prototype; engineering model; or fabricated, assembled, and integrated product is not available. Analysis includes the use of modeling and simulation as analytical tools (NASA Systems Engineering Handbook, 2016).

Term	Description
Assembly	The mechanical mating of components to form a system.
Certification	The audit process by which the body of evidence that results from the verification activities and other activities are provided to the appropriate certifying authority to indicate the design is certified for flight/use. The Certification activity is performed once regardless of how many flight units may be generated (NASA Systems Engineering Handbook, 2016).
Configuration Item	The combination of two components, subsystems, or systems of lesser complexity resulting in a combined assembly, subsystem, or system with greater complexity. Configuration Items exist at Integration Points; a sequence of Configuration Items along several Integration Points comprises an Integration Chain.
Demonstration	Verification by demonstration is an observed compliance to requirements accomplished by showing that the use of an end product achieves the individual specified requirement. It is generally a basic confirmation of performance capability, differentiated from testing by the lack of detailed data gathering. Demonstrations can involve the use of physical models or mock-ups (NASA Systems Engineering Handbook, 2016).
Inspection	Verification by inspection is a documented compliance to requirements. The visual examination of a realized end product. Inspection is generally used to verify physical design features or specific manufacturer identification (NASA Systems Engineering Handbook, 2016).
Integration	The process of combining less complex functions, understanding those functions, and controlling those functions to achieve a system satisfying its requirements.
Integration Chain	A series of Integration Points. Integration Chains can be represented as tree or fishbone diagrams where many components, subsystems, or systems of lesser complexity are combined as Configuration Items at Integration Points to create a system of higher complexity. Integration Chains are generally defined to realize a Technical Performance Measure.
Integration Point	The location on a schedule where two or more components, subsystems, or systems of lesser complexity are combined as a Configuration Item with greater complexity. A series of Integration Points comprises an Integration Chain.
Interface	An interface represents a constraint based on the logical and physical boundary conditions between two or more entities within a level of abstraction, between System of Interest elements, between other mission systems, between enabling systems, or between the System of Interest and its Operational Environment. Interfaces can be for physical connection, energy transfer (power or heat), matter, or data (Wasson, 2016).
Key Performance Parameter	Those capabilities or characteristics (typically engineering-based or related to health and safety or operational performance) considered most essential for successful mission accomplishment. They characterize the major drivers of operational performance, supportability, and interoperability (NASA Systems Engineering Handbook, 2016).
Mode	An abstract configuration, condition, or process that occurs with or without a corresponding physical state in a component, subsystem, or system at a given time. A non-tangible, non-physical concept.
Model	A mathematical representation of reality (NASA Systems Engineering Handbook, 2016).
Operational Environment	The surrounding systems, materials, or occurrences defining a system's ability to externally interact. The Operational Environment is comprised of a Human

Term	Description
	Systems Environment, a Natural Environment, and an Induced Environment (Wasson, 2016).
Primary TPM	A regular Technical Performance Measure, either a Key Performance Parameter, Technical Performance Parameter, or Technical Environmental Parameter; this distinction exists only as an organizational hierarchy.
Qualification	A subset of the verification program that is performed at the extremes of the environmental envelope and will ensure the design will operate properly with the expected margins. Qualification is performed once regardless of how many flight units may be generated as long as the design doesn't change.
Secondary TPM	A subdivision of a Primary TPM for the purpose of representing portions of Primary TPM concepts within a Domain Knowledge Map. Secondary TPMs are not tracked or reported and do not required a target threshold. Secondary TPMs exist only as an organizational hierarchy for conceptual organization. Secondary TPMs can break down further into more Secondary TPMs.
Simulation	The manipulation of a model (NASA Systems Engineering Handbook, 2016).
State	A physical mechanical configuration, environmental condition, operational condition, or other physical condition that either happens to or is initiated by a component, subsystem, or system at a given time.
Technical Performance Measure	A set of performance measures that are monitored by comparing the current actual achievement of the parameters with that anticipated at the current time and on future dates (NASA Systems Engineering Handbook, 2016)
Technical Performance Parameter	Those capabilities or characteristics (typically engineering-based or related to health and safety or operational performance) considered relevant to operational performance, supportability, and interoperability at any level.
Technical Environmental Parameter	Those capabilities or characteristics relevant to the definition of system interactions with the Operational Environment.
Test	Verification by test is a measured compliance to requirements. : The use of an end product to obtain detailed data needed to verify performance or provide sufficient information to verify performance through further analysis. Testing can be conducted on final end products, breadboards, brassboards, or prototypes. Testing produces data at discrete points for each specified requirement under controlled conditions and is the most resource-intensive verification technique. As the saying goes, "Test as you fly, and fly as you test" (NASA Systems Engineering Handbook, 2016).
Validation	Validation of a product shows that the product accomplishes the intended purpose in the intended environment—that it meets the expectations of the customer and other stakeholders as shown through performance of a test, analysis, inspection, or demonstration (NASA Systems Engineering Handbook, 2016).
Verification	Verification is a formal process, using the method of test, analysis, inspection or demonstration, to confirm that a system and its associated hardware and software components satisfy all specified requirements. The Verification program is performed once regardless of how many flight units may be generated as long as the design doesn't change (NASA Systems Engineering Handbook, 2016).

A.3 Nomenclature

Symbol	Description	Unit
τ_{spring}	Torque provided by the torsion springs in the hinge	Nm
n_{ts}	Number of torsion springs in the solar array hinges	–
k_{ts}	Torque constant of the torsion springs in the solar array hinges	Nm / deg
$\emptyset_{ots}$	No-load angle of the torsion springs in the solar array hinges	deg
θ_{sp}	Deployment angle of the solar panel	deg
$\mu_{s,b}$	Static friction coefficient of bushing	–
$\tau_{f,s}$	Hinge static friction torque	Nm
τ_{s}	Total torque of torsion spring	Nm
$\mu_{d,b}$	Dynamic friction coefficient of bushing	–
r_{s}	Radius of hinge shaft	m
m_{sp}	Mass of the solar panel	kg
r_{CM}	Distance from axis of rotation of hinge to center of mass of solar panel	m
$\tau_{f,d}$	Dynamic friction coefficient of bushing	Nm
L_{IC}	Individual Component Location	–
m_{IC}	Individual Component Mass	kg
θ_{back}	Backstop Angle of the Solar Panel	deg
r_{rot}	Distance from axis of rotation of hinge to center of contact region	m
n_{cr}	Number of hinge contact regions	–
N_{Total}	Metallic Structure Fatigue Life	–
N_{Dyn}	Number of dynamic stress cycles	–
N_{Therm}	Number of thermal stress cycles	–
$N_{\mathrm{Pr}\,eL}$	Number of pre-launch stress cycles	–
$N_{Therm\,d}$	Number of thermal cycles per day	–
t_{flight}	Time of flight	sec
$x_{S,MS}$	Seed Size	m
$r_{f,MS}$	Frequency Range	Hz

SPL_{MS}	Sound Pressure Level Spectrum	dB
r_{dB}	Decibel Range	dB
ρ_{MS}	Density of the Metallic Structure	kg/m^3
K_{MS}	Bulk Modulus of the Metallic Structure	Pa
ν_{MS}	Poisson’s Ratio of the Metallic Structure	–
E_{MS}	Elastic Modulus of the Metallic Structure	Pa
$\sigma_{A,MS_{FEA}}$	Launch Vehicle Acoustic Stress (FEA)	Pa
$\sigma_{A,MS_{Manual}}$	Launch Vehicle Acoustic Stress (Manual)	Pa
ζ_{MS}	Damping Coefficient of the Metallic Structure	–
$n_{\lambda,MS}$	Number of Eigenvalues	–
$S_{X,MS}$	Power Spectral Density Curve Data	G^2/Hz
$\sigma_{RV,MS_{FEA}}$	Launch Vehicle Random Vibrational Stress (FEA)	Pa
$\sigma_{RV,MS_{Manual}}$	Launch Vehicle Random Vibrational Stress (Manual)	Pa
λ_{sa}	Dimensionless Frequency Parameter	N/A
γ_{sa}	Solar Array Areal Density	$\frac{kg}{m^2}$
e_{sa}	Solar Array Linear Stiffness	$GPA \cdot m^3$
μ_{sa}	Solar Array Material Density	$\frac{kg}{m^2}$
E_{sa}	Solar Array Modulus of Elasticity	GPA
d_{sa}	Distance from neutral axis to seam of layer	m
k_{sa}	Solar Array Material Layer	N/A
m_{Sc}	Mass of Spacecraft	m
P_{ref}	Reference Pressure	Pa
f_{cent}	Frequency Center	Hz

L_{AP}	Acoustic Pressure Level	
F_{RV}	Random Vibrational Force	N
Acs	Component Cross Sectional Areas	m^2
a_{RMS}	RMS Acceleration	m/s^2

Appendix B Structures and Mechanisms Specific Information