Best Practices and Considerations for Planning and Conducting Integration of University CubeSats

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This paper seeks to serve as a resource for students entering the integration phase of a CubeSat project by compiling best practices and practical considerations from several projects in the Space Systems Design Lab at the Georgia Institute of Technology. The integration phase can be a particular challenge for university CubeSat programs given the value of practical experience in performing these activities and the challenge of managing a student workforce with constant turnover. The topics covered include best practices for planning the integration phase of a project, considerations when performing integration activities, and the characteristics of good assembly procedures. Although the focus is on spacecraft-level integration of CubeSats in a university setting, many of the considerations are applicable outside the academic setting and to subsystem-level integration activities as well. Finally, a case study will be presented illustrating the planning of integration activities for the VISORS mission, a two 6U CubeSat formation-flying mission.

I. Introduction

At the center of the space industry's transformation in pursuit of the classic "Faster, Better, Cheaper" motto is the concept of a CubeSat. Originating from a university-led effort called "the CubeSat Project", these nano-satellites are packaged in convenient, 10 cm cube "units" or "U" with common sizes ranging from 1U up to 12U [1]. The goal of this standard packaging was to democratize access to space by providing frequent and accessible launch opportunities via ride-share on launch vehicles with extra payload capacity. The potential for shorter development timelines and far lower costs in comparison to traditional space missions caused the popularity of the CubeSat to grow beyond its original educational roots into government and commercial sectors. One product of this widespread adoption of the CubeSat form factor is a wealth of published research and compatible components available both for purchase as commercial off-the-shelf (COTS) options and also in the form of open-source hardware designs [2,3].

These COTS and open-source components are incredibly valuable as they allow burgeoning CubeSat programs to use proven designs to get started integrating and operating space missions. University CubeSats now range from collections of flight-proven commercial components to entirely student designed and built systems with custom avionics and payloads. This "build versus buy" flexibility makes CubeSats an increasingly powerful tool for educating students in fundamental principles of spacecraft development and operation. But whether components are sourced from commercial vendors or designed and built in-house, there remains the challenge of integrating many, often disparate, parts together into a functioning spacecraft. Thus, the integration phase of development is a critical hurdle faced by university CubeSat programs of all levels from their first 1U LEO CubeSat to 6U deep-space and advanced technology demonstration missions.

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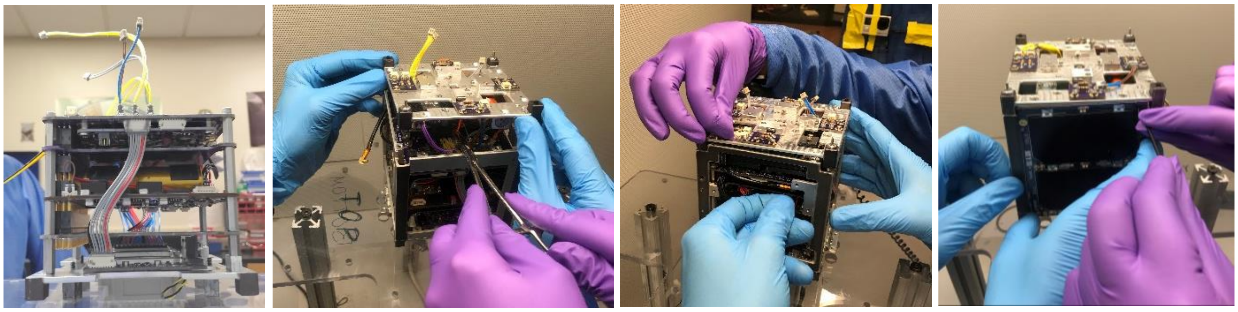


Fig. 1 GT-1 CubeSat undergoing final integration.

As in most activities, hands-on experience in performing integration is an invaluable asset. There is little substitute for experienced students who can provide instruction, guidance, and advice to student teams integrating CubeSats. While university CubeSat programs are designed precisely to create this type of experience, it is also an unavoidable feature that these students will graduate and need to be replaced. This high rate of turnover poses a significant challenge to conducting increasingly complex missions in university programs as even though mission development timelines can be relatively short, they will still usually exceed the tenures of individual students, and as with all space mission, delays are often inevitable. It is therefore important to create resources that preserve the institutional knowledge gathered through integration experiences and enable this knowledge to be transferred to future generations of spacecraft engineers in these programs.

This paper aims to serve as a resource to students entering the integration phase of a CubeSat project by compiling best practices and practical considerations from several projects in the Space Systems Design Lab at the Georgia Institute of Technology. The focus is on system-level integration of university CubeSats, but many of the items are applicable to subsystem or component integration and to other types of programs outside of academia. First, best practices for both planning and performing integration are presented. Then, a case study is shown in which these experiences are applied to create an optimized integration plan for a science mission using two 6U CubeSats.

A. Background on CubeSat Integration

Before proceeding, it is useful to define precisely what is meant by the "integration" phase of a spacecraft development project. For the purposes of this paper, "integration" refers to the activities conducted after all spacecraft subsystems and components have been procured and before system-level environmental and performance testing. In the typical NASA mission lifecycle, these integration activities begin in the later stages of Phase C and continue into Phase D, spanning the period shaded in green in Fig. 2 below.

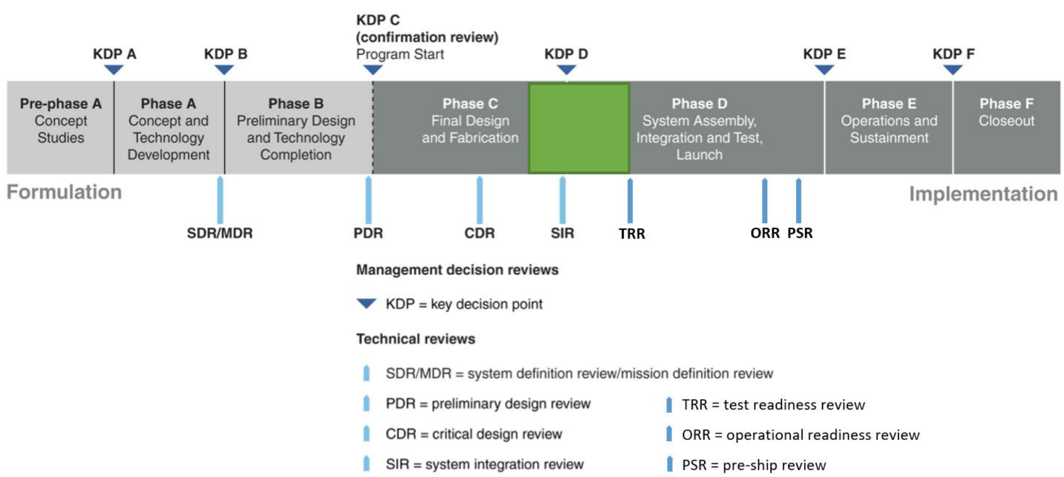


Fig. 2 NASA Program Lifecycle – integration occurs in early Phase D after all spacecraft subsystems and components have been designed and fabricated in Phase C [4].

Although there are many significant integration-related design considerations such as design-for-assembly (DFA), these concepts are out of the scope of this paper and a focus will be placed on effectively and efficiently integrating subsystems and components once they have already been designed and fabricated. Fortunately, it is reasonable to assume that the spacecraft design is complete by the time integration begins. Unfortunately, the integration process occasionally identifies the need for design changes or modifications as the result of non-conformances which arise. A process for troubleshooting and resolving such issues is discussed in the paper by Kolhof, et al. along with some design considerations to improve integration [5].

Similarly, most of the major testing activities such as environmental testing are also outside the scope of this paper. However, it is desirable and often necessary to incorporate some level of testing into the integration flow since integrating complex systems can introduce unexpected behavior and identifying any such issues as quickly as possible greatly aids the troubleshooting process and prevents mishaps. The testing which is conducted during integration is usually rather simple and intended to verify interface requirements or to confirm basic levels of functionality. These tests will be discussed in greater detail in subsequent sections.

II. Best Practices for CubeSat Integration

There are many "right" ways to integrate a CubeSat. Armed with a comprehensive understanding of the spacecraft system (easier said than done) and a basic training in practices such as electrostatic discharge (ESD) protection, cleanroom protocol, and requisite processes such as torquing fasteners, most competent student teams can successfully plan and execute the integration of a CubeSat. However, there are also numerous pitfalls which can complicate, lengthen, and potentially endanger the integration process. The best practices presented in this section are an attempt to capture knowledge gained through experiences, both successes and failures, that can help students and teams unfamiliar with integration navigate the process more efficiently and avoid common traps. This is not a comprehensive "how-to" on CubeSat integration nor is it intended to serve as a proxy for important hardware handling trainings.

First, the topic of activity sequencing to plan out the high-level phases of the integration process is discussed. Next, best practices are presented for acceptance testing, planning the final integration assembly process, and performing the various fit checks. Finally, the topic of documentation is discussed before concluding with practical considerations to keep in mind when performing integration.

A. Activity Sequencing

Before handling any hardware, it is crucial to develop a thorough integration plan. This ensures that every activity which needs to occur is captured and the activities are laid out in a logical and efficient sequence. Importantly, this also assists in management of the integration process from estimating time required to accommodating late delivery of components and staffing risk. Lastly, detailed planning ensures that every activity involving flight hardware has a dedicated procedure which prevents mistakes and oversight during integration [5].

Crucially, integrating a CubeSat involves more than just the final assembly process of the flight hardware. Before final integration, fit checks (potentially multiple) are required to verify that all the parts fit together correctly and the procedures for integrating them work well. These fit checks could involve mounting a single component to the structure to verify its as-built mechanical interface, or an entire "dry run" of the integration performing all the required activities without using any grease, thread-locker, or epoxy to allow for easy disassembly. At a minimum, the integration process of a CubeSat should include:

1. Subsystem/Component Acceptance Testing
2. Mechanical Interface Fit Checks
3. Harness Routing Fit Checks
4. Deployer Fit Check
5. Final Integration

Note that there are additional checks, such as safe-to-mate checks and intermittent functional testing, which occur within the assembly process to prevent electrical damage to hardware and confirm that subsystem functionalities are not impaired after integration with the spacecraft. In general, the way in which each of the fit checks are performed will vary depending on the system architecture. Table 1 shows the overarching rationale and test goals for each activity.

Table 1. Integration Activity Rationale and Goals

Category	Rationale	Test Goals
Acceptance Test	Hardware defects must be identified as early as possible to allow time for rework	Verify critical functionalities and confirm there are no hardware defects caused by damage during travel or overlooked by vendor checkout testing
Mechanical Fit	Mechanical interfaces between systems and components must be as designed to allow assembly	Verify that all mounting interfaces fit together properly, subsystems do not interfere, and mechanisms can move freely
Deployer Fit	The integrated CubeSat must conform to the interface with the deployer	Verify that the fully integrated CubeSat can be inserted into the deployer and slide freely
Harness Fit	Harness routing is complicated and difficult to accurately model in CAD	Determine appropriate harness lengths and verify that planned routing locations are feasible

In addition to the flight hardware, there may be qualification or flight spare units to be assembled. Including the integration of these non-flight hardware systems in the integration plan can provide valuable experience for the team. For example, the high-level flow of integration activities for a university CubeSat may look something like Fig. 3 below.

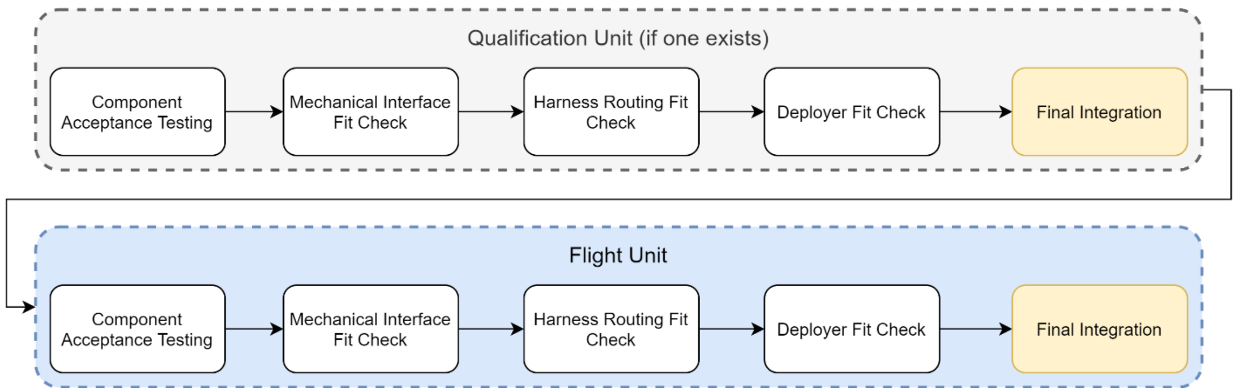


Fig. 3 Example high-level integration process flow diagram.

Note that the various fit checks do not necessarily need to be performed in a linear sequence and the order can be modified as needed for the project. The following sections provide details on best practices for performing the activities in each of these phases of integration.

B. Acceptance Testing

All components and subsystems should undergo acceptance testing prior to integration. This is especially important for components which are purchased from an external vendor or fabricated by a project team at another institution to screen for:

- Damage occurring during shipping or storage
- Oversights in vendor checkouts

Even for hardware manufactured in-house, acceptance testing is required to verify that the components have been produced to specification and operate as expected. Acceptance testing should be performed as soon as the hardware is received and again just prior to integration. This testing is vital to ensure that defective hardware is not integrated into the spacecraft and to identify defects early giving more time to rework or replace components.

Acceptance testing should at least include a comprehensive visual inspection, documented with photographs, as well as a basic checkout of the system functionalities such as the ability to power on and output nominal telemetry. Even harnesses and cables can, and should, be acceptance tested by checking continuity between the pins on each end to confirm connections are not crossed or broken. Critical functionalities of each system should also be tested to the degree which is reasonably possible. The rigor of acceptance testing will depend on the level of trust in the supplier and the amount and type of documentation delivered with the hardware, often called the end item data package (EIDP). If the vendor is an established source for the components and detailed documentation provides evidence that requirements have been properly verified, it is not generally necessary to re-test every aspect of the item's performance. Any mission-specific tests or inspections which were not included in the scope of vendor testing should be executed during acceptance testing.

If not already present, hardware should be assigned serial numbers prior to acceptance testing which are ideally permanently engraved or inscribed on each unit. These serial numbers can then be referenced in test reports and assembly procedures to track which articles have undergone which tests and are assembled into which final products. If multiple units are being integrated, such as flight spare or qualification hardware, it may be beneficial to use acceptance test results to assign serial numbers with minor, acceptable defects to non-flight assemblies [6].

Software Testing and System Testbeds

Although not the main focus of this paper, flight software is an important part of the spacecraft system and therefore of integrating a functional CubeSat. Similar to acceptance testing of hardware, software should be screened prior to uploading new programs to the spacecraft to ensure that bugs in code do not damage flight hardware. For this purpose, it is common to use a "FlatSat" or engineering development unit (EDU) of the spacecraft system like that shown in Fig. 4 below. Ideally, this testbed is a full hardware-in-the-loop simulation of the spacecraft with flight-like subsystems, sensors, and actuators or at least representative stand-ins of these components. In some cases, it is possible to use a partial testbed, such as a replica of the flight computer, for software testing, but a complete FlatSat testbed with flight-like replicas of all major subsystems has additional benefits during integration. A testbed of this type may offer the ability to swap in flight hardware subsystems for screening or acceptance testing or to verify electrical interfaces without requiring integration of the CubeSat.

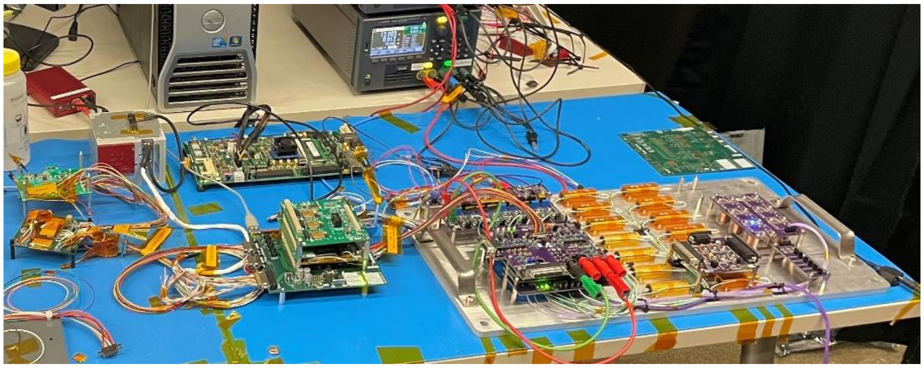


Fig. 4 Lunar Flashlight "FlatSat" system testbed (photo credit: Lunar Flashlight Operations team).

C. Planning for Final Integration

Final integration is the most comprehensive activity performed during the integration phase of a CubeSat project. The other fit checks will usually be carried out by following some subset of the complete assembly procedure used to conduct final integration. For this reason, the planning of final integration is discussed first and then the various fit checks are described before concluding with some practical considerations for documenting and performing integration.

Process Diagrams

The central component of final integration is a complete assembly procedure for the CubeSat. Creating this assembly procedure from scratch is a daunting task but can be aided by tools such as process flow diagrams like that shown in Fig. 5 depicting the integration process for a generic spacecraft subsystem. These diagrams help progressively decompose the assembly process into all the necessary steps which can then be grouped into individual assembly, integration and test procedures (AITP's). Creating similar diagrams for fit checks then allows for identification of the subset of integration procedures or steps in those procedures which are needed to perform these other activities. The process flow diagram for the final integration assembly procedure should include all of the following:

- Physical assembly steps: inserting fasteners to connect components together, mating harnesses and connectors
- Closeout Operations: staking down wire harnesses, staking connectors to housings, torque striping

- Quality Assurance (QA) checkpoints: for CubeSat-level assemblies this will mostly be inspecting staking, but could also include inspecting solder joints, wire stripping, and crimping
- Measurements and Inspections: for CubeSat-level assemblies this is determined by launch provider requirements and should include measuring critical interface dimensions like rail-to-rail lengths and checks for deployment switch actuation force
- Safe-to-Mate Checks: verify that connectors, harnesses, cables are properly constructed and installed to carry the intended signals in the correct pin positions and will not damage hardware when connected electrically
- Functional Tests: checks to confirm that subsystems/components are still functioning after being integrated

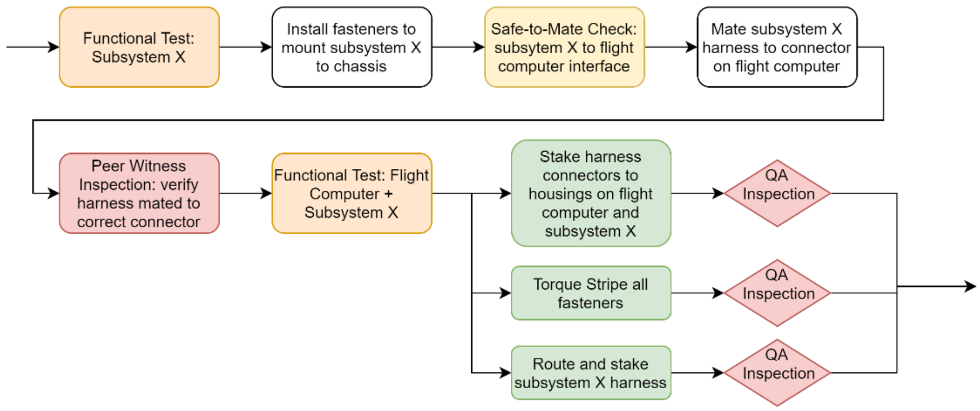


Fig. 5 Example process flow diagram for integration of "subsystem X" with spacecraft.

When creating diagrams like that shown in Fig. 5, it is likely easiest to begin by generating and sequencing a list of physical assembly steps and closeout operations. Then, consider which steps require QA as well as where safe-to-mate checks and functional tests need to occur. Required measurements and inspections should be derived from the launch provider requirements and then placed into the process accordingly.

Assembly Steps

Generating the list of assembly steps requires detailed knowledge of the spacecraft system and all its components. Because it can be challenging to identify the optimal starting point for assembling a complex system, the first goal should be to group the system into subassemblies wherever possible. Using subassemblies has several benefits:

- Independent subassemblies can be assembled in parallel or in any flexible order
- Smaller groups of components are more manageable in both planning and actual assembly
- Subassemblies provide a way to break up integration procedures into shorter, more manageable documents

A master equipment list or similar document is helpful for this process. If the spacecraft is designed with distinct subsystems grouped into electronics "boxes" or other physically distinct units, breaking out subassemblies may be fairly simple. However, many CubeSats are highly integrated which can make identifying subassemblies challenging. In these cases, it is usually still possible to identify electronics board stacks which can be assembled together or structural panels which can have components mounted to them prior to beginning the top-level assembly of the system.

The same process can then be followed to create a list of assembly steps either for integrating a subassembly from a group of components or for integrating a spacecraft from a group of subassemblies. One approach is to select a single item as the starting point, often large structural components as they are easy to fixture and build from, and then brainstorm and sequence steps to install all the necessary components. Especially if there is not an obvious starting point, this process may require some iteration to come up with an optimal assembly process. In selecting the order of assembly steps, the following considerations should be kept in mind:

- Mechanical necessity: do components build on top of each other, does installation of a component block access to other features or interfaces?
- Sensitivity: could the integrity or alignment of a component be affected by subsequent assembly or testing activities?
- Testing: what components are necessary to perform intermediate functional checks or inspections?
- Delivery dates or lead times: it may be necessary to begin integration before all components are available

Closeout Operations

Additional assembly steps are required for spacecraft systems given the intense vibratory environment during launch. NASA standards such as Ref. [7] can be used to determine when and how these closeout operations should be performed including: torque striping all fasteners to identify loosening, staking all connectors to their housings to provide secondary retention, and staking or tying down wire harnesses every 1 to 3 inches along their length.

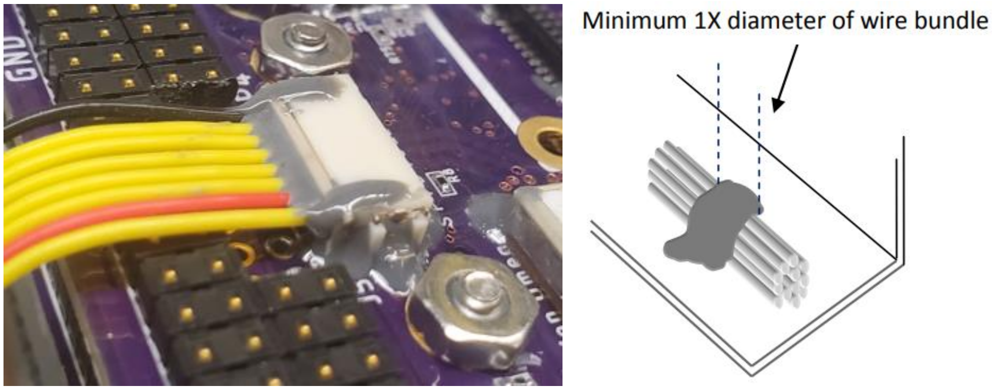


Fig. 6 Example of a connector staked to its housing (left) which is recommended even for locking connectors and diagram showing proper wire harness staking (right) [7].

It is usually desirable to leave staking operations to the last possible point in assembly so that batches of staking operations can be performed all at once since epoxies have a limited working time. In addition, assemblies should not be handled after applying staking until the epoxy has completed its initial cure to ensure the staking is not disturbed or spread to unwanted areas. Most importantly, waiting to perform staking minimizes the risk that staked harnesses or connectors will have to be reworked or removed, which can be difficult if not impossible.

Quality Assurance Inspections

Once an ordered assembly procedure has been created, it is easier to determine which steps require QA inspections. It should be noted that any activity or process involving flight hardware should be performed by one or more people in a "Technician" role with a separate individual as the "Peer Witness" observing and confirming that the process is being conducted properly. Quality Assurance checks are specifically required when the work performed needs to be evaluated against a workmanship standard such as those created by NASA for spaceflight hardware [8]. The following are examples of activities which require QA inspections:

- Staking
- Torque Striping
- Wire Stripping, Splicing, and/or Crimping
- Soldering

Any identified QA inspection hold points should be appropriately denoted in process flow diagrams with a special symbol or marking and in integration procedures with locations for a QA inspection approval signature.

Safe-to-Mate Checks

Before systems are electrically connected, either by mating harnesses or board-to-board connectors, testing should be performed to ensure that the interfaces are electrically compatible and that mating the systems will not short power to ground or harm the systems in any other way [9]. These Safe-to-Mate checks are often performed by connecting the interface to be mated to a breakout board, such as the one shown in Fig. 7, to aid in probing the pins of densely packed connectors with a multimeter.

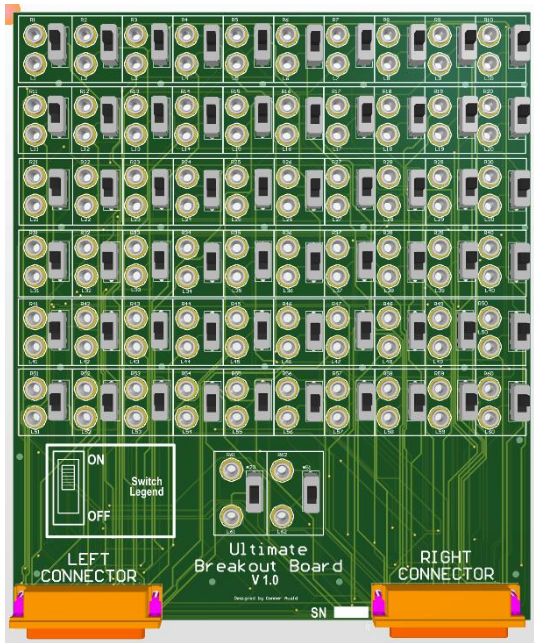


Fig. 7 Breakout board for performing safe-to-mate checks of electrical interfaces (photo credit: Conner Awald).

At a minimum, the Safe-to-Mate check should verify continuity among all ground pins in a given interface and proper isolation of ground from all other power and signal pins. This result can be accomplished by confirming that the resistance measured from each connector or harness pin to a known ground reference from the same interface is as expected based on the designed system pinout:

- Ground connections: very small, near-zero resistance
- Power, signal, or not-connected (NC) (i.e., anything except ground): very high or "overload" resistance

These continuity checks should be performed with the system un-powered, and this type of safe-to-mate test should be performed every time before an electrical interface is connected during integration.

Other measurements can also be made to perform a more comprehensive verification of an electrical interface. These generally involve providing power to the subsystem and then measuring voltages of power and signal pins relative to an appropriate ground reference to ensure they are within the acceptable ranges. Breakout boards like the one shown in Fig. 7, which can accommodate both ends of an electrical interface, are ideal for this type of testing as they allow select power and ground connections to be made while leaving the remainder of the interface isolated. This type of electrical interface verification is not necessary every time an electrical connection is made but should be conducted as part of the acceptance test process after components are first received and after any rework or hardware modification [10]. It may also be desired to perform these tests again if the hardware has been in storage or unused for extended periods of time.

Functional Testing during Integration

Similarly, consider where functional testing of components or subsystems is needed in the integration process. The goal of this testing is to confirm that the functionality of these parts or systems has not been impaired by integration with the spacecraft. It is vital to perform this testing intermittently throughout integration to detect issues as soon as possible after they arise. Performing functional testing only after assembly has been completed makes any detected issues more difficult to troubleshoot since the root cause could be related to any one of the many activities and processes performed to integrate the spacecraft. To this end, it is important to specify when and how functional testing must be performed prior to beginning the integration process. Leaving test frequency up to the technicians or in-the-moment decisions can lead to tests being compressed or skipped due to schedule pressure.

A functional test or check should be performed every time a new electronic component or subsystem is added to the spacecraft assembly. This could be a sensor which is installed into the assembly, a board which has been mated on top of a stack, or a subsystem which has been connected to the flight computer. While the integration of each new component adds new avenues for irregularities, performing this "stack-up" testing allows issues to be isolated as soon as they happen which greatly simplifies troubleshooting [5]. Testing should ideally be performed before staking or other bonding occurs to simplify any required rework or disassembly should the test fail. What exactly this functional testing looks like can vary. In most cases, a basic "aliveness" test is sufficient, for example:

- Subsystem: power on and verify received telemetry is within expected ranges
- Sensors: verify that reading (pressure, temperature, etc.) is as expected
- Actuators: power on/enable and verify that voltage and current draws and physical response are as expected

The rationale for performing only basic functional testing is that performance should have been verified in-depth at the subsystem or component level prior to integration and so only basic testing is required to confirm that the part continues to function as intended. This is particularly applicable to some actuators, such as deployment mechanisms or propulsion pumps and valves, which may not be safe to actually enable during functional checks in integration.

Measurements and Inspections

Lastly, the list of required measurements and inspections must be placed into the process. In general, these measurements should be taken as early as possible in the integration process so that if the inspection fails, corrective action can be taken quickly. When examining the process to insert inspections, try to determine at what point the measurement could first be taken. At a minimum, inspections should be performed before any permanent or semi-permanent bonding which would prevent or complicate rework of the relevant feature. If a subsequent assembly step or process may have altered a previously inspected feature, the measurement should be repeated.

For all inspections and tests included in the integration process, it is important to have clear pass/fail requirements for proceeding past the hold point. A detailed inspection including gathering critical interface measurements should be conducted once assembly has been completed with requirements derived from the launch provider or deployer interface control document (ICD).

Conclusion

Section III of this paper provides a case study of an integration plan created in the form of a process flow diagram which has been decomposed to include all of the types of activities described above. A comprehensive process flow diagram of this type which describes the final integration assembly process can then be transformed into a step-by-step integration procedure. This is not a trivial endeavor and some considerations for creating integration procedures are presented in Section II.E. In general, the exact instructions to perform an operation will not be immediately obvious and will need to be perfected through some amount of practice on actual hardware.

D. Fit Checks

Prior to beginning final integration, it is important to ensure that all parts of the CubeSat will fit together properly. Verification of the various physical interfaces within the spacecraft is accomplished through fit checks, which can be performed using modified versions of the assembly procedure to provide valuable practice to the integration team. This section presents considerations for several types of fit checks to verify mechanical interfaces within the CubeSat, the interface of the CubeSat with the deployer, and harness routing.

Mechanical Interfaces

Perhaps the most straightforward way to verify that all the components will properly fit together is to perform a full "dry run" of the complete assembly procedure and leave out any greasing, bonding, or staking to allow the system to be completely disassembled afterwards. This should be performed at least once prior to final integration and has the following benefits:

- Can verify clearances between subsystems in addition to individual interfaces with the structure
- Allows team to practice and improve assembly procedure
- Easy to ensure realistic fixturing, torque, etc. during assembly

Keep in mind that these dry runs are most valuable when performed using the actual assembly procedure planned for final integration to ensure realism and provide practice to the team.

There may be scenarios in which it is necessary or desirable to perform a fit check of an individual subsystem with the structure or to test an assembly of a subset of components:

- Hardware delivery is delayed, and full fit check is not possible
- Checking the range of motion of a mechanism or deployable
- Practicing and tweaking a particular assembly operation
- Practicing mechanical alignment without risking damage to sensitive electronics

These partial fit checks will not identify mechanical interferences between any omitted components and do not allow the ability to practice the full assembly procedure. However, as long as they are performed in as flight-like a manner as possible – using correct torque values for instance – they are still useful for verifying individual mechanical interfaces.

In particular, wherever the system has a variable assembly process to achieve precise alignment such as shims, set screws, or special alignment features, dedicated fit checks should be planned to practice the assembly. This will allow the final assembly procedure to contain precise, step-by-step instructions to obtain the correct alignment. For example, tolerancing issues in the primary structure were identified during integration of the GT-1 CubeSat which caused it to bind within the test deployer when assembled [5]. A structural assembly procedure was devised which used a perfectly square fixture and shims to enforce proper alignment during final assembly of the structure as shown in Fig. 8. This alignment procedure was practiced in a series of dedicated fit checks which validated that the correct alignment could be repeatably achieved and ensured the team could perform the procedure properly during final integration.

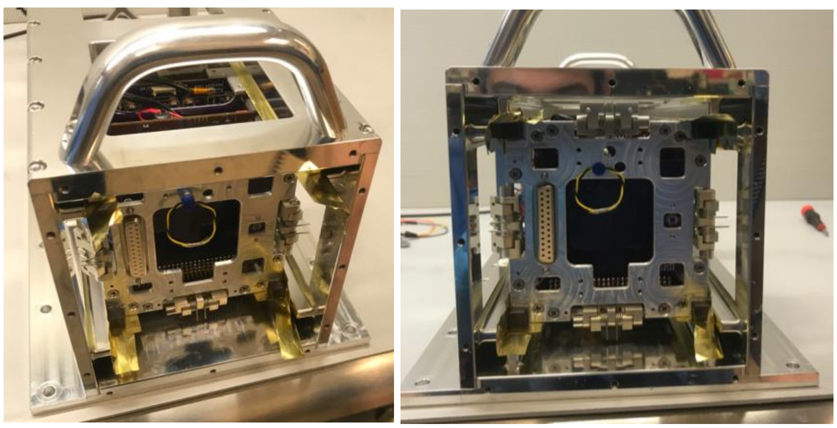


Fig. 8 Structural alignment of GT-1 CubeSat performed by shimming structure inside of a square fixture during final assembly.

Deployer

The most critical mechanical interface, and therefore deserving of separate treatment, is that of the CubeSat in the deployer. If the spacecraft cannot be smoothly inserted into the deployer and slide freely, the launch integrator may refuse to manifest the CubeSat or even worse it may fail to deploy on orbit. Most launch providers will require a fit check in the deployer after completion of final integration, but if issues are discovered at this point, it is far too late to rework the structure without massive schedule delays for disassembly and re-integration. For this reason, at least one initial deployer fit check should be incorporated earlier in the integration process, ideally in concert with a full dry run assembly. Although not necessarily part of the integration phase of a CubeSat project, it is also prudent to perform a fit check of the final flight structure in the deployer just after the structure has been fabricated.

Keep in mind that CubeSat structures, especially smaller and less rigid designs, could be sufficiently distorted by the mounting of components and torquing of structural fasteners to affect the fit inside the deployer. The following considerations are recommended to ensure that all deployer fit checks are accurate:

- Flight-like structure (rails anodized, etc.)
- Mass simulators or actual payload components mounted within the primary structure
- Follow the same assembly process as will be used for final integration (order of assembly and torque values for fasteners)

Performing an initial deployer fit check in tandem with a full dry run of integration ensures that these criteria are met.

Initial fit checks of the GT-1 structure in its deployer were successful, but these only used the primary structure components, and the assembly process was not representative of the final integration procedure. When the fully integrated CubeSat was inserted into the dispenser for the first time, it would bind and stick within the deployer. The clamping of structural components during assembly and the addition of heavy avionics components led to deformation in the structure that negatively impacted the alignment. Had the initial deployer fit checks been more realistic, these issues could have been detected and resolved earlier avoiding weeks of troubleshooting during integration [5].

Harnessing

One of the biggest challenges in integrating CubeSats is routing the many harnesses and cables within a constrained space. While these harnesses can and should be included in CAD models, this does not always give an accurate representation of how the wires are able to bend and where they can be routed and staked along the way. There are two potential approaches to practicing and confirming harness lengths and routing for flight:

1. Practice the harness routing during a fit check of flight or qualification hardware
2. Create a simulation of the spacecraft (via 3D printing) to test and confirm harness lengths and routes

The first approach was successfully implemented during the integration of the GT-1 CubeSat but required fully or partially assembling the spacecraft several times, and thus can be both risky and time-consuming. Therefore, unless a qualification vehicle is available to test harness routing without using the flight hardware, it is recommended to take the second approach, which was successfully implemented during the integration of the Lunar Flashlight Propulsion System [11], and 3D print a simulation of the hardware for harnessing fit checks. This has the added benefit that the hardware simulators can also be used to practice aspects of the assembly process without handling flight hardware.

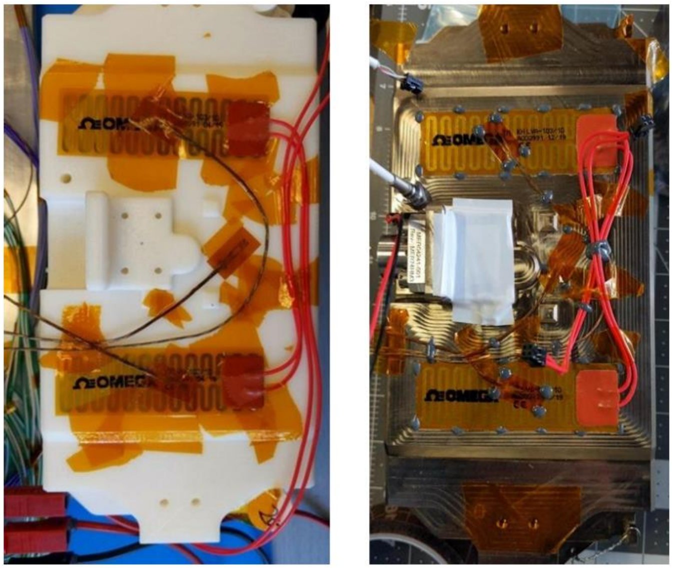


Fig. 9 3D-printed replica (left) used to perform wiring fit checks before final integration of Lunar Flashlight Propulsion System (right) [11].

Regardless of which approach is selected, it is important to replicate and verify all the following during harnessing fit checks:

- Length: harness connects both/all interfaces without excessive stress
- Routing: planned harness path provides sufficient locations for staking or tie-downs and does not interfere with other components or exceed the spacecraft mechanical envelope
- Bend radii: verify acceptable per NASA-STD-8739.4A [12] or similar
- Access and Insertion: confirm that all locations for harness mating and staking are accessible when following the planned assembly procedure

E. Documentation

Integration Procedures

Well-written integration procedures are the solid foundation upon which proper documentation of integration processes and activities are built. No activity should be performed on flight hardware without an integration or test procedure to guide the technicians. Even in routine or familiar activities, procedures are vital to prevent mistakes and oversights when human errors creep in due to stress or tiredness.

All integration procedures should be under version control and thus contain the attendant document tracking cover pages with at least: project name, document title, tracking number, signature and approvals page, revision history log. There are many acceptable ways in which to format integration procedures, and any template should also include the following introductory material:

- Prerequisites for performing the procedure: could include other acceptance testing or subassembly procedures
- Number of required personnel and training
- Required equipment and supplies: spacecraft components; hardware such as fasteners and shims; tools; any inspection implements such as mirrors and borescopes; and supplies such as gloves, IPA, and wipes
- Process flow diagram: gives the reader an overview of what the procedure contains and what activities will be performed
- Export control and proprietary information disclaimers
- Notices to follow ESD protection and cleanliness practices

Additionally, the template should include page numbers, places for time and date stamps, and locations for technician and peer witness initials at each enumerated step.

Throughout the procedure, there should be plenty of empty space to accommodate notes, observations, and redline modifications while the procedure is being performed. Additional features should be included to cover specific activities:

- Callouts to check grounding of personnel and hardware before beginning work on sensitive electronics
- Required Personal Protective Equipment (PPE)
- QA and Peer Witness inspection hold points where appropriate
- Instructions to record measurements (mass, torque, dimensions etc.) and locations to record them
    - For torque measurements, include lines for running, design, and total torque as needed
    - Specify the desired number of significant digits to record
- Prompts to take photographs of assembled parts
    - If procedures are performed on tablets, include locations to directly insert images

The last critical feature that should be included are caution flags. These should begin with a word such as “Caution” or “Warning” and be formatted in a different color and in bold or a callout box to visually set them apart from the procedure. Caution flags can be used for a variety of purposes including to:

- Call attention to common pitfalls: in the way an experienced technician may say “it’s easy to mess this up by accidentally doing…”
- Alert to changes in the system state or behavior: activities that will power on the spacecraft for example
- Identify potentially hazardous mistakes: steps which could damage hardware if performed incorrectly
- Identify safety concerns for technicians: dangerous chemicals, electrical hazards, pressurized systems, etc.
- Remind to follow proper handling practices: working time of epoxy, careful handling of solar cells, etc.

The need for some caution flags will be immediately obvious, while others will be identified through learned experience. This is an example of the need for iterative improvement of integration procedures. In many cases, the correct way to do something will not be immediately obvious. Notes, observations, and redlines from completed (or “as-run”) integration procedures should be used to revisit and improve these living documents. As correct and incorrect ways of doing things are identified, more detail should be added to the procedures to guide the technicians towards the established, most efficient way of accomplishing each task. Keep in mind, however, that more detail is not always better. The eventual level of detail in a given step should reflect the criticality of the task and the precision required. If there is exactly one way to do the task or if it is crucial for the task to be performed in a very particular manner, then a lot of detail is appropriate (provided that these details are derived from practice and are validated to work). But if there are several correct ways for the task to be done or if some highly specific instructions are actually incorrect, then excessive detail will require extra effort from the technicians to create a "redline" of the procedure to account for every minor deviation.

A final consideration when creating integration procedures is the length. This ties in closely with the sequencing of activities and how the integration process is broken up into different subassemblies, phases, or procedures. Very long procedures can take days or weeks to perform which complicates documentation as different people fill the technician, peer witness, and QA roles and activities are stopped and started in the middle of the procedure. It can also be very difficult to find desired information buried inside a 70- or 90-page procedure. Breaking integration activities and procedures down into more manageable sizes, ideally so that they could be completed in a single sitting, can make the documentation much easier to follow. Procedures that are broken out by subassemblies or other units are also more modular making them easier to string together to perform more flexible activities.

As-Run Procedures

When integration activities are performed, copies of the procedure used should be filled out and marked up to create an "as-run" procedure which documents exactly what was done to the hardware, when, and by whom. This can be done on paper or on a tablet, and one way to make as-run procedures easier to follow is to use different colors of ink when marking it up:

- Blue (preferable) or Black: filling out the procedure (signatures, measurements, etc.) and recording notes or observations
- Red: any alterations or changes to the procedure

These as-run procedures should be archived for the duration of the mission to form a complete history of the activities performed on the hardware. This record is vital when attempting to trace back the source of an anomaly during troubleshooting; without a clear history of what has been done to the hardware, it may be difficult or impossible to identify the cause of damage or failures observed later.

Process Images

At a minimum, there should be prompts to capture images of the hardware after activities which modify it in some way such as: applying staking, soldering wires, torque striping bolts. If desired, these images can be embedded directly into the as-run procedure to clearly correlate them with the instructions followed to perform the activity. Otherwise, the images can be filed in a database where they should be labeled with at least the date, procedure, and procedure step during which they were taken.

Prompts and embedded images within procedures should be limited to critical activities, such as those listed above, but in general it is best to capture as many images of the integration process as is practical. When collected and archived properly, these images can literally provide a look inside the system even after it has been sealed up in final integration. These photographic records of the system can be an invaluable resource during troubleshooting, as was the case on the GT-1 mission when an anomaly was detected in the behavior of the burn wire circuits for the deployable solar panels. Initial investigation suggested that the root cause was an improperly manufactured harness with a reversed pinout which was installed on the spacecraft. Images taken during final integration, such as the one shown in Fig. 10, were used to confirm this cause, a conclusion which would have normally been impossible to reach without de-integrating the spacecraft [5].

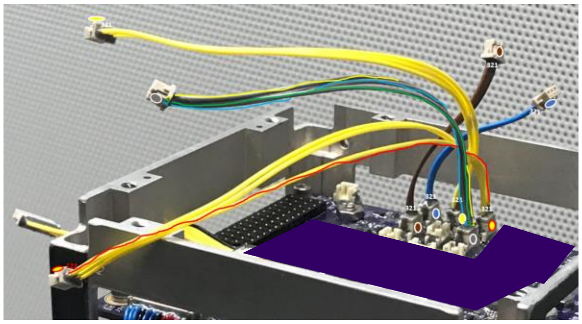


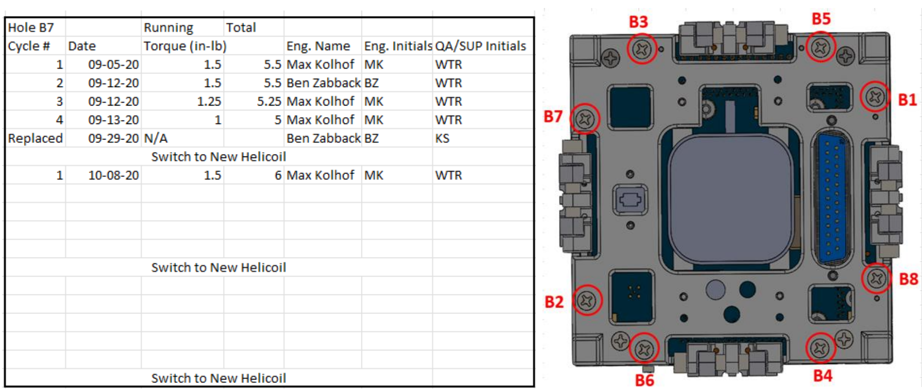
Fig. 10 Image taken during integration of GT-1 CubeSat used to identify reversed polarity of cable as root cause of an anomaly observed during testing.

Although it not necessary to place all of these images in an as-run procedure, while performing integration it is wise to capture images of all components and subassemblies, from multiple angles, both before and after installation onto the spacecraft. Videos can also be a useful resource when used to document events like initial power-on of the spacecraft or fit checks in a deployer. Keep in mind when capturing images during integration that they are only useful if properly archived so that they can correlated to specific steps in as-run procedures.

Auxiliary Tracking Systems

While as-run procedures are a good resource for tracking what happened during each integration activity, finding measurements recorded in the procedures like as-built masses or external dimensions can be time-consuming. In these cases, it is often helpful to create auxiliary documents to track these important measurements. For example, tables for recording component masses in an assembly procedure could be replicated in an Excel spreadsheet to collect as-built masses in a single location for easy reference. Values can be transcribed from the as-run procedure at a later date or filled out as the procedure is performed. The auxiliary document or spreadsheet should have some mechanism, such as copying and renaming a worksheet, to correlate recorded measurements to a specific as-run procedure. It can also be helpful to have the format mirror that of the integration procedure by referencing step numbers or other landmarks.

An example of another useful application of these systems is for tracking torque values and helicoil cycles in hardware. Helicoils are a common method of secondary retention for fasteners in CubeSat applications, and an important consideration is their limited cycle life. They should be replaced when the running torque is observed to degrade, with replacement after five cycles being a common rule of thumb.



Hole B7		Running	Total			
Cycle #	Date	Torque (in-lb)		Eng. Name	Eng. Initials	QA/SUP Initials
1	09-05-20	1.5	5.5	Max Kolhof	MK	WTR
2	09-12-20	1.5	5.5	Ben Zabback	BZ	WTR
3	09-12-20	1.25	5.25	Max Kolhof	MK	WTR
4	09-13-20	1	5	Max Kolhof	MK	WTR
Replaced	09-29-20	N/A		Ben Zabback	BZ	KS
		Switch to New Helicoil				
1	10-08-20	1.5	6	Max Kolhof	MK	WTR
		Switch to New Helicoil				
		Switch to New Helicoil				

Fig. 11 Example torque and helicoil cycle tracking log from the GT-1 mission.

Above in Fig. 11 is an example of a torque log from the GT-1 mission; the values in the chart shown above are also recorded in specific as-run procedures from each time the system was assembled. The images and bolt numbers in the chart correspond exactly to the instructions in the integration procedure, making it easy to correlate between the two. By gathering torque values together in a single document spanning multiple procedures, it is easy to track trends in the running torque to identify when the helicoils need to be replaced or to determine when in a planned sequence of fit checks and assembly activities replacement will need to occur.

F. Practical Considerations when Performing Integration

The focus in previous sections was largely on planning for major activities during integration. In this section, miscellaneous practical considerations to keep in mind when performing integration activities are addressed.

Scheduling

When planning for and executing integration activities, it is important to accurately predict the time and effort required. If the difficulty of or time required for a particular activity it underestimated, work will be started too late and the schedule will slip as a result. In particular, it is helpful to keep in mind:

- Number of students on the integration team and weekly time commitments
- Allocation of extra time to critical events
- Inclusion of margin to cover "unknown unknowns"

Facilities

In many cases at the university level, integration facilities are shared among projects. Although not ideal, this is often unavoidable. When sharing facilities, it is important that the various project teams understand and clearly communicate the sensitivities of their systems to environmental disturbances or contaminants. This allows each team to ensure that their activities will not put their hardware or any other team's hardware at risk. For example, certain systems may allow or require the use of grease or lubricants, but these substances are very messy and can easily contaminate surfaces such as optics, radiators, or solar cells and therefore may be hazardous to other project hardware.

Flexibility

One of the most important aspects of a good integration plan is flexibility. Delays and reworks will inevitably creep into CubeSat projects during integration; if integration activities follow a very rigid and linear flow, delays to any component threaten the entire schedule. If integration activities can be flexibly reordered, either by changing the order of subassembly integration or performing certain fit checks out of order, this can help alleviate the effects of individual delays and keep the project on track. Dividing the spacecraft into independent subassemblies wherever possible is a good way to introduce more flexibility to the integration plan.

Awareness and Understanding

It is important to be aware at all times of the implications of the activities being performed on the behavior of the system. Perhaps the most important example is to understand the operating limits of the hardware so that test or assembly activities will not unacceptably stress the system. Considerations which integration technicians should be aware of include:

- Temperature or humidity limits for operation
- Systems which cannot operate in Earth gravity or at atmospheric pressure
- Components with limited cycle life
- Cleanliness requirements or ESD sensitivity of components

Although procedures should be constructed to avoid dangerous activities or conditions, it is hard to account for every scenario, especially when failures or anomalies occur. Integration team members which possess a comprehensive understanding of the spacecraft system are better equipped to recognize and respond to situations which pose a threat to the hardware.

Furthermore, the CubeSat will spend most of the time during integration in an incomplete state with some components missing and will always be operating in non-flight-like conditions. This can further complicate the system's behavior since the expected values during intermediate or ground-based tests may not exactly correspond to the nominal values for flight. Although procedures should account for these circumstances, it is hard to exactly predict how the system will behave and so there is occasionally the need to determine whether observed idiosyncratic behavior is indicative of a fault or simply a product of the hardware setup and conditions. A subtle example arose during the integration of the Lunar Flashlight Propulsion system in which a pressure sensor appeared to be malfunctioning, reading 0 psi instead of the ambient 14.7 psi atmospheric pressure. This apparently errant reading was actually an acceptable accumulation of error since the sensor's operating range is close to 100 psi, near the point of normal on-orbit operation inside a pressurized propellant tank but far from the ambient conditions during integration [13]. More obvious examples could include nonsensical telemetry values being read because a corresponding component is not yet connected.

Personnel and Training

When planning and conducting integration activities, it is important to ensure the proper personnel with sufficient training are available. Whenever flight hardware is being handled, at least two people should be present: one to serve as a technician and another to serve as a peer witness. The peer witness can perform QA inspections as long as they have sufficient familiarity with the appropriate workmanship standards and did not help perform the activity being inspected. Integration team members should receive at minimum the following training:

- ESD protection training: required
- Cleanroom training: required
- Task-specific training: as needed for staking, torquing, wire stripping/crimping, soldering/splicing, etc.
- QA training: gaining familiarity with NASA workmanship standards in order to perform QA inspections

If certain activities require collaboration between two technicians to accomplish, it can be helpful to have a third team member serve as a more independent peer witness due to the tendency for "group-think", although this is not strictly required. Figure 12 shows an initial procedure step enumerating typical requirements for integration personnel.

Step	Description	Initial / Date	Peer Witness
1	The persons performing this procedure must be current in all training requirements before handling flight hardware. The assembler, peer witness, and additional supports should initial next to the trainings that they have completed. ESD: _____ _____ _____ Cleanroom: _____ _____ _____ Mate/Demate: _____ _____ _____ Torqueing: _____ _____ _____		INSPECTION HOLD POINT

Fig. 12 Example procedure step for technicians to attest to required trainings.

Maintain a Vigilant Mindset

Whenever possible, every assembly or integration activity should be treated as if the hardware will be going to space, even when performing fit checks or assembling qualification or test hardware. Maintaining this flight hardware mindset ensures that these preliminary activities provide realistic practice for final integration and also helps entrench good habits. Developing good habits reduces the likelihood of mishaps when handling flight hardware. For example, even if assembly of non-flight, development hardware is not performed in a cleanroom, it is helpful to follow the same procedures which will be used for the flight hardware and practice activities such as torquing bolts in a "flight-like" manner.

Cleanliness

One of the most important ways in which CubeSat integration differs from assembly activities in many other disciplines is the need for rigorous cleanliness. Foreign object debris can cause mechanical damage to hardware or clog fluid passageways, dust and other particles can cause ESD events or shorts in electronics, and oils from human skin can contaminate radiator surfaces, optics, and solar cells reducing their effectiveness. For these reasons, it is important that integration occurs in a cleanroom or clean bench environment and that all parts and components are thoroughly cleaned before being integrated. Isopropyl alcohol and non-particulating wipes are a good solution for cleaning most parts before they are brought into the clean environment and to ensure they remain clean during handling. In certain cases, more rigorous cleaning may be necessary if components:

- Have undergone industrial processes or machining involving masking or oil/grease
- Contain internal passageways which can be clogged
- Will house reactive chemicals
- Contain optics sensitive to non-volatile residue (NVR) contamination

Precision cleaning or simply more rigorous cleaning (with soap and water to remove machining oil) may be required in these cases. If precision cleaning is required, it is important to understand when in the process cleaning should occur and whether it needs to be repeated later in assembly. Parts should be inspected to ensure they have been cleaned to the proper standards and once cleaned they should be kept sealed in clean bags or inside a cleanroom or clean bench.

III. Case Study: Integration Planning for VISORS Mission

In order to illustrate the best practices presented in the previous section, a practical example is included in the form of a case study of the VISORS mission. As the mission is just beginning integration activities, the focus is on implementing the planning considerations discussed in Sections II.A through II.D to create a comprehensive integration plan that provides modularity and flexibility.

A. VISORS Mission Overview

Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS) is a National Science Foundation-funded CubeSat mission seeking to further knowledge of the solar corona and the heating processes therein. VISORS is a formation-flying mission consisting of two 6U CubeSats forming a distributed telescope instrument which will align in low Earth orbit to capture coronal imagery. The mission was created from the CubeSat Ideas Lab in February 2019 and includes partners at 11 institutions with Georgia Tech serving as the Systems Engineers and System Integrators. The mission cleared its Critical Design Review in November 2021 and is preparing to enter integration with a targeted launch readiness date of March 2024.

Science and Engineering Objectives

In order to allow observation and study of hypothesized heat release regions in the corona with a characteristic scale of 100 km, VISORS seeks to capture coronal imagery in the extreme ultraviolet (EUV) spectrum at an unprecedented resolution of 0.2 arcseconds. Such high resolution in EUV wavelengths is incredibly difficult to achieve with traditional mirror-based optics, so the mission makes use of a diffractive optic called a photon sieve [14]. To accommodate the 40-meter focal length of the photon sieve optic, developed by NASA Goddard Space Flight Center, VISORS divides the telescope instrument across two spacecraft, a Detector Spacecraft (DSC) and an Optics Spacecraft (OSC) which will fly in formation to capture imagery.

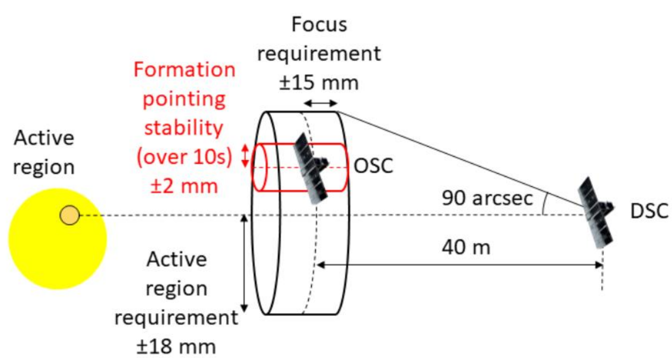


Fig. 13 VISORS formation-flying requirements for distributed instrument alignment (not to scale) [15].

The formation-flying alignment requirements, illustrated in Fig. 13, are incredibly stringent and drive many design decisions. Demonstrating the requisite millimeter level precision in formation control leads to the following technology demonstration objectives:

1. Onboard algorithms for differential GPS relative navigation and autonomous relative orbit control
2. Intersatellite link for autonomous exchange of navigation information
3. Miniaturized satellite propulsion for formation-keeping maneuvers

More comprehensive information on the mission design and Concept of Operations can be found in the paper by Lightsey, et al. [16]. The paper by Kimmel, at al. [17] provides details of the testing phase which will bring the VISORS spacecraft from the end of integration through to flight readiness.

Spacecraft and Subsystem Overview

Both the OSC and the DSC consist of a commercial avionics unit, the XB1 procured from Blue Canyon Technologies (BCT), and a payload comprised of various subsystems to carry out the formation-flying and science functionalities of the mission all housed within a 6U CubeSat chassis also provided by BCT. Figures 14 and 15 on the following pages show the internal layouts of the DSC and OSC, respectively, with BCT components called out in blue and payload components in orange. The entire BCT Bus segment (XB1 and chassis) is delivered in a fully integrated state and consists of the following subsystems and components listed below in Table 2.

Table 2. BCT Bus Segment Subsystems and Components

Subsystem	Components
Command & Data Handling (CDH)	Xilinx FPGA processor, onboard memory, serial communications, payload electrical interface connectors, and flight software
Attitude Determination & Control System (ADCS)	Reaction wheels, magnetorquers, star tracker, sun sensors, inertial measurement unit, magnetometer, L1/L2 GPS antenna, GPS receiver, external star tracker (DSC only)
UHF Communications	Half-duplex UHF transceiver, deployable monopole UHF antenna
Electrical Power System (EPS)	Batteries, power conditioning and distribution electronics, solar cells mounted on triple-deployable solar arrays
Thermal Control System	Heaters, thermistors, software-based thermostats
Structure	Mounting and support for all subsystems and mechanisms, resettable electronic release mechanisms for solar arrays and monopole UHF antenna
Harnessing	Cables connecting all the above subsystems, bulkheads for payload electrical interfaces with Bus

Heaters and thermistors for thermal control of the CDH and EPS subsystems are contained within the fully integrated XB1 avionics unit provided by BCT, and there is an additional pair of BCT-provided heaters and a thermistor which must be affixed to the propulsion system during integration of both spacecraft. The BCT Bus segments of both spacecraft are nearly identical except for small differences between the structures to accommodate different payloads. Also note that the DSC Bus contains a second (pre-installed) star tracker within the payload compartment while the OSC does not.

All of the subsystems and components shown in Table 2, including harnessing, are delivered in an assembled state ready for integration with the payload. Only some structural panels and the deployable solar arrays will need to be removed and re-installed during integration activities and the procedures for doing so will be provided by BCT.

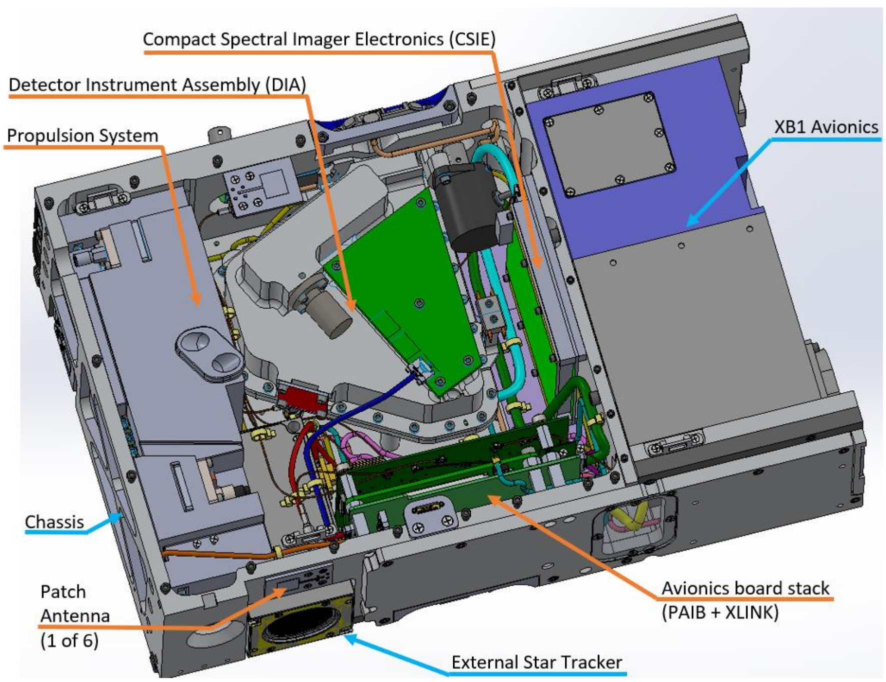


Fig. 14 Detector Spacecraft with top cover and solar panels removed (payload components labeled in orange).

As shown in Fig. 14, the solar arrays and top cover are removed from the structure to provide access to the payload compartment in the main chassis where the additional subsystems are installed. These payload subsystems, listed in Table 3, enable the unique mission objectives in formation flying and coronal imagery. Note the distinction between the instrument systems carried on the DSC and on the OSC.

Table 3. Payload Subsystems and Components

Subsystem	Components	
	DSC	OSC
Propulsion	3D-printed cold gas propulsion system	
Avionics Board stack	Payload Avionics Interface Board (PAIB) Intersatellite Link (XLINK) Radio boards	
Patch Antennas	6 antennas (one on each CubeSat face) connected to the XLINK radio	
Instrument	Detector Instrument Assembly (DIA) Compact Spectral Imager Electronics (CSIE)	Photon Sieve Optic Laser Rangefinder (LRF)
Harnessing	Cables, harnesses to connect payload subsystems together and to Bus electrical interfaces	

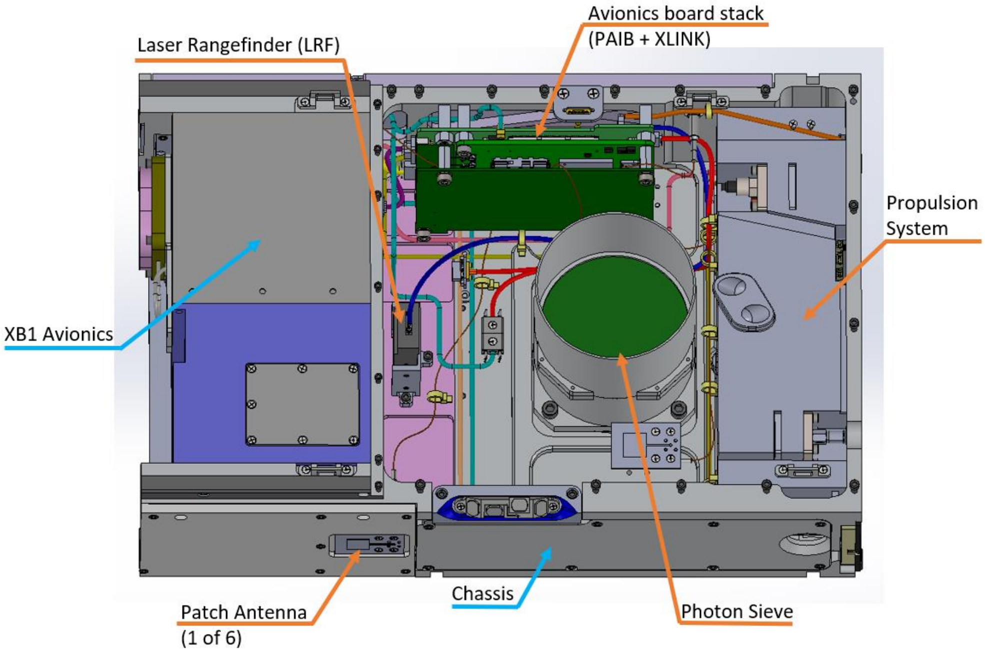


Fig. 15 Optics Spacecraft with top cover and solar panels removed (payload components labeled in orange).

All of the payload subsystems on both spacecraft interface mechanically with the Bus chassis and all electrical interfaces with the XB1 Bus avionics are routed through the PAIB.

Payload Subsystem and Interface Details

The cold gas propulsion systems for each of the VISORS spacecraft are manufactured by a team at Georgia Tech and use R-236fa, a non-toxic refrigerant, as propellant. Each propulsion system consists of sensors, valves, and control electronics mounted to a monolithic structure containing integrated tanks, nozzles, and flow passages which are 3D-printed in SOMOS PerFORM as a single part. There are slight differences in the geometry of the printed structure, but the mechanical mounting interface and electrical interface are identical for both the DSC and OSC propulsion systems. Each propulsion system interfaces with the PAIB onboard each spacecraft via a 15-pin nano-D wire harness. There are a pair of payload heaters controlled by a single thermistor which are provided with the BCT Bus and must be installed onto the propulsion system during integration with each spacecraft.

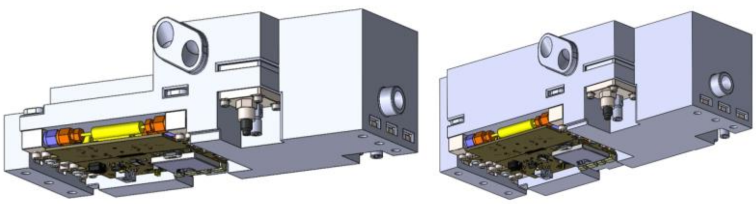


Fig. 16 Propulsion systems for the DSC (left) and OSC (right) VISORS spacecraft [18].

Each spacecraft also contains an avionics board stack consisting of a Payload Avionics Interface Board (PAIB) and an Intersatellite Link (XLINK) radio (3 boards) as shown in Fig. 17. The subassembly of 4 boards has a single mechanical interface with the Bus chassis. The PAIB serves as a power and data interface between the BCT Bus and the payload subsystems. All of the XB1 Bus-side payload electrical interface connectors are connected to the PAIB as detailed below.

- 31-pin nano-D Bus bulkhead: connected to PAIB via 31-pin nano-D wire harness
- 9-pin micro-D Bus bulkhead: connected to PAIB via 9-pin micro-D wire harness
- 9-pin nano-D and 4-pin Winchester Bus bulkheads: connected to 15-pin nano-D connector on PAIB via multi-point wire harness

The PAIB then breaks these connections out to separate electrical interface connectors for each payload subsystem, with power switching and monitoring capabilities for each payload interface included on the PAIB. There are slight differences in the OSC and DSC boards to accommodate different payload-side electrical interfaces, as well as non-volatile memory on the DSC PAIB for long-term storage of science data from the instrument. An avionics team at Georgia Tech is responsible for developing the PAIB and integrating the avionics board stack.

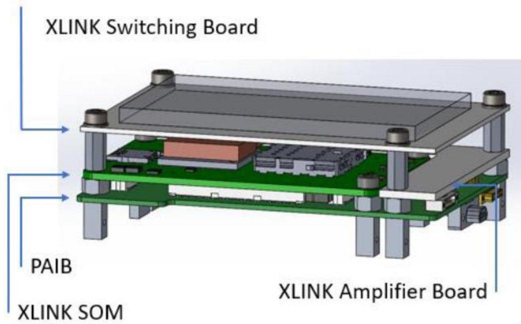


Fig. 17 Avionics board stack [19].

The XLINK radio, developed by teams at Ohio State University and Washington State University, consists of a software-defined radio (SDR) board, an amplifier board, and a switching board. These electronics boards interface with the PAIB via several board-to-board connectors. Both spacecraft contain identical XLINK electronics boards and six identical patch antennas, one for each face of the CubeSats. The patch antennas connect to the XLINK switching board via SMA to U.FL (a type of miniature surface-mount coaxial connector) coaxial cables.

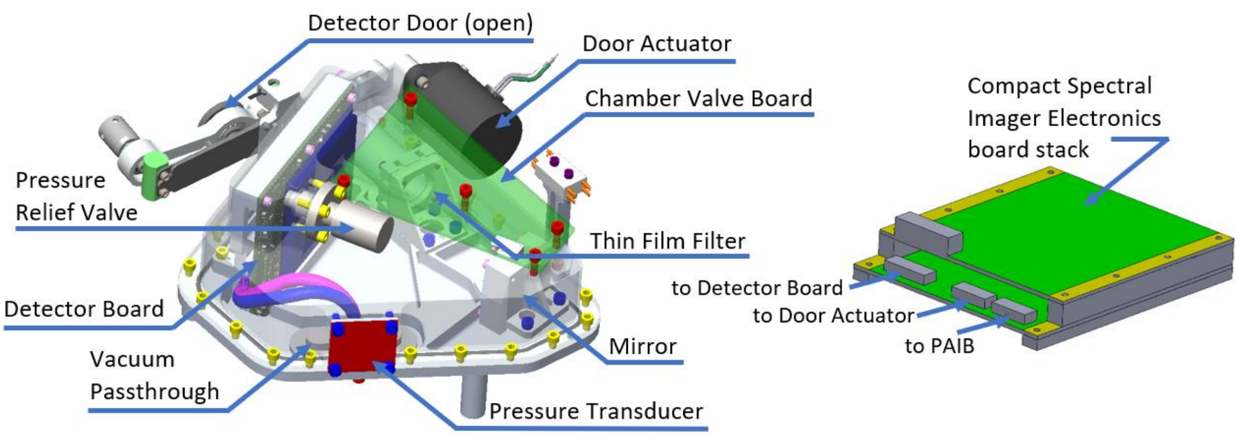


Fig. 18 Detector Instrument Assembly (DIA) (left) and Compact Spectral Imager Electronics (CSIE) (right).

On the DSC, the instrument consists of the Detector Instrument Assembly (DIA), developed by NASA Goddard Space Flight Center (GSFC), and the Compact Spectral Imager Electronics (CSIE) board stack, developed by the Laboratory for Atmospheric and Space Physics (LASP). Each has a distinct mechanical interface with the Bus and electrical interface with the PAIB. There is also a pair of electrical interfaces between the two subsystems.

Contamination of any of the optical elements housed within the detector chamber, pictured at left in Fig. 18, will reduce EUV throughput and decrease the ability to perform science on orbit, so the detector chamber is pressurized with dry nitrogen gas and sealed prior to spacecraft-level integration. The detector door is held closed by a resettable electronic actuator. A Chamber Valve Board (CVB) on the top of the DIA provides support electronics for a pressure relief valve and pressure transducer. The entire DIA has a single mounting interface with the Bus chassis and the CVB interfaces with the PAIB via a 15-pin nano-D wire harness.

The CSIE contains image processing electronics for the data collected by the CMOS chip in the detector chamber as well as an actuator control circuit for the door release mechanism. As such, a 51-pin wire harness connects a micro-D vacuum passthrough on the DIA to a nano-D connector CSIE, and the door actuator has a cable which interfaces with a 31-pin Omnetics nano-D connector on the CSIE. The CSIE board stack mechanically mounts to the Bus chassis and interfaces with the PAIB via a 31-pin nano-D wire harness.

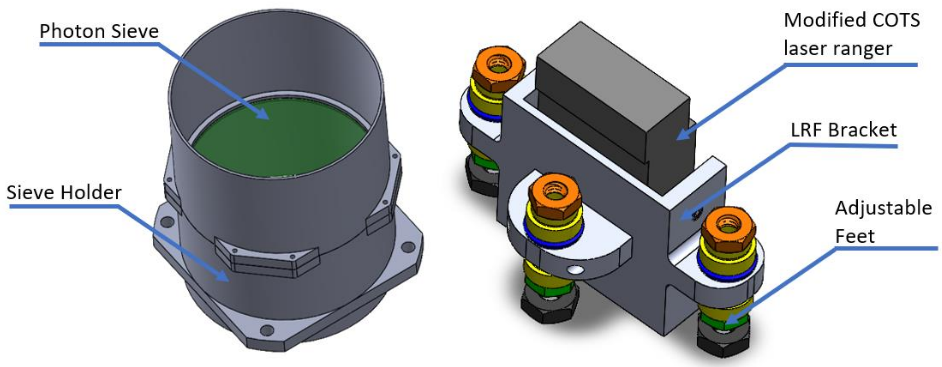


Fig. 19 Photon Sieve (left) and Laser Rangefinder (right).

A Laser Rangefinder (LRF) and Photon Sieve Optic, both developed by GSFC, compose the instrument on the OSC. The photon sieve is a passive component which mounts to the Bus chassis and fits in a large hole in the cover panel and chassis. An additional, smaller aperture in the chassis allows the LRF's laser beam to shine towards a target patch of white paint on the DSC structure. The LRF is a modified COTS component held within a custom mount which includes alignment features, shown in Fig. 19, to fine-tune the device's pointing. The LRF interfaces electrically with a 15-pin nano-D connector on the PAIB.

B. VISORS Integration Plan

There are several unique aspects of the VISORS mission that guide choices made during planning for integration. In general, the use of a commercially procured Bus from Blue Canyon Technologies containing many of the spacecraft subsystems greatly simplifies the integration process. However, the somewhat generic nature of the XB1 hardware necessitated the use of the PAIB as a central location for electrical interfaces. This makes the avionics stack (composed of PAIB and XLINK electronics) a focal point of integration as it is coupled with every system. However, because each subsystem has a distinct electrical interface with the PAIB and all payload subsystems mechanically interface independently with the Bus chassis, the system still remains largely modular. This modularity is reflected in the integration plan for the VISORS spacecraft in order to reserve as much flexibility as possible.

Another challenge is the fact that VISORS is a two-spacecraft mission. This provides the integration team opportunities to learn and improve in a unique way but creates an additional challenge in how to manage performing activities for both spacecraft either in series, which expands the schedule, or in parallel, which poses a significant staffing challenge. The limited staffing resources for performing integration are an important consideration for designing the integration plan. Finally, the distributed nature of the project team, with various payload subsystems developed across several partner institutions, requires extra effort in coordination, but simplifies some activities as subsystems are shipped to the Systems Integrators at Georgia Tech in an integrated state.

The process flow diagram in Fig. 20 depicts the high-level plan for VISORS integration activities.

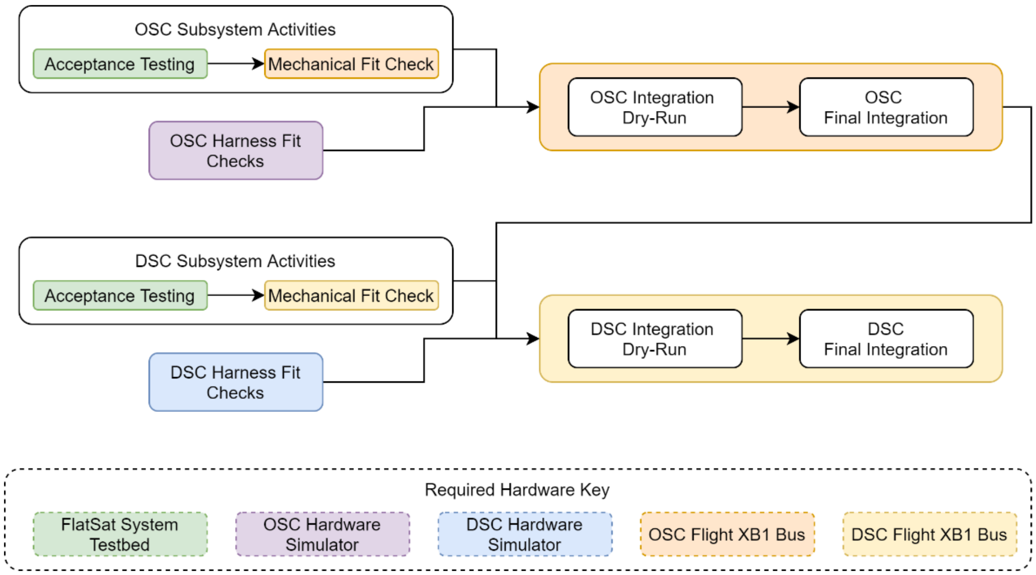


Fig. 20 High-Level VISORS Integration Plan

The arrows in Fig. 20 show the prerequisites for each activity and the coloring denotes the major hardware systems required. Subsystem acceptance testing for both spacecraft is performed using various benchtop setups including the VISORS FlatSat system testbed. Each spacecraft has a 3D-printed hardware simulator used for performing harness fit checks. All remaining activities require the BCT Bus hardware to be received and acceptance tested before proceeding. Note that OSC integration is a prerequisite for beginning the DSC dry run, as the VISORS team currently plans to perform integration of the OSC prior to that of the DSC. However, there is flexibility to partially parallelize the dry runs or integration of both spacecraft while still working within the project staffing constraints and allowing for lessons learned from integrating the less-complex OSC to be used to improve DSC integration. This is due to the division of the entire assembly into sub-procedures as discussed in Section III.C.

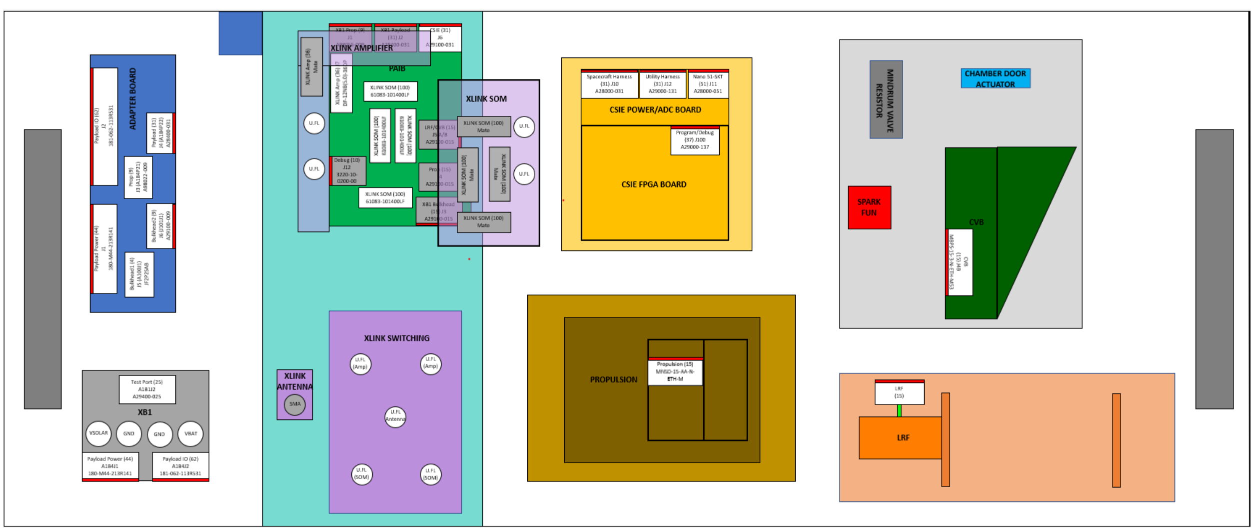


Fig. 21 Diagram of VISORS FlatSat testbed (courtesy of Dominik Fill).

Acceptance testing for all OSC and DSC subsystems will be performed primarily through use of the VISORS FlatSat system testbed, shown in Fig. 21. At the heart of this testbed is the XB1 Bus EDU which contains hardware or software replicas of all the BCT Bus avionics subsystems from Table 2 (excluding solar arrays, batteries, and structure). An adapter board allows all of the subsystems to be connected to the XB1 EDU using flight-like electrical interfaces, so combinations of EDU and flight hardware payload subsystems can be connected as needed to support acceptance testing. These acceptance tests will be performed on each subsystem in turn as components are received from the various teams at partner institutions. Harness fit checks will be performed using the 3D-printed hardware simulators of both the OSC and DSC. The DSC hardware simulator is shown in Fig. 22. These activities are naturally flexible as they have no prerequisites and use independent hardware. Acceptance testing and harness fit checks can proceed in parallel for both spacecraft, but priority should be given to OSC activities when necessary to maintain the project schedule.

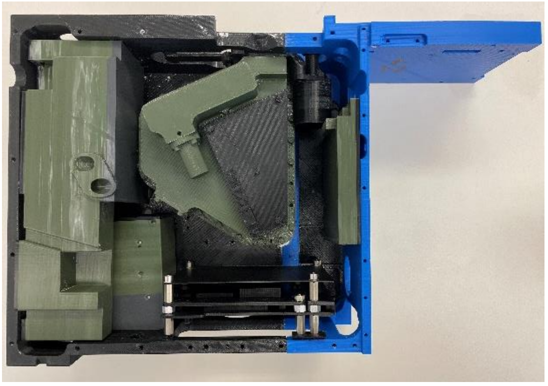


Fig. 22 DSC 3D printed hardware simulator for harness routing checks.

Once the Bus hardware has been delivered by BCT, subsystems which have been acceptance tested can undergo a mechanical fit check to verify that the mounting interface with the Bus chassis is correct and that there are no interferences with the walls of the payload compartment. These fit checks should be performed using the same assembly procedures created for final integration, but no electrical connections should be made, and no epoxy or thread locker should be used. Experiences from these fit checks should be used to improve assembly procedures.

Allowing these acceptance tests, harnessing, and mechanical fit checks to proceed somewhat in parallel for the two spacecraft despite the OSC's earlier integration will allow any issues with hardware to be identified as soon as possible to provide sufficient time for resolution. This parallelism in initial integration activities also provides more flexibility to accommodate any subsystem delivery delays.

The final set of integration activities, the dry run and final integration, proceed in sequence upon completion of acceptance testing and fit checks. The dry run is performed by following the full spacecraft assembly procedure but without any thread-locker or staking. Experiences from the dry run integration should be used to inform and improve the assembly procedures and any issues or anomalies identified during the dry run must be resolved before performing final integration.

C. Spacecraft Assembly Process Design

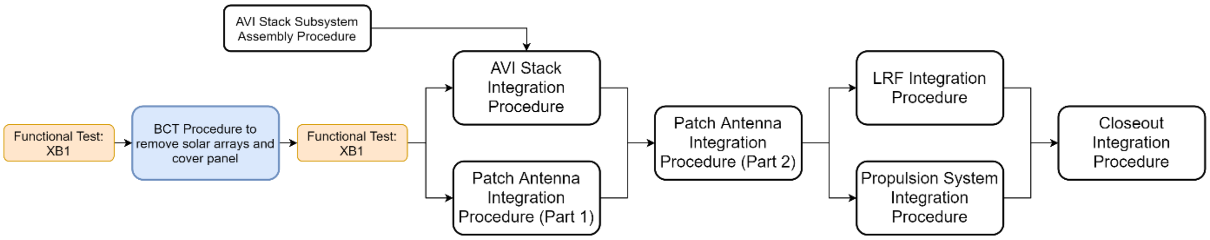


Fig. 23 OSC Integration Sub-Procedure Flow.

The entire spacecraft integration process has been broken out into several major sub-procedures. Figure 23 shows the overall flow of OSC integration through its sub-procedures with arrows representing prerequisites. These sub-procedures create shorter, more manageable documents with an aim to make the integration process as modular as possible. This approach allows procedures to be performed in any acceptable order as denoted by the prerequisites to accommodate subsystem delivery delays. A second benefit of this modularity is that most of these sub-procedures are nearly identical between the two spacecraft which will make the creation of two sets of integration procedures easier for the team. Although this is not currently planned, the high degree of commonality between sub-procedures provides additional flexibility to parallelize dry runs and final integration of the two spacecraft by: performing a sub-procedure on the OSC, making necessary improvements to OSC and DSC versions of the procedure, and performing the same sub-procedure on the DSC. As shown in Fig. 24, the DSC integration process is composed of many of the same blocks, but with an unfortunately more linear process flow as the more crowded payload compartment imposes more mechanical constraints on the order of assembly.

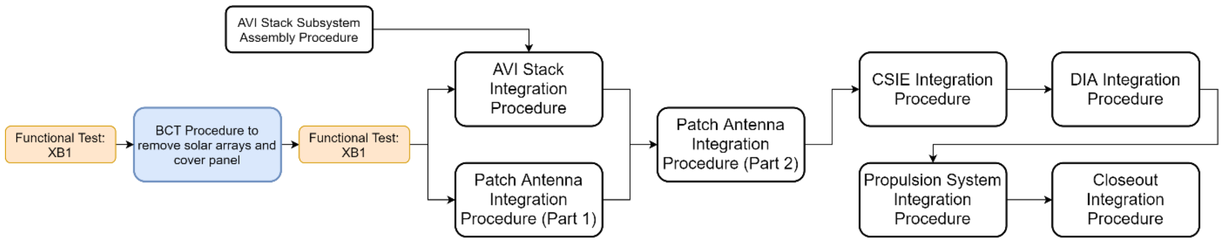


Fig. 24 DSC Integration Sub-Procedure Flow.

There are minor differences in several of the sub-procedures for the DSC which are summarized in Table 4. These differences are shown in more detail in the process flow diagrams in Fig. 26 and Fig. 27 which break down the entire spacecraft assembly process for the OSC and DSC, respectively. Included in these diagrams are all of the major types of activities discussed in Section II.C: assembly steps, staking, Quality Assurance inspections, Safe-to-Mate checks, and functional tests. Steps in green are performed only during final integration and not during the dry run as shown in the key in Fig. 25. Note that while some peer witness inspections are specifically called out, these are mostly for emphasis as all flight hardware activities require a peer witness to be present and attest to the proper execution of each procedure step. The prerequisites for each step in these diagrams, depicted by the arrows, represent the mechanical necessity of installing some components in a particular order and the desire to leave staking operations to the last possible point in integration. Connector staking operations which were identified as physically impossible to perform after all payload components have been installed are included at the last point at which there is sufficient access. Activities or procedures with the same prerequisites can be performed in any order as needed.

Table 4. Changes to integration sub-procedures for DSC

Shared Sub-Procedures	Changes for DSC relative to OSC baseline
AVI Stack Integration Procedure	Mate CSIE and CVB harnesses to PAIB instead of LRF harness
Patch Antenna Integration Procedure	Part 1: -Y patch antenna uses right-angle SMA connector and therefore must be installed to chassis before mating coaxial cable Part 2: no change
Propulsion System Integration Procedure	Must be performed after installation of DSC instrument subsystems (CSIE, DIA), but can be performed either before or after installation of LRF in OSC
Closeout Integration Procedure	Photon sieve installation step is removed, staking of -Y patch antenna SMA connector is moved out of closeout procedure as a prerequisite to DIA installation

Also note that the functional tests performed in the later stages of integration will differ between the two spacecraft once the unique instrument subsystems have been installed. Although not broken down in any detail here, the XB1, XLINK, and Propulsion system functional tests will be identical for both the OSC and DSC. Small differences will exist between the functional tests of the DSC and OSC PAIB's as a result of the design differences mentioned in Section III.A. Similarly, the Safe-to-Mate checks for all common electrical interfaces, such as PAIB to Propulsion system and PAIB to BCT Bus bulkheads, will be the same for both spacecraft. These benefits are a result of the largely identical hardware outside of the science instrument subsystems.

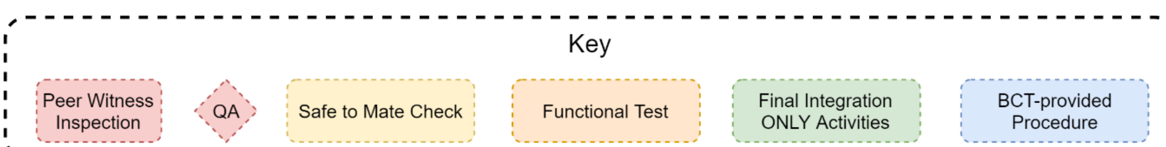


Fig. 25 Activity classification key for integration process flow diagrams.

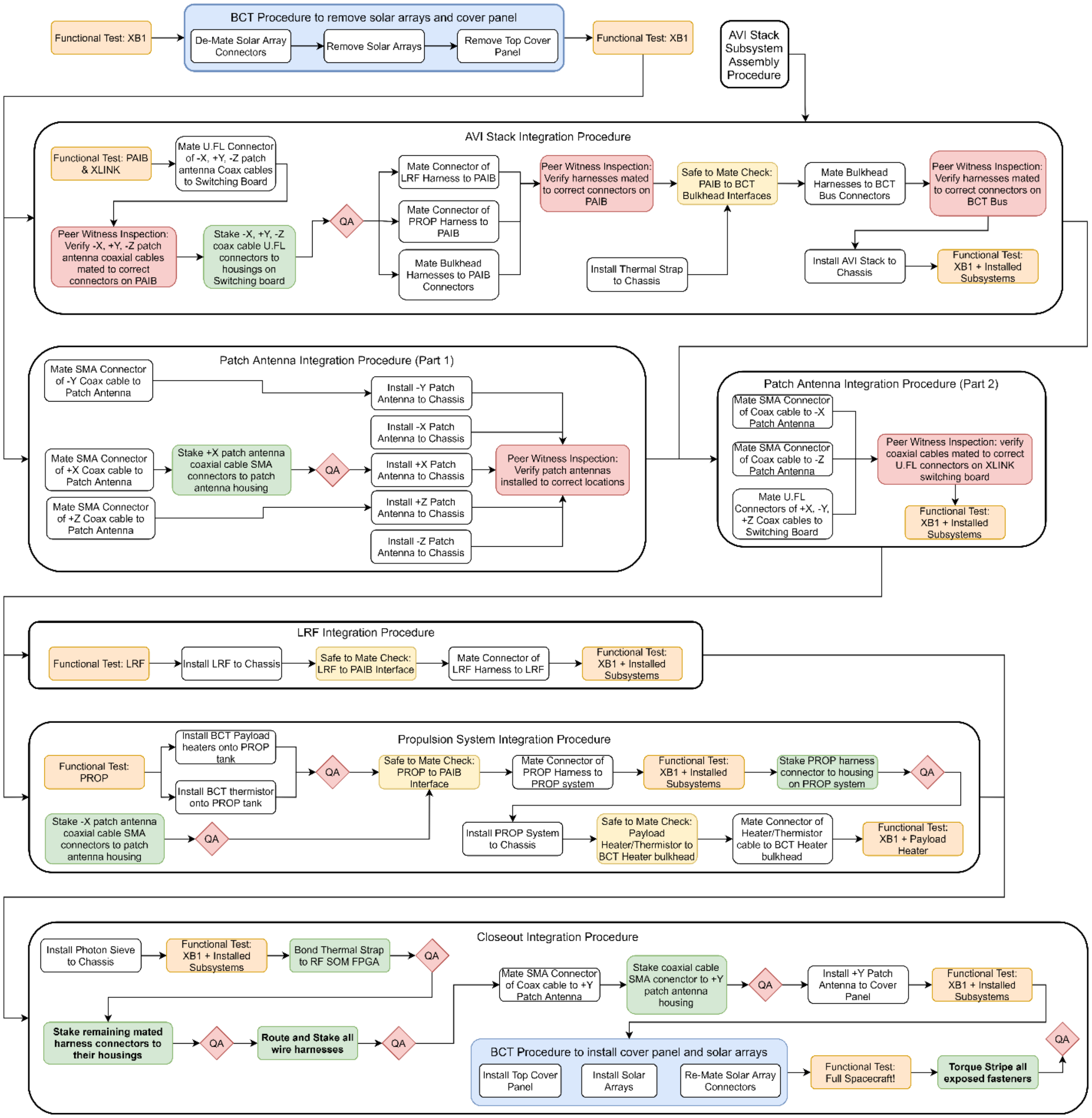


Fig. 26 OSC Integration Process Flow Diagram.

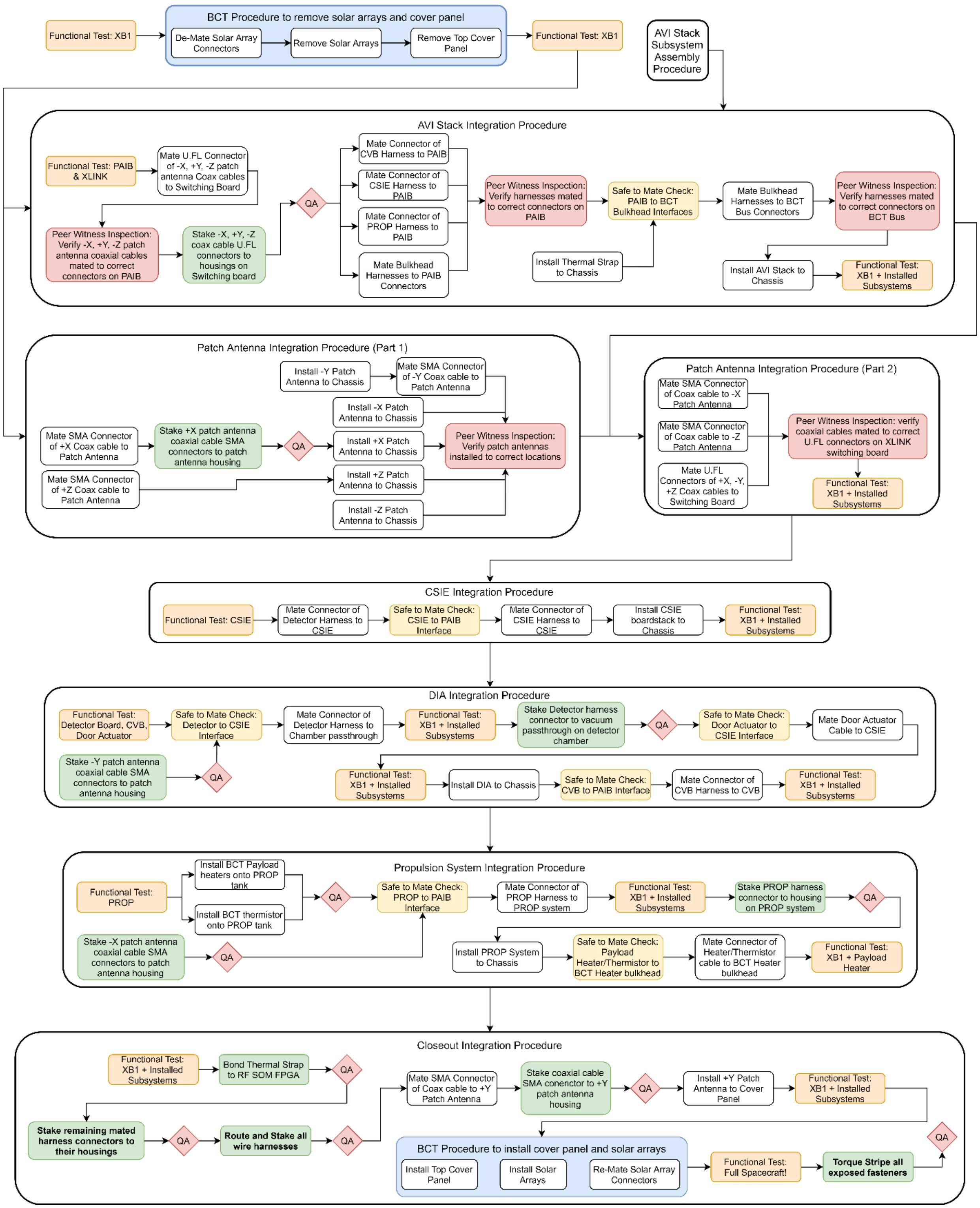


Fig. 27 DSC Integration Process Flow Diagram.

D. Fit Check Focus Areas

Although the sequencing of assembly steps presented in Figs. 26 and 27 represents the current best knowledge of how these activities must proceed in terms of mechanical necessity and optimal workflow, fit checks and other preliminary activities will inevitably identify errors and areas for improvement. Iterative updates should be made to these process flow diagrams and corresponding integration procedures to ensure final integration can proceed as smoothly as possible. Several areas of concern to which special attention should be paid during fit checks and integration dry runs are described below.

DIA Door Actuator

The electrical interface of the door actuator with the CSIE was overlooked for a long time during design. As a result, the cable connecting these two systems may be difficult to integrate while installing the DIA. Additionally, the body of the door actuator obscures access to the other CSIE connectors potentially making it difficult to stake these connectors after the DIA is installed.

Access for Staking

The connector and harness staking activities have been left toward the end of the assembly process with only a few connectors staked along the way where it has been identified that they will be inaccessible after a certain point in integration. In addition to those already identified, the following areas on the DSC should be investigated to confirm they have sufficient access to be staked after all payload subsystems have been installed:

- Harnesses which run partially underneath the DIA: detector board to CSIE, CSIE to PAIB, -Z patch antenna
- CSIE connectors obscured by door actuator

Access for Mating and Harness Lengths

Several tight or obscured areas in both the OSC and the DSC pose challenges for mating harness connectors during assembly. One common workaround exercised in the proposed VISORS assembly processes is to mate harness connectors prior to fastening mechanical interfaces to allow more space for access to mate connectors and tooling to fasten connector jackscrews. The extra length required for this modified mating is hard to determine in CAD models and this why harness fit checks are critical to verify that all harnesses can not only be routed from point A to point B, but also be properly installed during a realistic assembly process. During harness fit checks, special attention should be paid to the length and installation process of the following harnesses:

- Propulsion system to PAIB: connector on propulsion system is obscured when propulsion system is installed into the chassis
- -Y patch antenna to switching board coaxial cable: -Y patch antenna is mounted to the top cover complicating the installation process
- PAIB to 9-pin micro-D Bus bulkhead connector: difficult to access once PAIB is installed
- PAIB to 4-pin Winchester and 9-pin nano-D Bus bulkhead connectors: difficult to access Bus bulkhead connectors once PAIB is installed (DSC only)
- Propulsion system heater/thermistor cable to 4-pin Winchester connector: the edge of the DIA may restrict access to install the Phillips-head fastener used to retain the Winchester connector after mating since the DSC propulsion system must be installed after the DIA

Extra length may also be required for some harnesses to allow routing along a surface to which the harness can be staked for retention. In particular, the ability to stake the very short harnesses connecting the PAIB to both the 9-pin micro-D and 31-pin nano-D Bus bulkhead connectors should be confirmed during harness fit checks.

Patch Antenna Coaxial Cables

As reflected in the process diagram for the Patch Antenna Integration procedures, some of the patch antenna coaxial cables (-X, +Y, and -Z) must be mated and staked to the U.FL connectors on the XLINK switching board prior to installation of the avionics board stack into the chassis. Since these connectors can rotate freely when mated but not after staking, it will be important to confirm and document the proper orientation of the U.FL connectors during harness fit checks and the integration dry run. Additionally, access for tooling to torque the SMA connector of these three cables to the patch antennas after their installation to the chassis must be verified. If additional clearance is required, it may be possible to route the cable through the hole in the chassis for the SMA connector and fasten the connector outside of the chassis prior to installing the patch antenna, although this may require additional length to be added to the coaxial cable. These complications are why the other three coaxial cables (+X, -Y, and +Z) are mated to their respective patch antennas prior to installation to the chassis since the cable can easily be threaded through hole in the chassis beginning with the U.FL end. Note that mating a right-angle SMA connector, used on the DSC to allow the -Y patch antenna to fit below the DIA, requires installing the patch antenna to the chassis first and precludes either of these workarounds.

+Y Patch Antennas

The +Y patch antennas are the only payload components mounted to the top cover panel on either spacecraft. Since this panel is removed from the Bus to integrate the rest of the payload and the +Y patch antennas must be connected via a coaxial cable to the XLINK switching board, their installation is more complicated. It will be important to practice this portion of the integration procedure on the harnessing hardware simulator and identify where and how the +Y coaxial cable can be staked without inhibiting integration.

In addition to these areas to investigate during fit checks and dry runs, there are a couple elements of ongoing final design and analysis which may necessitate modifications to the assembly process.

Thermal Strap

A late addition to the spacecraft design to combat high predicted temperatures, the thermal strap is intended to interface with the FPGA on the XLINK RF SOM board. The mechanical mounting interface is awkward and likely precludes pre-bonding the thermal strap to the FPGA prior to integrating the avionics board stack with the Bus. Having to bond the thermal strap while the system is fully integrated inside the spacecraft will impair the quality of thermal contact and reduce the strap's efficacy in sinking heat to the chassis. However, improved thermal models have recently shown greatly reduced temperatures in the avionics board stack and so the necessity of including this thermal strap should be reevaluated.

Laser Rangefinder

The mechanical mounting interface of the LRF is currently undergoing design iteration to improve the ability to achieve repeatable alignment. These developments and any requirements for managing or adjusting alignment during integration must be tracked and accommodated with extra mechanical fit checks as needed. Additionally, the electrical interface is still under design and the exact harnessing solution for connection to the PAIB has yet to be confirmed.

Propulsion System Alignment

Misalignment of the propulsion system to the spacecraft ADCS will contribute to directionality errors in maneuver execution on-orbit which will impair the precision achieved in the formation flying control of the spacecraft. Although some amount of such error is budgeted for, it is desirable to minimize the contribution from installation. On-orbit calibration could be used to achieve this but will add operational complexity, so it is worth investigating how the alignment of the propulsion system could be controlled such as through the use of temporary shims during installation.

IV. Future Work: VISORS Integration and Testing

The planning work presented here provides a foundation for the successful execution of the VISORS integration campaign, but more work is needed to complete detailed planning and create actionable procedures. In particular, the following significant action items remain for the team at Georgia Tech:

- Develop, in collaboration with other VISORS project teams, acceptance and functional test procedures for all subsystems and the XB1
- Add required inspections to the integration plan once launch provider requirements are available
- Convert the process flow diagrams in Figs. 26 and 27 into procedures, with individual documents for each sub-procedure and an overall integration procedure which references and connects them

Mission documents have already been created detailing the plans for spacecraft-level environmental testing, which directly follows integration, and similar planning is underway for performance testing to verify critical functions of the two spacecraft for performing the formation-flying mission. Procedures will also need to be developed for these various testing activities.

As planning of the testing campaign is completed and integration activities begin, the choice will need to be made to either exercise the flexibility described in Section III.C to parallelize OSC and DSC integration or continue with them proceeding in series as shown in Fig. 20. This decision will be driven by the status of the overall project schedule and progress towards the planned date of readiness for handover to the launch provider of January 1st, 2024.

V. Conclusion

Integration is a critical phase of all spacecraft projects, particularly university CubeSats. Care must be taken when connecting all of the various mechanical and electrical interfaces to avoid damaging hardware, identify and resolve issues as early as possible, and verify that the synthesized system demonstrates the proper functionality. Leveraging lessons learned from past experiences in the form of best practices, such as those presented in this paper, is an important way to avoid potential pitfalls during integration. When seeking to apply best practices from any source, it is important to evaluate the underlying motivation and assess whether it is appropriate in the new, applied context. CubeSat projects often have more relaxed risk postures than the traditional space missions from which many best practices and standards have been derived. Even among CubeSat projects, there is a vast diversity of project goals and team compositions which can alter how integration should be conducted. While using established practices will rarely introduce more risk to a mission and can be a valuable way for new teams to get off the ground, blindly applying standards which are intended for much more risk-averse projects can impose unnecessary burdens and slow development. It is vital to carefully consider where to strictly adhere to standards and best practices and where to tailor or deviate from them in order to conduct more ambitious missions under the schedule, budget, and staffing constraints of university CubeSat projects.

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