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TESTING METHODOLOGY FOR SPACECRAFT PRECISION FORMATION FLYING MISSIONS

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Distributed space systems, and specifically spacecraft formations, have been identified as a new paradigm for addressing important science questions. However, when it comes to verifying and validating these systems before launch, there is the added challenge of figuring out how to test the formation's holistic operations on the ground since a full end-to-end mission simulation is likely infeasible due to the need for costly testing infrastructure/facilities. Building on established methods for single-spacecraft testing, this paper presents a two-phase testing methodology that can be applied to precision formation flying missions with budget, timeframe, and resource constraints. First, a testing plan with unique considerations to address the coordinated and coupled nature of precision formation flight is devised to obtain high system confidence on the ground, and second, the formation's holistic behavior is refined on orbit during the mission's in-space commissioning. This approach structures the pre-launch testing to make efficient use of the limited test infrastructure on hand and leverages a sequential configuration process combined with built-in operational flexibility on orbit to safely finish characterizing the formation's performance so that it can meet mission requirements.

INTRODUCTION

As space missions become increasingly complex, the need for more affordable ways to achieve such mission objectives grows. One potential way of reducing cost for more complex missions is through distributed spacecraft systems. A distributed spacecraft system (DSS) is a system that consists of multiple spacecraft, which work together to achieve the mission objectives that would otherwise be significantly more expensive and or infeasible to perform with a single spacecraft. A subcategory of DSSs relevant to this paper is formations or swarms, where the position of multiple spacecraft is controlled relative to one another. More specifically, precision formation flying (PFF) occurs when the relative position of multiple vehicles must be controlled autonomously on-board in a continuous manner with a high level of precision, due to the stringent relative state requirements.

An example of a PFF mission from which the primary motivation for this paper is derived is the Virtual Super Resolution Optics using Reconfigurable Swarms (VISORS) mission, where two 6U

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CubeSats navigate, guide, and control themselves relative to each other in Low Earth Orbit (LEO). They will form a 40-meter focal length distributed space telescope to capture images of the sun, achieving a resolution of 0.2 arcseconds, with the scientific goal of studying energy release regions of the solar corona. One spacecraft contains a detector capable of capturing diffraction patterns which are post-processed to produce images of filaments within the solar corona and is referred to as the Detector Spacecraft (DSC). The other spacecraft contains an optical photon sieve to focus the incoming light before it reaches the detector and is called the Optics Spacecraft (OSC). In order for the image collected to be in focus, both spacecraft must continuously control their relative position and velocity to tens of millimeters and hundreds of micrometers per second, respectively. This basic concept is shown in Figure 1.

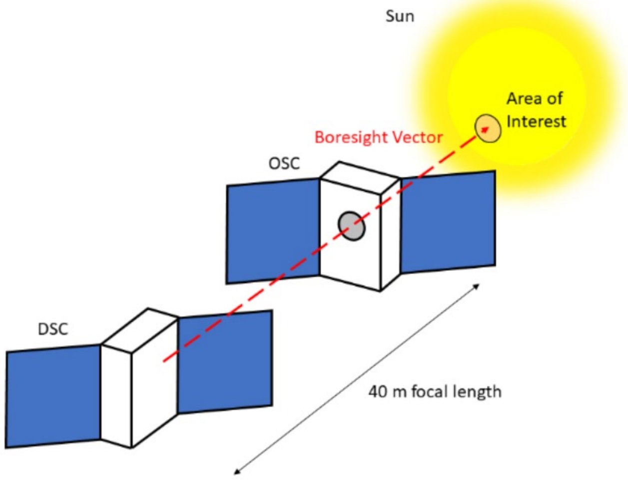


Figure 1. Conceptual depiction of VISORS distributed telescope formation geometry.[1]

While the spacecraft formation mission concept allows otherwise inaccessible science to be conducted, it also presents unique challenges. The individual formation-enabling technologies (such as inter-satellite links, on-board relative state estimation, relative propulsion, formation control algorithms & autonomy) are relatively mature, but integrating these all together in a continuous, coordinated, and reliable fashion to demonstrate PFF operations is a difficult feat, particularly in a relatively low cost 6U CubeSat framework. In addition to this, realistically testing PFF operations and system-level performance on the ground is challenging due to its complex nature and the cost and resources constraints of most missions. Consequently, unique solutions must be implemented to address these challenges. These solutions, first theorized for VISORS, have served as motivation for the content of this paper, which presents generalized guidelines for the development of a testing methodology for low-cost PFF missions.

COMPONENT VIEW OF SPACECRAFT FORMATIONS

An abstracted component view of spacecraft formations can be formalized so that it is applicable and scalable to any PFF mission. This abstracted view will form the basis of the two-phase testing methodology that will be discussed later in the paper. In this view, there are formation-enabling components (FECs) and core components (CCs). FECs are components that consist of a hardware and/or software element that contribute a unique capability to a spacecraft that enables it to fly in formation with other spacecraft. On the other hand, CCs are hardware and/or software elements that do not directly enable formation flying operations, but support the FECs on a spacecraft by providing them with electrical power, computing ability, etc. The respective components and accompanying descriptions are shown in Table 1.

Table 1. Definition of Core and Formation-Enabling Components on a spacecraft.[2]

Core Component (CC)	
Power Generation & Storage	Electrical power system responsible for generating, storing, regulating, and distributing power to the rest of the spacecraft
Ground Communications	Space-to-ground radio and supporting software
Avionics + Command & Data Handling	Hardware and software to enable receipt of commands, data distribution and management
Attitude Determination & Control	Hardware and software responsible for managing the attitude of the spacecraft
Formation-Enabling Component (FEC)	
Inter-Satellite Link (ISL)	Radio Frequency (RF) hardware and software to enable continuous communication between the spacecraft in the formation
Formation-Keeping Algorithms (FKA)	Software responsible for generating relative navigation, guidance, and control solutions to maintain the formation's relative geometry, as well as handling autonomous operations & coordination between all spacecraft
Navigation Sensors (NavSen)	Hardware and software that allows raw navigation measurements to be generated and sent to FKAs that can process it into relative state estimates[3]
Relative Propulsion (Prop)	Propulsion hardware/software capable of executing the control solutions generated by the FKAs to maintain the formation's relative geometry, usually involving very small impulse maneuvers

A generic spacecraft can be illustrated using the CCs as shown in Figure 2, with the boxes representing each component, and the arrows between representing their data/electrical interfaces. These four components are delineated as such because they each contribute a unique and non-redundant capability to the regular operations of a single spacecraft. The Avionics and C&DH CC is the most important of the four CCs, and as a result each of the other three CCs interface bi-directionally with it. In addition, the Power Generation & Storage CC supplies the other three components with the necessary power for them to operate.

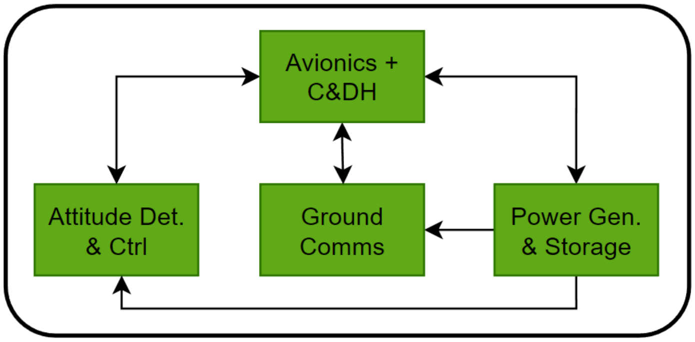


Figure 2. Core components and their typical interconnections.

Next, the interactions and flow of information between the FECs that allow for PFF operations to happen are shown in Figure 3. The FECs on each spacecraft have data connections between them, RF connections to the rest of the formation through the Inter-Satellite Link (ISL), and causal connections to the environment and relative dynamics as the formation's geometry is controlled over time. This continuous loop of data/causality can be explained starting with the Navigation Sensors (NavSens), which measure the current state of the local spacecraft with respect to the rest of the formation. The measurements are sent to the Formation-Keeping Algorithms (FKAs) and the ISL (which then transmits it to the rest of the formation). Simultaneously, incoming navigation measurements from the rest of the formation are received at the ISL (via the same process just described occurring with the NavSens on the local spacecraft) and also sent to the FKAs. Next, the FKAs perform computations to filter these navigation measurements and generate a guidance and control solution to move the local spacecraft to a desired location in space relative to the rest of the formation. This solution is sent to the Relative Propulsion (PROP) component which executes the control inputs, imparting an acceleration on the local spacecraft relative to the rest of the formation. As time moves forward, this acceleration translates into a change in relative state of the local spacecraft, as well as link closure conditions between the ISL component on each spacecraft. This entire process repeats on each spacecraft in the formation as a continuous loop during PFF operations.

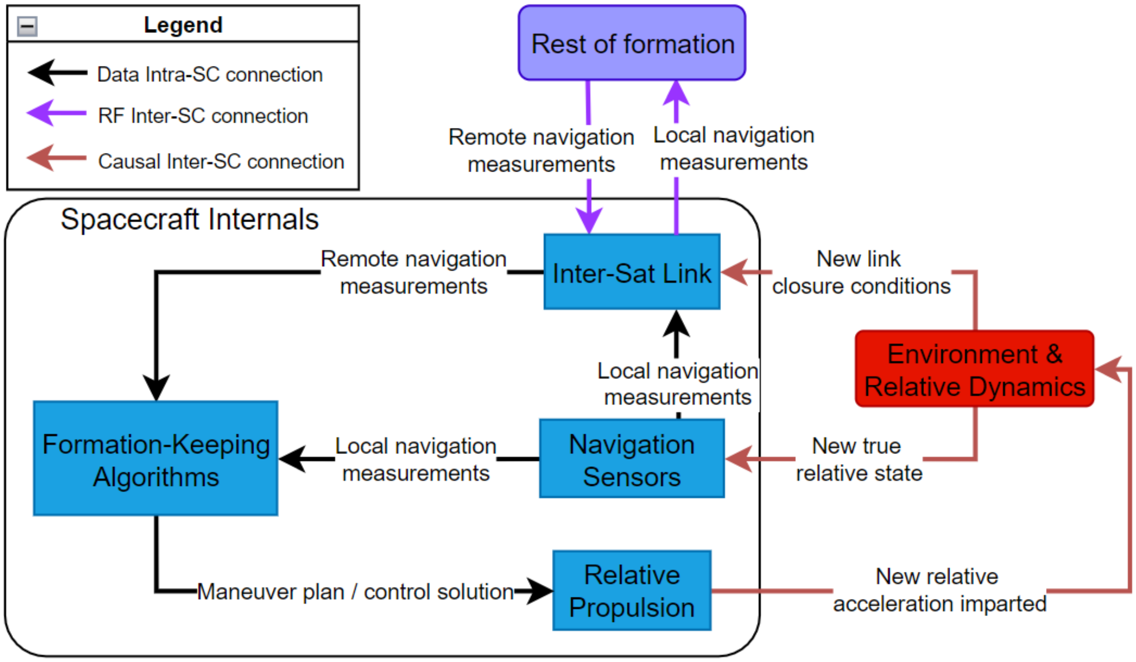


Figure 3. Multi-spacecraft FEC interaction loop during PFF operations.

Having understood how FECs interact with each other during PFF operations, a more concrete and detailed view of how they work together with the CCs in a formation is shown in Figure 4. The CCs are abstracted away as a singular block component in this diagram and in further discussion for brevity. In this diagram, the connections between FECs and CCs represent literal software/electronic connections, instead of just one-directional data flow that was shown in the previous diagram. As can be seen, there is a high degree of coupling between the CCs and the FECs on all the spacecraft within the formation, which makes the performance of each FEC vital to successfully achieving PFF operations capable of meeting mission requirements. As a result, each FEC on each spacecraft must be tested rigorously to gain confidence in the system. The abstracted view of the spacecraft formation shown in Figure 4 helps with planning these tests because it breaks down and specifies the key interfaces and functionalities that need to be tested during a system level test campaign.

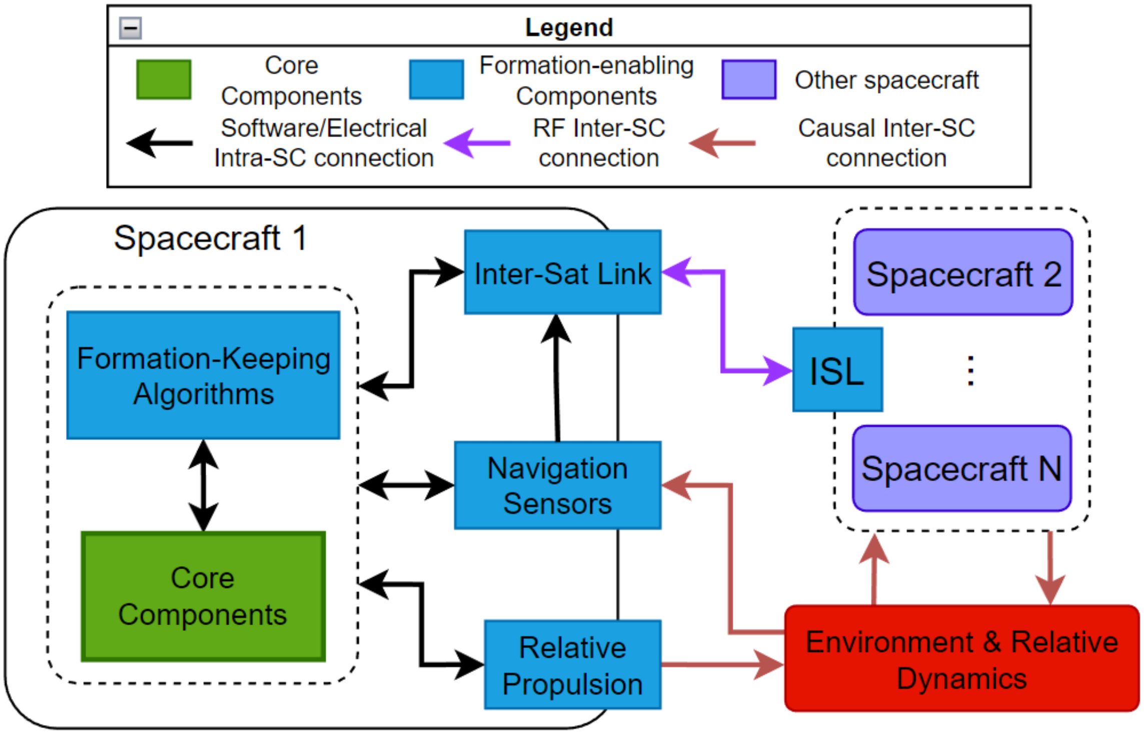


Figure 4. Functionality and interface diagram for a general N-spacecraft formation.

TWO-PHASE TESTING METHODOLOGY FOR OVERVIEW

The task of validating system level performance for spacecraft precision formations on the ground is difficult because there is no simple way to replicate the space environment for all spacecraft in the formation in a continuous/synchronous manner. The performance of each FEC can be verified on its own, but in order to validate PFF mission operations, one would need to close the FEC interaction loop between all spacecraft with sufficient simulation fidelity while still on the ground. For a monolithic spacecraft, existing testing infrastructure can replicate the external space environment for that spacecraft, and the interaction loop between all its CCs and payload can largely be closed in a synchronous manner – enabling an almost full end-to-end test of the spacecraft.[4,5] However, this is much more difficult to do for spacecraft formations since there is usually not enough testing infrastructure to emulate the space environment/dynamics and the connections between FECs on multiple spacecraft in a synchronous manner. For example, most university-level spacecraft integration labs would have the capabilities to spoof part of the space environment for a NavSen to derive its navigation measurements through something like a Global Navigation Satellite Systems (GNSS) simulator, but not to do this for multiple spacecraft at the same time. Additionally, as the number of the spacecraft in the formation increases, the cost of buying testing infrastructure to test all the spacecraft synchronously scales poorly.

Therefore, a two-phase testing methodology that instead aims to achieve high confidence in PFF system-level performance with existing testing infrastructure is proposed. Instead of replicating the multi-spacecraft FEC interaction loop synchronously, it should instead be replicated asynchronously on the ground. Then, built-in operational flexibility is used to precisely configure the formation in space to make up for any pitfalls of the asynchronous ground testing. The goal here is to tailor the ground testing and in-space testing configuration to make maximal use of the advantages offered by each environment and avoid redundant tests. In this manner, the team can focus on validating aspects of the system-level performance that are simple to test on the ground with existing ground testing infrastructure. Once in space, where the multi-spacecraft FEC interaction loop can be synchronously closed, time can be spent during the mission's commissioning to optimally and safely configure the formation to achieve the desired system-level performance. This paper explicitly focuses on the testing methodology for FECs while often glancing over details of CCs testing since those components already have mature and established testing methodologies. An overview of this methodology is shown in Figure 5.

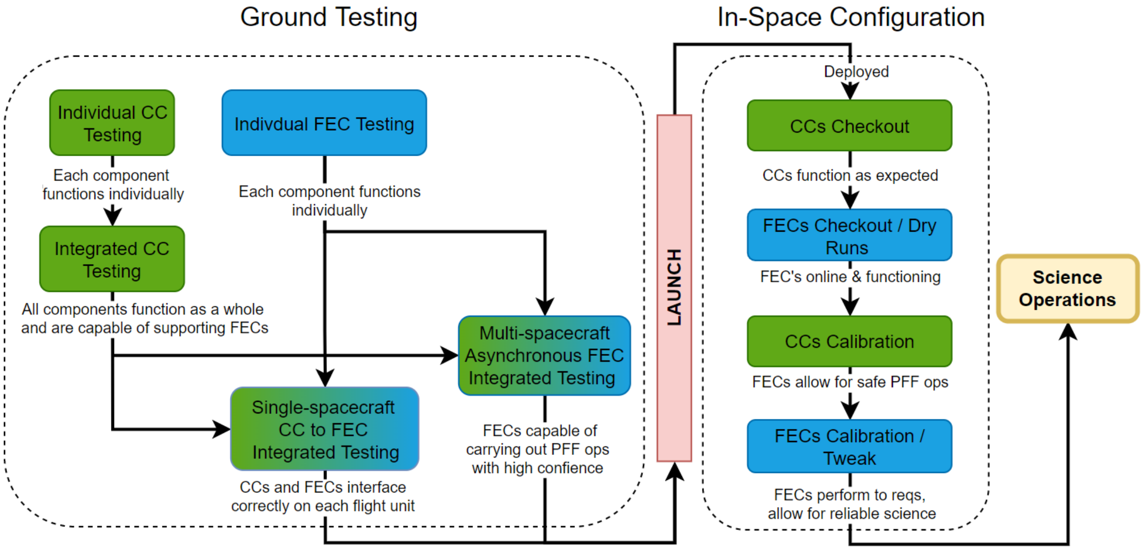


Figure 5. Two-phase testing methodology overview.

The ground testing phase for this methodology is presented as a high-level sequence of testing blocks focusing on the CCs and FECs. The sequence is derived from well-established testing procedures for monolithic spacecraft and adapted to accommodate the unique testing needs of FECs.[6] After the design and manufacturing of each CC and FEC element is complete, it should undergo thorough individual testing to ensure that it performs according to its requirements. For example, the NavSens should be tested to demonstrate that they provide navigation measurements with appropriate accuracy, the Prop component executes correctly sized impulses, the ISL transmits/receives at the required data rate, and the FKAs generate a valid control solution. After individual testing of the CCs, they are connected together as the spacecraft is assembled and subsequently undergo integrated testing to verify that they function together and are capable of supporting the FECs. At this point, two steps can be carried out in parallel to save time: single-spacecraft CC to FEC integrated testing, and multi-spacecraft asynchronous FEC integrated testing. The former involves integrating the FECs (likely as flight units) into each spacecraft and verifying the interaction between the FECs and CCs to ensure that each spacecraft on its own functions correctly as a single unit. The latter involves integrating the FECs (likely as engineering units) into a testbed and verifying the multi-spacecraft FEC interaction loop asynchronously. This latter step is where the majority of PFF operations are verified and a high degree of confidence in the formation's system level performance is gained while still on the ground.

The in-space configuration phase is a sequence of checkouts and calibrations of the CCs and FECs once the formation is on-orbit. After deployment, the CCs on each spacecraft are brought online and checked out to ensure that they function as expected. Next, the FECs are checked out individually and brought online on each spacecraft so that the formation can begin to function collectively and establish an initially stable configuration. This is where the built-in operational flexibility will prove to be useful, as it is hoped that unexpected behavior or issues caused by the formation's idiosyncrasies once on orbit can be corrected by adjusting system parameters or slightly modifying the Concept of Operations (CONOPS). After this, the performance of the CCs may be calibrated/refined based on initial observations of the FEC performance to help smooth out operations. At this point, the formation can be fully established; once it has demonstrated that it is capable of PFF operations in a safe and autonomous manner, then the FECs themselves can be calibrated/tweaked to improve the formation's control accuracy and allow it to meet its stringent relative state requirements.

PHASE 1: FORMATION GROUND TESTING

With an overview of the testing methodology laid out in the previous section, the ways in which formation ground testing should be carried out are detailed in this section. These are not presented in a sequential order of tests, as that order will likely depend on mission-specific considerations – such as when different components are complete and ready to be tested. Instead, recommendations are provided for the appropriate testing infrastructure (physical setup of engineering hardware, flight hardware, and/or Ground Support Equipment (GSE)) and test categories that are used to verify and validate all the different components.[7]

Ground Testing Infrastructure

Ground testing infrastructure and support equipment that can be designed/acquired cheaply are able to accommodate the tests to be performed in each of the high-level testing phases defined in Figure 5. The individual testing of both the CCs and FECs necessitate infrastructure that is unique to each component under test, so there is no common set of infrastructure that can be discussed. Additionally, the infrastructure needed to perform integrated CC testing is not discussed since CC integrated testing is already well-established. For the remaining two high-level testing phases, the most efficient solution is to have only one testing setup for each testing phase that is tailored specifically to its unique needs. These are shown in Figure 6 with the Formation Flying Testbed (FFTB) setup being used to conduct "Multi-spacecraft Asynchronous FEC Integrated Testing" and the Single Flight Unit (SFU) setup being used to conduct "Single-spacecraft CC to FEC Integrated Testing". Another advantage of this approach is that having two separate setups that do not necessitate use of the same hardware allows both high level testing phases to occur in parallel.

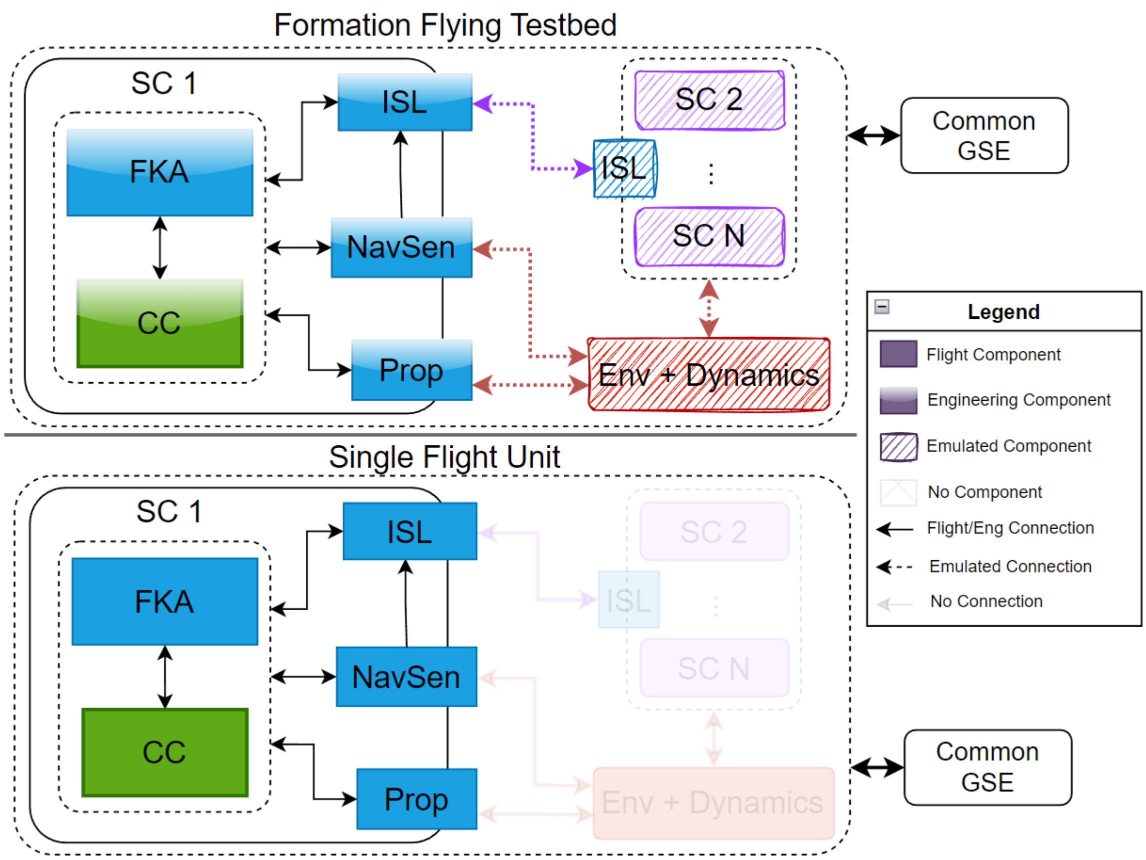


Figure 6. Two unique testing setups that can be used in parallel.

The goal of the FFTB setup is to allow the multi-spacecraft FEC dynamics loop to be asynchronously closed on the ground, thus enabling the team to evaluate a high-fidelity simulation of PFF operations using flight-like hardware/software with minimal testing infrastructure. Instead of creating a testbed to represent each spacecraft in the formation communicating together synchronously, one can simply create a testbed to represent one spacecraft using Engineering Development Unit (EDU) hardware components and take advantage of pre-recorded formation simulation data to emulate the presence of the remaining spacecraft in the formation. This FFTB setup consists of EDUs of all the FECs and CCs on a single spacecraft connected to each other in a flight-like manner – with an additional connection between the spacecraft under test and the other members of the formation through an emulated ISL – as well as simulated pre-recorded relative formation dynamics and messages coming through the emulated ISL in real-time during a test. In order to validate PFF operations for the whole formation, the relevant tests are performed on the testbed for one spacecraft at a time, with all data going to/from the emulated portion of the formation being recorded for playback to each subsequent member of the formation under test.

The SFU setup consists of a single fully integrated spacecraft for flight with supporting GSE. The goal of this setup is to allow the team to verify that each individual spacecraft (as built for flight) has CCs and FECs that correctly function individually and together – a prerequisite for enabling multiple spacecraft to execute PFF operations. This sort of testing could be performed on the testbed, but in order to save time and allow the parallelization of test phases, it is recommended to perform this testing directly on the assembled flight hardware. This recommendation for testing infrastructure has several advantages that were discussed previously. In addition, the choice to use engineering units for the FFTB setup allows it to be used throughout the entire integration and test campaign all the way into mission operations without needing to be modified or re-assembled. One consideration is that these test setups are only valid for a formation that is symmetrical – i.e. all the spacecraft in it are identical in terms of the functionality and interconnections of the CCs and FECs. If the formation is asymmetrical, then a separate test setup (for the testbed as well as the flight unit) corresponding to each unique member of the formation will be necessary.

Formation Flying Testbed

Since the FFTB is used for the majority of PFF operations validation on the ground, a detailed look at recommendations and considerations for its design will be discussed. Of course, the desired fidelity of a testbed is always a consideration in its design, and results in a trade-off between resources/money/time and desired level of fidelity. A recommendation cannot be made regarding a single best level of FFTB fidelity as it will vary for each PFF mission. Figure 7 shows examples of two possible FFTB configurations of differing fidelity, presented in terms of the multi-spacecraft FEC interaction loop from Figure 3. Both FFTB examples show that by recording data output over the ISL during one simulation, the same data can be played back during another simulation testing another spacecraft as many times as is necessary to asynchronously connect all spacecraft in the formation. Of course, this method is limited by the open-loop responses of the emulated rest-of-formation because the other spacecraft cannot respond to the actions of the spacecraft under test in real time. Despite this, the method is still valuable and should be capable of catching system-level idiosyncrasies before launch that would affect PFF operations.

In Figure 7, a connection is considered flight-like if it uses a similar/the same medium to transmit the data as would be used in flight. For example, the RF link between two ISL components would be considered flight-like if it was actually transmitting the data over RF (even if the correct signal attenuation that would occur from the representative distance between transmitter and receiver in-flight was not induced) but would not be considered flight-like if a data transmission cable was used to connect both ISL component. Software connected to the testbed logs navigation measurements going out to the rest of the formation and plays them back for the next spacecraft-under-test. Additionally, spoofed data about the space environment and relative dynamics is modelled and fed to the spacecraft-under-test to properly validate its behavior using conditions similar to those on orbit. Depending on the type of navigation sensors used for a particular mission, this could include generating the RF environment created by a GNSS constellation for a GNSS receiver, generating laser pulses for a laser ranger, or generating images for a computer vision/camera system.

The first main difference between the two example FFTBs is that the first uses a data cable to record/playback data over the ISL, whereas the second uses an extra ISL engineering unit to have both ISLs communicating in a flight-like manner over RF. The second main difference is that the first FFTB plays back the dynamics and environment from a pre-defined trajectory during a test, whereas the second FFTB is capable of taking the control solution sent to the Prop component and translating it into accelerations using a model of the Prop system's performance to actually close the feedback loop by propagating a new trajectory based on the maneuvers executed. Furthermore, the second example would have the additional capability to vary the link closure conditions of the ISL component based on the propagated trajectory of the spacecraft-under-test relative to the rest of the formation.

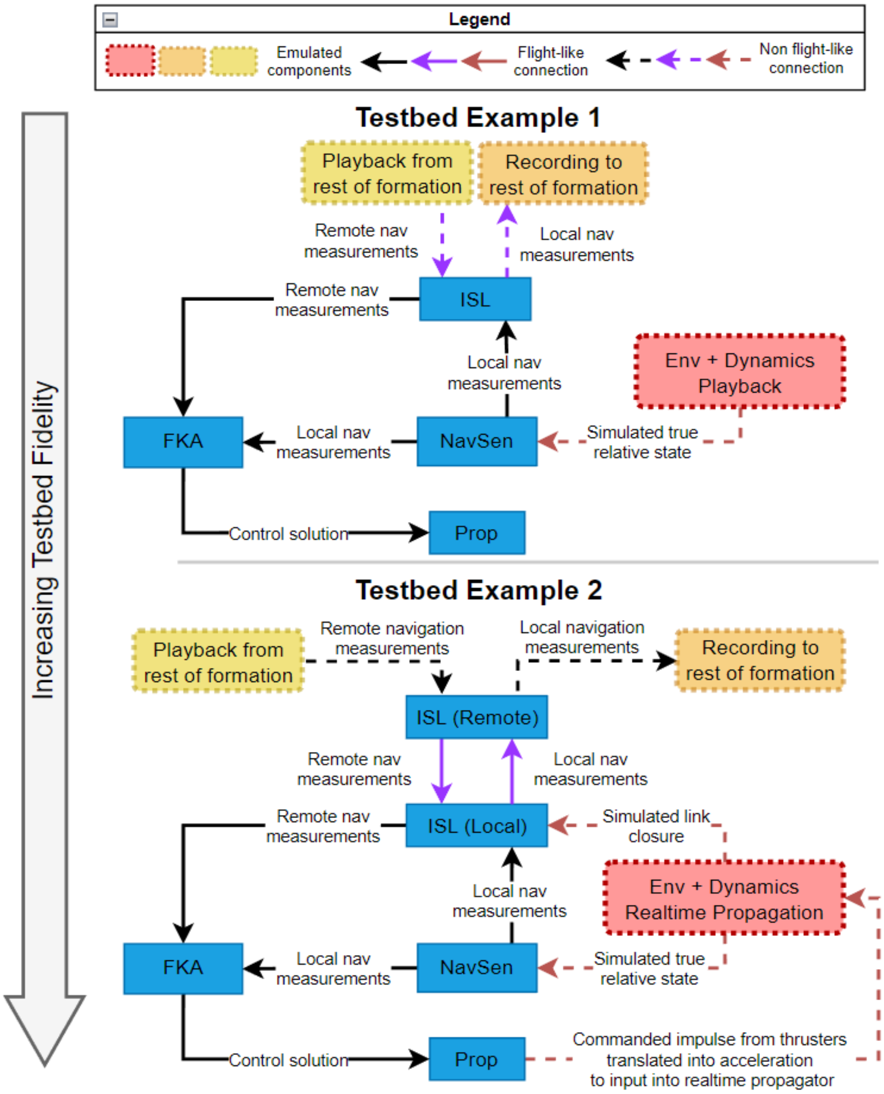


Figure 7. Examples of Formation Flying Testbeds that asynchronously reconstruct the multi-spacecraft FEC interaction loop using data recording/playback and emulation.

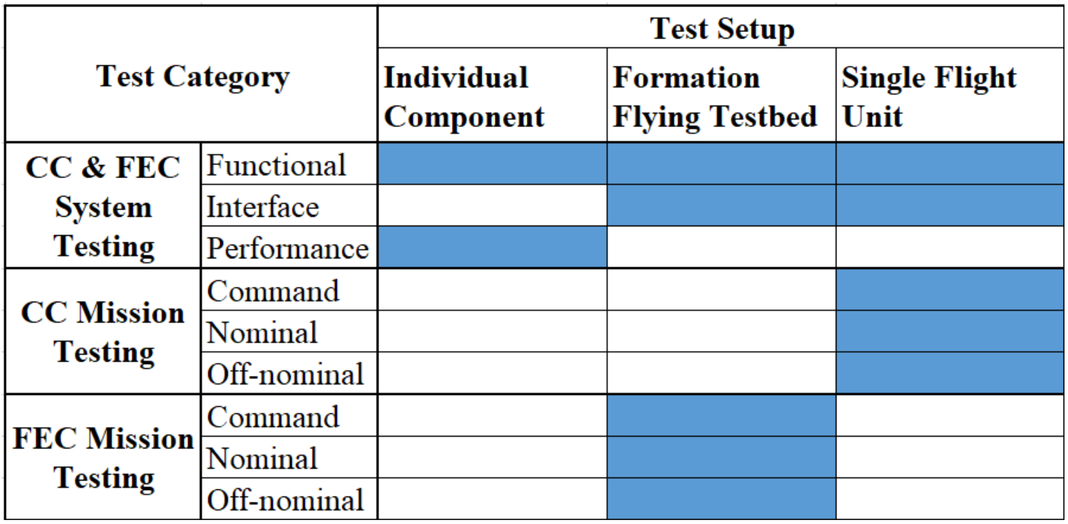
Ground Testing Categorization

Next, the categories of testing that are best suited to be performed on each test setup are detailed. Two general categories of tests to be used with this methodology are system testing and mission testing. System testing aims to verify that the component/system meets its requirements and is usually performed under conditions that are not necessarily flight-like where the component/system can be interacted with in a way that would not be possible during flight. Mission testing aims to validate that the component/system is able to operationally execute the mission it was designed for and should be performed under flight-like conditions where only interactions with the component/system that would be possible on-orbit are allowed.[8] Additionally, mission testing can be used to train an operations team on the spacecraft/formation while it is still on the ground. Each of these general categories is split into three specific categories, which are detailed in Table 2.

Table 2. Definitions of main test categories.[9]

General Category	Specific Category	Definition / What it includes
System Testing	**Functional Testing**	- **Definition:** Basic testing that verifies that the component meets all requirements - **Examples:** Includes checking that the behavior of the component is consistent with what is written in the requirements when certain inputs are prescribed to it
	Interface Testing	- **Definition**: Testing specifically verifying component correctly connects to and interfaces with adjacent components - **Examples:** Includes safe to mate tests, verifying that data packets transfer correctly, ensuring mechanical connections fit properly, etc.
	Comprehensive Performance Testing	- **Definition:** Testing that pushes component to the limits and wholistically characterizes the envelope of what it can do - **Examples:** Includes stress testing the component with low quality or almost out of range inputs to see how its performance changes, determine at which point the component no longer works as intended
Mission Testing	**Command Execution Testing**	- **Definition:** Testing that validates the formation's ability to be controlled from the ground - **Examples:** Includes sending every registered command to the formation and checking the resulting behavior
	Nominal Scenarios	- **Definition**: Testing that validates the system's ability to execute the desired mission operations - **Examples:** Includes executing CONOPS and analyzing data collected to see if mission objectives would have been met
	Off-nominal Scenarios	- **Definition:** Testing that validates the system's ability to go from off-nominal operations (unexpected or undefined in the CONOPS) and return to executing the desired mission through system fault response - **Examples:** Includes fault injection tests during nominal ops, as well as commissioning practice runs

Next, the recommended categories of tests for the CCs and FECs to be performed on each test setup are explained and shown in Figure 8. Each specific test category includes a series of tests that should either be performed automatically (such as software unit testing) or in an uninterrupted sequence over a period of time (such as Day-in-the-Life (DITL) testing). Test categories for the CCs and FECs assigned to each test setup are chosen to benefit from the unique testing capabilities of each test setup and to avoid redundancy in the total number of tests performed. In Figure 8, the "Individual Component" test setup is shown in addition to the FFTB and SFU, even though it is not a singular setup and instead an arbitrary one that is unique to each CC/FEC.



Test Category		Test Setup		
		Individual Component	Formation Flying Testbed	Single Flight Unit
CC & FEC System Testing	Functional	🟦	🟦	🟦
	Interface		🟦	🟦
	Performance	🟦		
CC Mission Testing	Command			🟦
	Nominal			🟦
	Off-nominal			🟦
FEC Mission Testing	Command		🟦	
	Nominal		🟦	
	Off-nominal		🟦	

Figure 8. Test categories to be performed on each test setup.

In terms of system testing, the CCs and FECs are considered identical. At the individual component level, both functional and comprehensive performance testing should be carried out on the CCs and FECs to first ensure that they each work, as well as stress test them to figure out what their operational envelopes are. Next, once the CCs and FECs are connected together in the FFTB and SFU, there should be another round of functional testing to ensure that the components still work, as well as a round of interface testing on each setup to ensure that the connections between the components function as expected.[10]

In terms of mission testing, CCs and FECs should be tested on separate setups. First, no mission testing can occur at the individual component level. The FEC mission testing should occur on the FFTB setup, as it is specifically designed to enable the FECs to function together and replicate PFF operations through asynchronous emulation/playback. This FEC mission testing should include nominal mission scenarios to confirm that PFF operations are possible, off-nominal mission scenarios to confirm that PFF operations are resilient to failures, and command execution tests to confirm that every necessary instruction given to the formation from the ground produces the appropriate response. The FEC mission testing is not performed on the SFU because the FECs are not able to work together without emulation of the rest of the formation on the ground. Notwithstanding, the CC mission testing should be carried out on the SFU setup instead of on the FFTB setup (and not on both) since the CCs are more likely to function properly out of the box (since they are often bought as COTS components) and need to be tested on the flight hardware to ensure that each spacecraft is able to support its own FECs.

PHASE 2: FORMATION IN-SPACE CONFIGURATION

In order to account for any oversights in the ground testing, the second phase of this testing methodology is designed to leverage operational flexibility that is built into a PFF mission to perform in-space configuration of the formation and allow it to meet its mission requirements.

Operational Flexibility and Multi-Spacecraft Redundancy

Operational flexibility, as it relates to this testing methodology, is defined as the ability for a spacecraft formation to modify the behavior of its CCs and FECs in flight to affect the formation's system-level performance. A PFF mission's ability to meet its system-level performance requirements depends on the coordination and actuation of all spacecraft in the formation, which means that one spacecraft can make up for a drop in performance/FEC failure on another spacecraft under certain circumstances. This result is only possible if there is redundancy in the FECs across the formation. In contrast, this idea has very limited applicability to monolithic spacecraft, since redundant CCs are usually not included for most missions, and there is no "second spacecraft" that could help in the event of a CC failure. The design redundancy of each FEC – number of failures that can occur while still enabling PFF operations – is related to how the underlying technology in each FEC works and is shown in Table 3. This table assumes that the formation is symmetric in terms of FECs – i.e. that the FECs layout on each spacecraft is identical. If the formation is asymmetric then there will be less redundancy.

Table 3. Definitions of FEC redundancy for spacecraft formations.

FEC	Redundancy for N-SC formation	Rationale
ISL	0	All N spacecraft need a functioning ISL to communicate with the rest of the formation, so there is no redundancy if PFF operations for the specific mission depends on the participation of all spacecraft.
NavSen	0 to N-1	Depends on type of Navigation Sensors used. For example, differential GNSS has a redundancy of zero but laser ranging or cameras/computer vision have higher redundancy.
Prop	1	Only N-1 spacecraft with a functioning Prop system are strictly required for formation control.
FKA	N-1	Only 1 spacecraft with functioning FKAs is strictly required for relative navigation, guidance, and control solution computation.

The redundancy available during early phases of a PFF mission's design should be supplemented with reconfigurability of the CONOPS and modification of the performance of mission component on each spacecraft once in-flight to achieve true operational flexibility. CONOPS reconfigurability can be achieved by allowing in-flight modification of operations sequences and taking advantage of the redundant FECs spread across the formation to change the participatory role of any spacecraft in the formation. On most spacecraft, it is possible to re-flash the entire flight software executable from the ground if needed but this is often a dangerous and complicated procedure that is reserved for emergencies. Instead, the reconfigurability is recommended to be built into the flight software from the beginning, by defining operations sequences and FEC performance parameters in an abstracted way so that they can be reconfigured via ground commands. If possible, it is also recommended to have re-flashable flight software on the subsystems representing the FECs in case a particular bottleneck arises with that subsystem. While the specifics of what parameters for what component should be reconfigurable will differ from mission to mission, key parameters that should be made reconfigurable for the greatest amount of operational flexibility on orbit are detailed in Table 4.

Table 4. Examples of key parameters for on-orbit configuration.

Category	Component	Parameters
CCs	Avionics + Command & Data Handling	- Length of watchdog timers for transitions to safe modes or flight software resets
	Attitude Determination & Control	- Attitude control gains and settling times - Modifiable pointing profile
FECs	Navigation Sensors	- Exposure/gain settings to vary signal-to-noise ratio
	Inter-Sat Link	- Transmit and receive power thresholds - Antenna switching/neighbor discovery sequence - Length of RX and TX queues and resending of failed packets
	Relative Propulsion	- Propellant injection pressures and temperatures - Multi-valve firing strategy - Max and min maneuver magnitudes
	Formation-Keeping Algorithms	- Navigation filter tuning - Guidance algorithm used - Control law used - Modification of mission modes - Fault detection thresholds for incoming telemetry[11] - Fault recovery sequences - Modification of formation configuration through relative orbit changes or leader-follower/chief-deputy architecture changes

While most of the on-orbit configuration will focus on the FECs, it is important to include on-orbit configuration capability for CCs as well. By having a broad range of editable parameters, operators will be better equipped to easily handle any idiosyncrasies emanating from PFF operations that are encountered on-orbit. Additionally, the degree or amount of operational flexibility built into the formation's design and the flight software should largely be inversely proportional to the expected amount of ground testing that will be carried out given the mission's budget, timeframe, and testing resources on hand. If it is determined that certain FECs will not undergo the most thorough testing on the FFTB, then the amount of flexibility built into the software for that component should reflect this.

In-Space Configuration Sequence

The plan for achieving operational flexibility through in-space configuration is divided into two steps: component commissioning/functional checkouts and component calibration. Figure 8 shows the order in which the sequence takes place: CC checkout, then FEC checkout, then CC calibration, and finally a cyclic process of FEC calibration. The discussion below focuses on PFF missions that involve proximity operations, specifically accounting for and attempting to minimize the additional inter-satellite collision risk generated when the formation is brought into its operational relative orbit before the multi-spacecraft FEC interaction loop is fully validated. For PFF missions that don't involve proximity operations, certain precautions regarding minimum inter-satellite separation during commissioning can be disregarded.

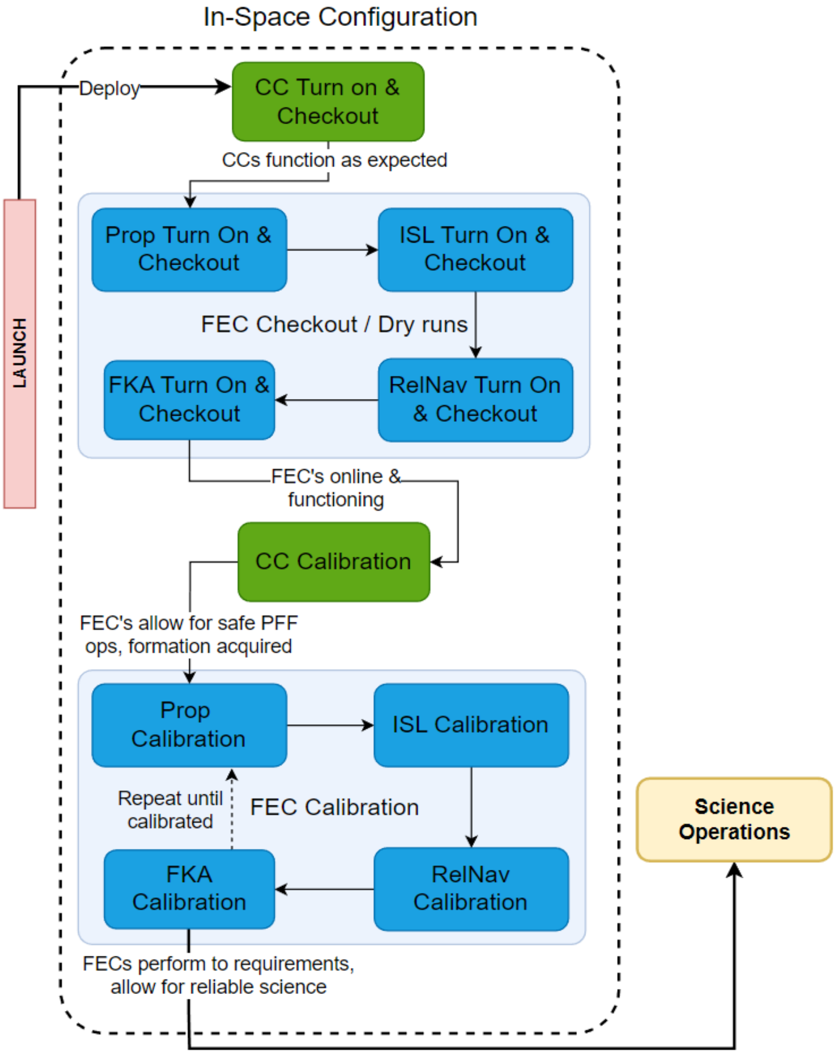


Figure 9. Detailed in-space configuration sequence.

Following the checkout of all CCs and the verification that they work as expected on each spacecraft in the formation, the FECs can be turned on and checked out one by one in a specific order.[12] The relative propulsion FEC on each spacecraft must be checked out first. This will allow the ground to plan maneuvers for formation acquisition using the best ground calculated orbit solution. After this maneuver, all spacecraft should be in a small enough relative orbit such that the ISLs are in range of each other and can be checked out next, but large enough to maintain enough passive safety margin that the formation can be fully controlled and maintained from the ground. Next, the NavSens on each spacecraft should be checked out, and their navigation data post-processed on the ground to verify that they are working correctly. Finally, the FKAs can be checked out as they now have all the data necessary to navigate, guide, and control the formation autonomously. However, it is vital that the ground remains in the control loop during this entire process, as operators verify that all CCs and FECs function correctly.

At this point, it should be relatively clear if any additional tweaks should be made to the CCs so that they can better support the functioning of the FECs across the formation. For example, if it is observed that the attitude control response on a spacecraft is too sluggish to keep up with pointing requirements, causing temporary ISL outages, then the Attitude Determination & Control CC should have its control gains modified appropriately. Finally, at this point, with ground confidence in the CCs on each spacecraft as well as the basic functioning of FECs on each spacecraft, the formation can be maneuvered into its operational (closest) relative orbit for further calibration of its FECs. FEC calibration will proceed iteratively in the same order as with FEC checkouts, so that small changes to system parameters shown in Table 4 can be made and the resulting change in system performance observed without endangering the formation's safety. These changes could include tweaking the FKAs navigation filters, control gains, adjusting the ISL's link closure procedure, adjusting nozzle firing procedure on the Prop system, or increasing the sensitivity of the RelNav sensors. It could take multiple iterations of FEC calibration on all spacecraft before the formation is capable of meeting its stringent relative geometry requirements and can proceed with science/commercial operations.

CONCLUSION

The rising popularity of formation flying mission architectures warrants significant investigation into the testing methodology employed for such missions. This paper provides a comprehensive and generally applicable two-phase testing methodology for adequately verifying the system-level performance of PFF missions within the constraints of limited resources. During the ground testing phase, the multi-spacecraft FEC interaction loop can be replicated asynchronously, offering a high-fidelity simulation that only requires one FFTB setup. Then, multi-spacecraft redundancy and built-in operational flexibility is leveraged to precisely configure the formation in space to make up for any pitfalls of the asynchronous ground testing. This methodology aims to make maximal use of the advantages offered by each environment and avoid redundant tests, while also ensuring that the formation is configured optimally and safely to achieve the desired system-level performance.

For PFF missions with greater budgets and access to more sophisticated ground testing infrastructure, this testing methodology could be expanded upon as to more fully replicate end-to-end performance on the ground. This could be done by using an FFTB composed of engineering units representing multiple/all spacecraft in the formation to allow for the multi-spacecraft FEC interaction loop to be closed synchronously. While these strategies are currently resource intensive, there is potential for improved PFF testing methodology as PFF missions become more common and this type of testing becomes more standardized.

The team responsible for creating this generalized methodology is currently using it to develop a detailed testing plan applied to the VISORS mission. The current schedule forecasts the ground testing phase to last for about a year throughout 2023 and into early 2024. The launch is planned for mid-2024, with the in-space configuration phase lasting between 1-2 months. During this process, the team will keep track of any modifications or adaptions made to the general testing methodology for future revisions and clarifications.

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