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BurstCube: Behind the Scenes of a Do-No-Harm I&T Production

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ABSTRACT

BurstCube is one of the most recent 6-U CubeSats built and developed by NASA Goddard Spaceflight Center (GSFC). As an astrophysics mission, BurstCube will be a rapid detection alert end-to-end mission system for short astrophysical gamma-ray bursts with the aim of increasing the chance of coincident detection of gamma-ray bursts. In addition, the mission is intended to augment the current fleet of gamma-ray astronomy satellites. The payload instrument includes 4 scintillator heads read out by arrays of silicon photomultipliers which will detect short astrophysical gamma-ray bursts. BurstCube provides a high field of view previously unavailable to larger missions and is intended to provide rapid alerts for follow up observations with other assets, increasing the chance of a coincident detection of an event.

From the design to the integration and test phases, the project aimed to provide realistic test plans and stimulus to help verify and validate reachable areas of this innovative payload/instrument system and even spacecraft performance. Typical robust integration and test phases for space missions are unaligned with the budget and risk postures of small satellite or CubeSat missions, often designated as "Do No Harm" projects where the primary requirement is not harming the host platform or other payloads. Despite this status, CubeSats are complex missions that mix new and prior technologies. Integration and test for these missions requires responsible engineering, creative collaboration, and careful observation to deliver a reliable mission. This paper will provide an overview of the payload instrument and mission system, areas of injected automation (current and future), environmental testing results, and lessons learned during the integration and test phase.

INTRODUCTION

Small satellites have been part of the NASA fleet of scientific missions since Explorer 1 in 1958, the first scientific payload satellite launched by NASA. At 13.9 kg, Explorer 1 meets the modern small satellite mass requirement[1] (by convention Explorer 1 meets the classification of a microsatellite, 10-100 kg[2]). NASA achieves its science goals through all sizes of spacecraft,

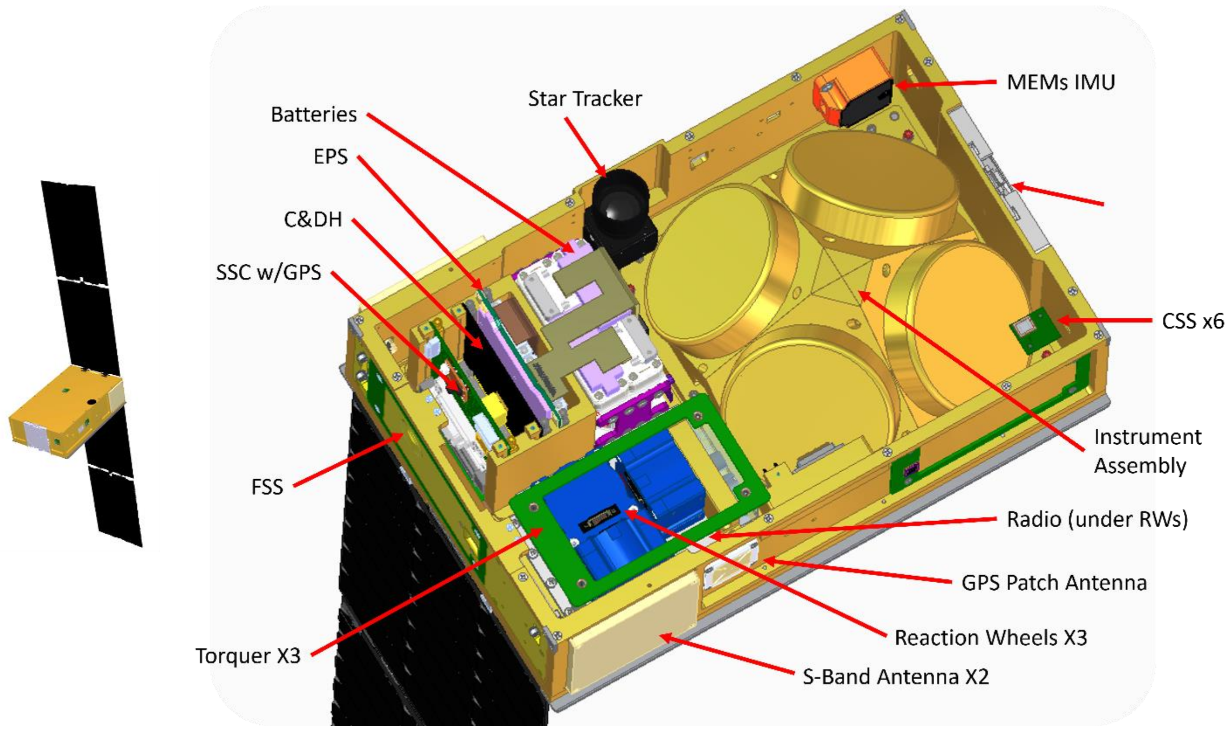

Figure 1: Side Cut out of Burstcube showing components in relation to the instrument payload

from the tennis court sized James Webb Space Telescope to CubeSats.

CubeSats, with their specific form factor and ride share abilities, have enabled new technologies, allowing science to be done on a smaller mission scale. Combined with the shared wealth of knowledge from the small satellite industry and community, these missions are becoming miniature components in other missions, such as Mars Cube One (MARCO) was used to help successfully land the InSight project on Mars[3], or as a part of a greater science fleet, such as with the Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellations of Smallsats (TROPICS) and IceCube[4,5,].

IceCube was one of many missions from the Small Sat Project Office (SSPO) at NASA Goddard Space Flight Center (GSFC). NASA GSFC is the agency's premiere space flight complex and has a focus on heliophysics, earth science, astrophysics, and planetary science. The SSPO at NASA GSFC has been developing CubeSat missions for technology demonstration (the Dellingr satellite[6)], Astrophysics (HaloSat[7]), Earth Science (IceCube[5]), and heliophysics (CeREs[8]). After many successes with these and other missions, the SSPO has been awarded several different missions to be built similarly to Dellingr, harnessing a common spacecraft bus and ACS architecture across several different spacecraft. While the science done by each varies greatly, the missions can benefit from similar hardware and configurations.

BurstCube Mission Overview

BurstCube is a 6U (10 x 20 x 30 cm) astrophysics CubeSat built in-house at NASA GSFC and currently undergoing commissioning in low Earth orbit (LEO). This CubeSat is adding an asset to the NASA fleet of gamma-ray astronomy spacecraft and instruments. Figure 1 shows a cutaway of the BurstCube spacecraft displaying internal components. The mission will enhance the search for electromagnetic counterparts to gravitational waves (GWs) by increasing coverage of the transient gamma-ray sky. With a view of the full unocculted sky and sensitive to the 50 keV – 1 MeV energy range, the spacecraft will search for short gamma-ray bursts (sGRBs), which last <2-3 s in duration but are among the most powerful explosions in the universe. Short GRBs are produced in conjunction with GWs from binary neutron star (BNS) and neutron star–black hole (NSBH) mergers; a joint, "multi-messenger" detection between BurstCube and on-ground GW observatories would provide crucial insight into fundamental physics, cosmology, element formation, GRB physics, black hole formation, and the neutron star equation of state.

While the mission expects to detect sGRBs at a rate of ~20/year, the science instrument will also trigger on other interesting transient high-energy phenomena such as long GRBs, various galactic sources (magnetar flares, accreting binaries), and local sources (solar flares, terrestrial gamma-ray flashes). Within minutes of detecting a transient, BurstCube will generate a science alert that will be :

1) Autonomously transmitted to ground via the Tracking and Data Relay Satellite System (TDRSS)

2) Processed on-ground for preliminary source localization and characterization

3) Disseminated via the General Coordinates Network (GCN) to the worldwide astronomical community for multi-wavelength follow-up.

All BurstCube science data will be publicly available via NASA's High Energy Astrophysics Science Archive Research Center (HEASARC) database.

BurstCube was integrated with its 12U Nanoracks CubeSat deployer on Dec. 14, 2024. It launched to the International Space Station on Mar. 21, 2024 aboard a Falcon 9 rocket as a rideshare on SpaceX's Commercial Resupply Services (CRS)-30 mission. The spacecraft was deployed from the ISS into Low Earth Orbit (LEO) on Apr. 18, 2024, and the BurstCube team is currently undergoing spacecraft and instrument commissioning.

System Assembly and Integration and Test

This work will be concerned primarily with Phase D of the NASA Implementation Phase program for Burstcube. These phases are listed in table 1.

Table 1: NASA Implementation Phase Program[9]

Phase	Description
A	Concept and technology development studies
B	Preliminary design and technology completion
C	Final design and fabrication
D	System assembly, integration and test, and launch
E	Operations and sustainment
F	Closeout

Phase D begins after the system integration review and is completed after flight readiness review. The main activities are assembly, integration, verification, and validation of the system before systems environmental testing[9]. This phase also serves as the initial training for operating personal and for contingency planning.

For Burstcube, this phase began in the spring of 2022. The spacecraft was delivered in December 2023 and launched in March 2024. The scope here will focus on the time before delivery. Integration covers the instrument payload, the satellite structure, the flight software (FSW), the electronics, and the attitude control system. The environmental tests conducted are thermal vacuum (TVAC) testing, magnetic calibration, end-to-end communications testing, and GPS testing.

BURSTCUBE SPACECRAFT DESCRIPTION

The spacecraft is a 3-axis stabilized, CubeSat Mission with one instrument for science. The spacecraft, shown figure 1 and figure 2, contains an aluminum alloy baseplate structure to mount most of the internal components. There is only one closeout panel located on the top of the spacecraft. Figure 5 shows the spacecraft system architecture.

Figure 2: Internal view of the spacecraft prior to close out and solar panel integration (Photo credit: NASA/Jeanette Kazmierczak)

Power system

Power is generated through deployable solar panels and stored in a battery with an approximately 90 Whr capacity. The solar arrays are deployed by a memory shape alloy rotary release mechanism. Special consideration was given to allow the spacecraft to charge its two batteries (90 Whr combined capacity) while the arrays are stowed. The arrays are double 6U panels (24U total area), each with 6 strings that each provide 12V. Each string has 8 2.4 V solar cells, with 450mA each. The arrays unfold to look like wings as shown in figure 1. The inhibit system for the bus was designed to the launch provider (Voyager Space- Nanoracks). A passive thermal design utilizes the baseplate and panels as a heatsink and radiator.

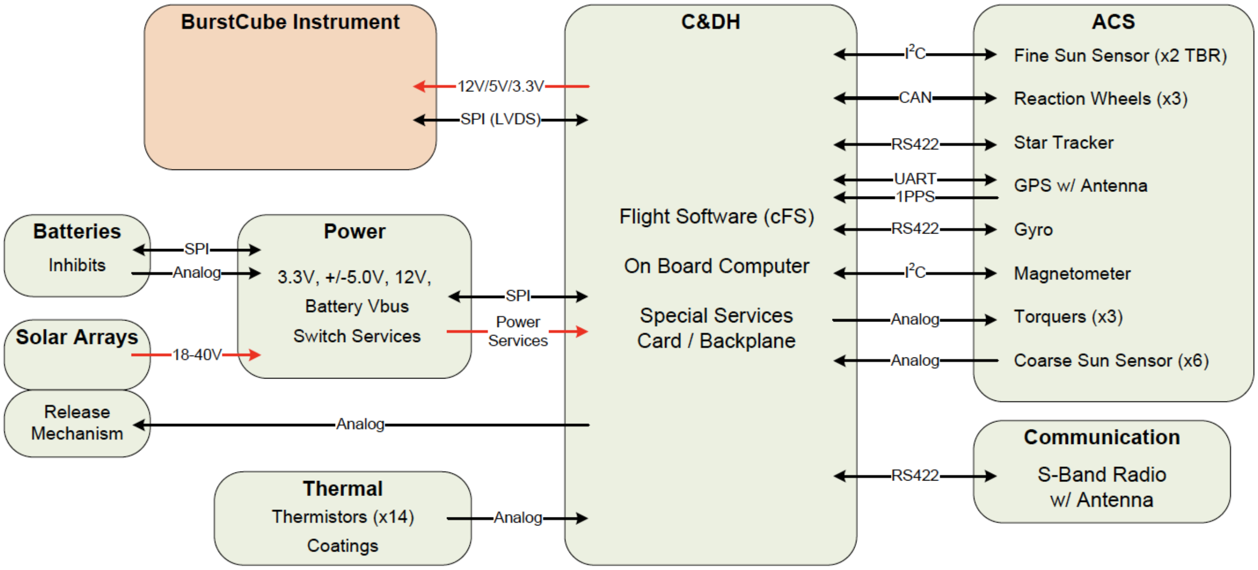

Figure 3: BurstCube system architecture diagram

Communication

The communication system is comprised of the S-Band Radio and two patch antennas with a downlink/uplink capability at a 2.0 Mbps/64 kbps data rate. The S-Band Radio is capable of communicating with the Near Space Network (NSN) Direct to Earth (DTE) and Space Relay (SR) via the Tracking and Data Relay Satellite System (TDRSS).

Attitude Determination and Control System

To achieve the mission objectives of BurstCube, the Attitude Determination Control System (ADCS) uses a suite of sensors and actuators to determine the spacecrafts spatial orientation and maintain required pointing for the science instruments. The suite of actuators used for attitude determination includes a Sensonor STIM300 Inertial Measurement Unit (IMU) for angular rate measurements, two GOMSpace NanoSense Fine Sun Sensors (FSS) for precise Sun vector knowledge, a GOMSpace NanoSense M315 magnetometer (MAG) for measuring Earth's magnetic field, a AAC Hyperion Star Tracker (ST) for inertial attitude quaternions, and six custom coarse Sun sensors based on the Hamamatsu S5106 Si PIN photodiode for coarse Sun vector knowledge. The primary actuators are three CubeSpace Medium Reaction Wheels (WHL) for attitude pointing and three custom torquer coils for momentum management.

The spacecraft uses three attitude controllers for the various mission modes. Along with a typical magnetic field time derivative (BDOT) controler and SunSafe controller[10], the primary science mode uses a three-axis stabilized controller with the option of running concurrent momentum management. The science controller uses a TRIAD algorithm to determine desired pointing direction, where a desired primary and secondary vector provide a target reference frame. For nominal science operations the ram direction is primary, and the Sun vector is secondary in forming the desired reference frame. Momentum management is run concurrently with the SunSafe and Science controllers to maintain the momentum of the WHLs within desired capacity.

Flight Software

The on-board computer, running the cFE/cFS[12] Core Flight Executive software on top of Linux, is responsible for all command and data handling including guidance, navigation and control algorithms and software applications. The Flight Software (FSW) architecture was simplified due to the design of the mission. A single board computer was to be used for all custom developed software, controlling both critical and non-critical functions. This was a NASA GSFC developed Mini-Z processor from Code 587[11]. This processor provided a fault-tolerant design and software packages supporting Linux and the core Flight System (cFS) FSW out of the box. The Zynq chip included both a dual core ARM processor and FPGA space to be configured as needed. Peripheral I/O chips were added to the custom backplane and special services cards as needed to support communications to all the components.

The NASA Operational Simulator for Small Satellites (NOS3)[13,14,15] was leveraged to provide a means to perform development and testing with limited resources in the lab for testing. Our mission repository was

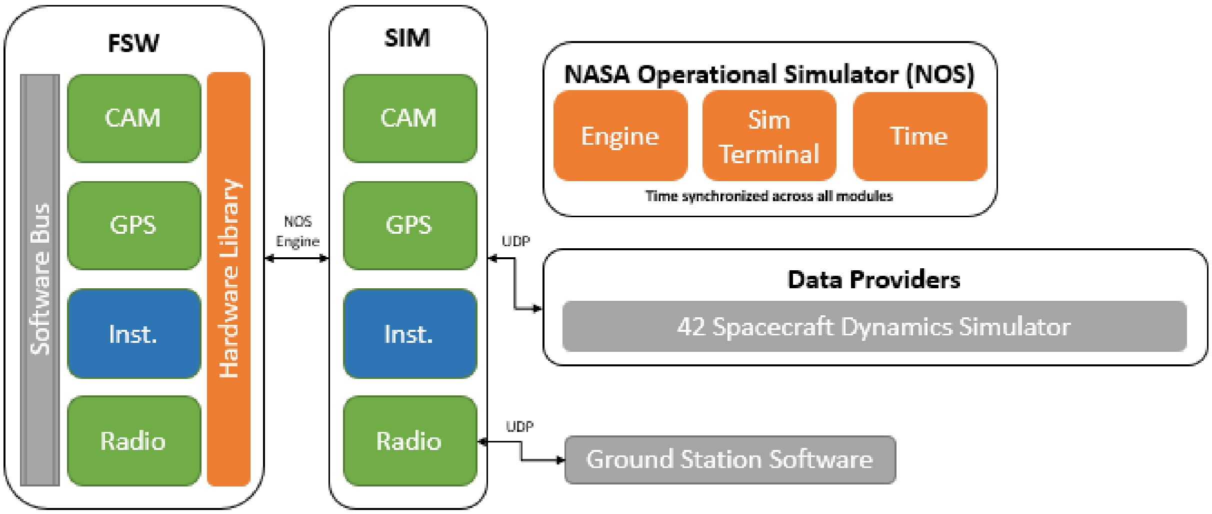

Figure 4: NOS3 architecture implemented with FSW

configured to cross compile for the NOS3 environment as well as use the custom flight toolchain all with a single build command to ensure that any additional warnings or errors found with the other could be addressed at once before committing code. The hardware library included with NOS3 makes this cross-compilation possible to provide the FSW applications with the same APIs no matter the desired platform. The NOS3 architecture as implemented for the FSW is shown in figure 4.

A majority of the open source cFS applications were included in the design: Command Ingest (CI), Data Storage (DS), Limit Checker (LC), File Manager (FM), Stored Commands (SC), Scheduler (SCH), and Telemetry Output (TO) were the major ones. Each physical component included in the mission followed the now open-sourced NOS3[13,15] design of having an application, simulation, and checkout application for standalone testing. While developing both flight software and a simulation added to the overall workload, having the simulation platform to system level testing, and even drive conversations between the separate parties doing development to submit questions in clarification with the vendors early in the design process before hardware was even in hand.

The ADCS components leveraged a Data Ingest (DI) and Data Output (DO) flow where sensors provided data at a rate of 10Hz to the ADCS algorithms and actuators were driven at the same rate after processing what should be changed. The major development of these algorithms occurred directing within NASA GSFC's 42 mostly harmless spacecraft simulator. This same code was ingested by the flight software team and able to be tested in the NOS3 environment to ensure the same results were obtainable. While NOS3 testing was previously limited to real-time and ran slower due to the number of components, newer versions are tackling that to further improve efficiencies.

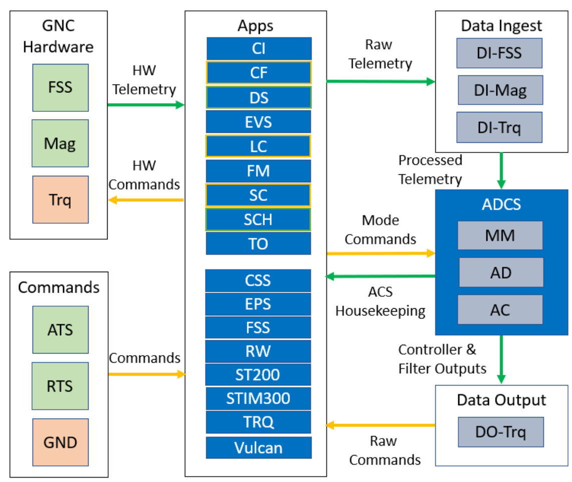

Figure 5: FSW architecture diagram

A shared mission spreadsheet was maintained by the FSW team to provide a single point of reference between the various subsystems and systems engineers. This spreadsheet contained a short summary of the concept of operations, data budget, power budget, as well as Fault Detection and Correction (FDC). While a simple acronym, FDC in cFS involves multiple applications and table applications to be configured in concert with one another. The LC application as watch points of telemetry it monitors, and action points set on those values before it commands the SC application to run a relative time sequence (RTS). Extra care must be taken to ensure that these also don't fire continuously and are limited or rather reset to fire again after a set timeout as part of the

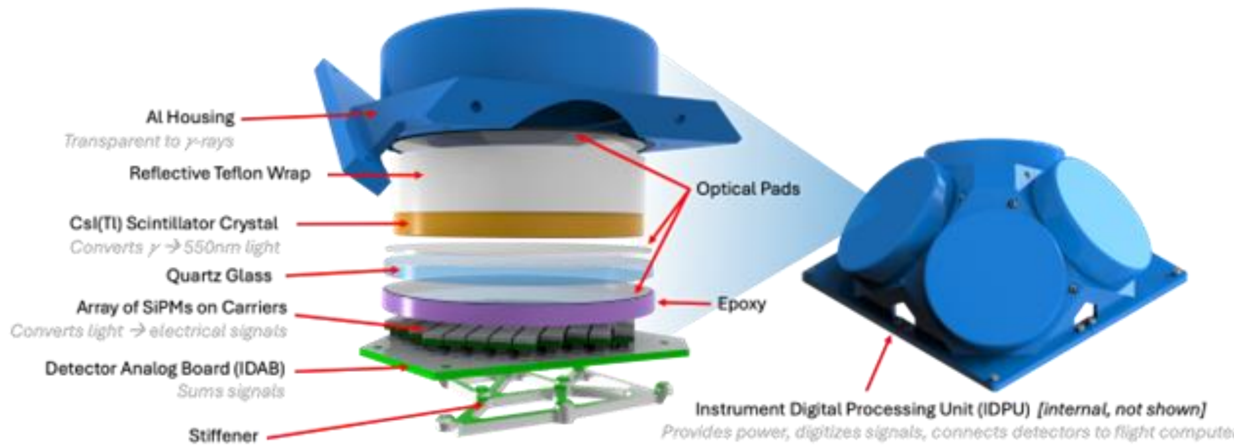

Figure 6: BursCube science instrument and internal components

process. The FSW architecture diagram is shown in Figure 5.

The instrument payload

The BurstCube science instrument is approximately 4U (20 x 20 x 10 cm) and consists of four 1U Single-Quarter Detectors (SQDs) assembled in a pyramidal shape, each pointed 45 degrees away from zenith. A burst's relative brightness (photon rates) seen by the different detectors allows the science team to approximate the location of the transient. Each SQD contains a thallium-doped cesium-iodide (CsI(Tl)) scintillator crystal, 9 cm diameter x 1.9 cm thick, optically coupled to an array of 116 low-power silicon photomultipliers (SiPMs) biased to ~54 V, as shown in Fig. 6.

A gamma-ray photon passing through a detector's aluminum housing will enter the CsI crystal, which produces visible scintillation light of ~550 nm. This visible light then passes through a transparent quartz window and is read out by the SiPMs as electrical signals. The SiPMs are mounted to the SQD's Instrument Detector Analog Board (IDAB), which sums the amplified SiPM signals to produce a single analog output signal for the individual SQD. A single IDAB signal or "hit" indicates a single photon interaction, with the signal amplitude proportional to the incoming photon energy. The four total IDABs are connected to a central, octagonal-shaped Instrument Digital Processing Unit (IDPU) board at the base of the instrument; the IDPU routes power to the four SQDs, digitizes the IDAB signals, and communicates with the spacecraft's flight computer – i.e., the onboard command and data handling (C&DH) unit. The detectors and IDPU sit atop the instrument interface plate, which is secured to the spacecraft baseplate (figure 7).

BurstCube is meant to complement larger space-based observatories such as Fermi and Swift for a fraction of the cost, but the mission is unique in that it is a fully capable GRB instrument packaged into the size of a shoebox. The instrument takes advantage of low-power, low-mass SiPMs rather than the much larger photomultiplier vacuum tubes used by older missions.

The instrument's shape and multiple detector heads provide localization capabilities, which in turn drive the science need for ACS pointing capability and/or knowledge, in contrast with GRB CubeSats that have only 1-2 detector heads and cannot localize transients. BurstCube's detector performance is comparable to that of larger instruments: the effective area of an SQD is ~70% that of a single sodium-iodide detector on the Fermi Gamma-ray Burst Monitor (GBM) instrument at 100 keV. Since BurstCube was additionally designed to provide rapid science alerts at any given time, it is one of the first CubeSats to take advantage of the TDRS network, if not the first. Larger instruments such as Fermi-GBM have significantly larger budgets and more personnel support, making BurstCube a unique challenge in achieving full GRB science capabilities with limited resources.

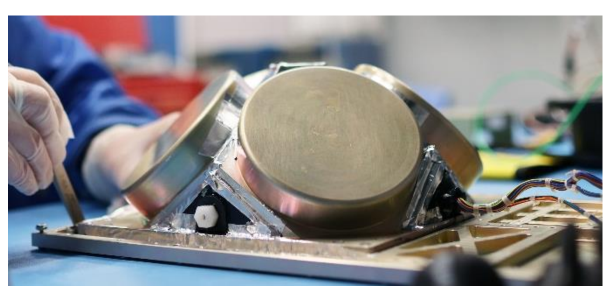

Figure 7: BurstCube instrument, detector heads (gold) visible on the mounting plate during integration (Photo credit: NASA/Sophia Roberts)

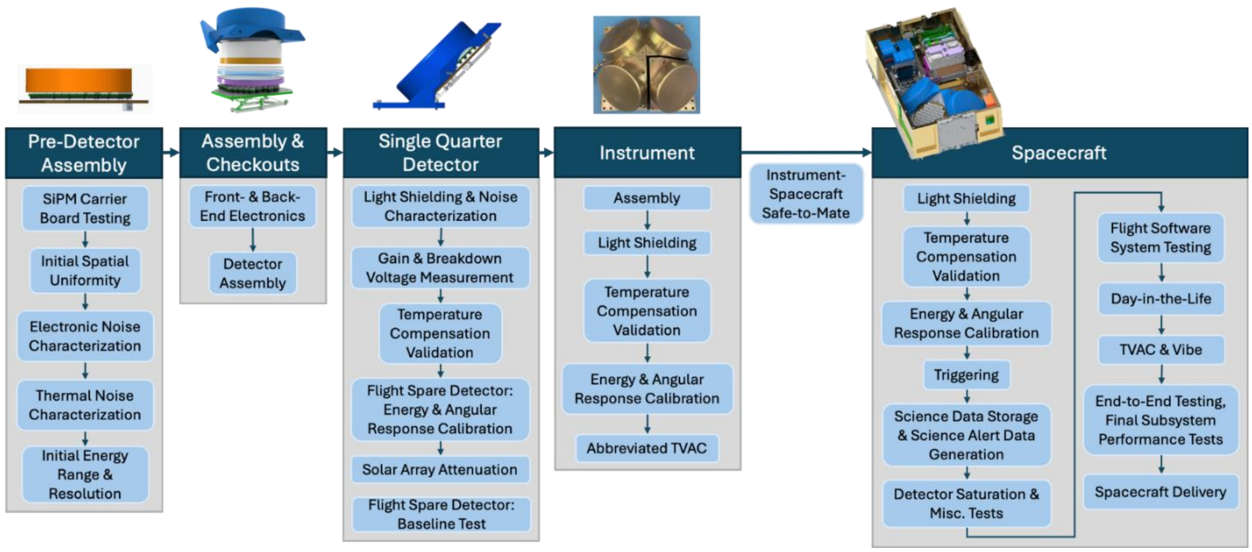

Figure 8: Instrument testing at each level of assembly and integration.

INSTRUMENT ASSEMBLY, INTEGRATION, AND TESTING

An overview of the instrument assembly, integration, and test (AI&T) process is outlined in Fig. 8. Due to some hardware swaps that were needed after instrument assembly and/or instrument integration with the spacecraft, some activities were performed multiple times outside of the order shown. The instrument's functionality was assessed before and after all major integrated activities such as environmental testing, with more comprehensive performance tests performed using gamma-radiation sources where reasonable. The following subsections describe select instrument I&T activities in further detail.

Light Shielding

Any stray light entering the instrument can produce spikes in the SiPM signals that look like gamma-ray photons, so adequately shielding the instrument's internal electronics from external light is critical. After the instrument was assembled from the four SQDs, staking and conductive tape were respectively applied to the cracks between the detector heads and along the instrument base. The instrument's "light-tightness" was checked at multiple points throughout I&T – in particular, after hardware de-/re-integrations. The team used both lasers and the fine sun sensors' collimated tungsten halogen light source to probe the instrument's externally sealed areas and screws, watching the live event-rate telemetry for repeatable spikes (figure. 9) as each light source was moved slowly across these areas. The same test was initially conducted with the lab lights turned off vs. on for increased contrast, but this appeared to have negligible impact. Any areas with observed light leaks were covered with additional staking or tape.

Instrument Calibration

Instrument energy and angular-response calibrations were performed at different stages of assembly and integration to characterize instrument performance as well as photon scattering around the instrument. The calibrations allow the science team to validate or adjust simulations of the detector response, which is used to localize GRBs and produce energy spectra. In addition, the datasets help verify that instrument performance remains comparable across AI&T.

Two observatory-level calibration campaigns were carried out with as many spacecraft components integrated as possible. As shown in Fig. 8, the spacecraft was secured onto a rotating rack that allowed for 360-degree pointing, and one of six radioactive sources peaking at different gamma energies (137Cs, 57Co, 60Co, 109Cd, 241Am, 22Na) was placed in a source holder on an opposing table. For setup repeatability, a

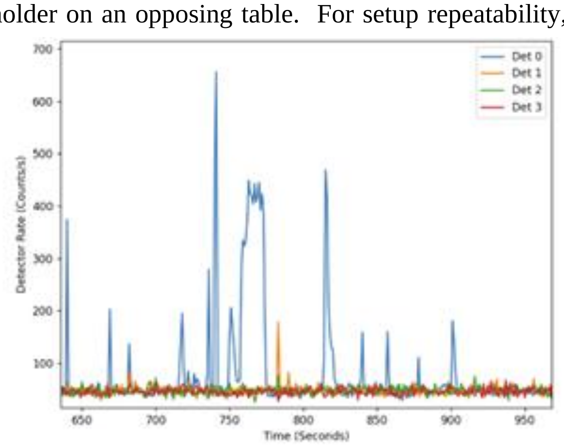

Figure 9: Light-tightness test revealing a light leak near detector (SQD) 0.

Figure 10 (a): Sample Calibration Setup with radiation source holder (left, gray hoop) and spacecraft rotated upside down(right)

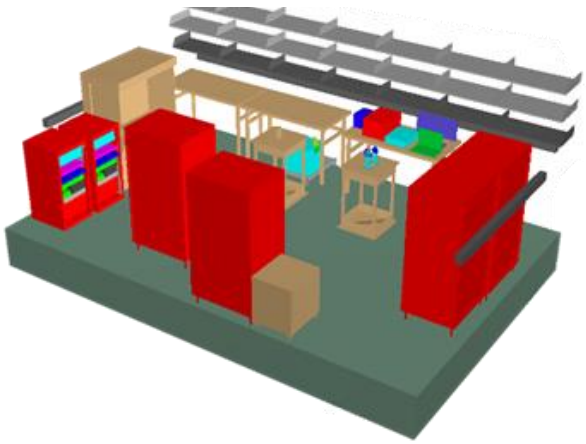

Figure 10 (b): Mass model of calibration lab for simulations

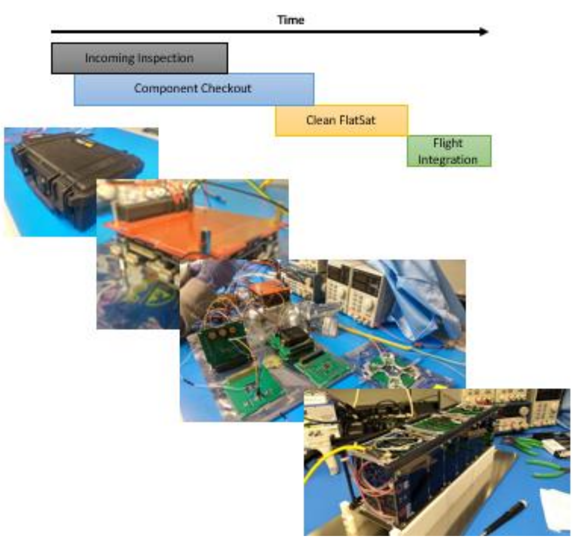

Figure 11: Timeline for component checkout

laser distance measure was used to verify that the calibration and laboratory furniture remained within +/- 1 cm of their appropriate positions. Daily calibration activities were driven by a pre-determined schedule of spacecraft angles vs. radiation sources vs. distance between source and spacecraft. Both the integrated spacecraft and the calibration laboratory setup (Fig. 10) were modeled to accurately simulate the gamma-ray photon interactions. Because the size and fragility of the solar arrays prevent them from being integrated and deployed for calibration activities, the solar array attenuation effects were tested separately.

Triggering

To detect bursts for autonomous alerts, the science instrument must be able to distinguish key phenomena from background fluctuations. The instrument flight software "triggers" on a transient when it sees elevated event rates on at least two SQDs. The trigger generates small Alert Trigger Data (ATD) packets for the spacecraft to transmit via TDRSS to ground for preliminary science analysis, including source characterization and localization. This information is pushed out rapidly to allow other instruments to perform follow-up observations of the transient at various wavelengths. The ATD packets also provide the context needed for the team to request specific windows of high-resolution data around the trigger time for downlinking on the next scheduled overhead pass. The "triggered" state lasts for 10 minutes to prevent repeated triggering on short timescales, since a prolonged TDRSS power mode could drain the spacecraft battery.

The instrument triggering process was tested extensively in the lab at different angles and with radiation sources of varying strengths. In addition, triggering was included as part of the regular Day-in-the-Life (DitL) spacecraft tests and other activities, either induced via radiation sources or forced via a software command. The team also tested the use of Absolute Time Sequences (ATS), i.e., sending commands for the spacecraft to execute at a pre-determined future time. ATS commands are required for the spacecraft to disable/re-enable its triggering when entering/exiting the South Atlantic Anomaly (SAA) and polar horns, regions of relatively high levels of radiation that can produce spurious triggers.

SPACECRAFT BUS INTEGRATION

BurstCube was integrated by component subsystems, then the subsystems were integrated at a top-level approach. When a component was ready to be integrated, such as a Reaction Wheel, the component was tested independently for functionality, then tested within the spacecraft flight harness. Once the component responded as expected, the component was then physically integrated into the designated hardware or bracket, and only then was the component mated to the spacecraft harness. The component would then have a final functionality check out in the flight configuration before being verified as flight-ready. This subsystem approach (visually represented in figure 11) was used so that multiple components could integrate in parallel, and all steps of the process would be verified.

There was also a one to one flatsat for the common bus components between the different SSPO mission to allow for testing new software and firmware on non-flight components. This system also allows for a flight like comparison for running tests on the ground during mission operations.

For the entire phase D, the spacecraft had dedicated electrical ground support equipment. This consisted of :

- A rack for the digital multimeter, computer servers, ground software defined radio, radio server, power supply, and inhibit system.
- A protective, clear, acrylic carrying case.
- A Kistler table
- Special fabricated connectors.

The entire integration process was completed on a clean, vertical flow bench in an electrostatic discharge safe lab.

Kernel Panic

Before the spacecraft could be fully environmentally tested, the spacecraft FSW began to exhibit a pseudo-random kernel panic. The kernel panic originally presented itself during instrument flight software testing on the flight hardware. The only artifact from these panics were a kernel dump. The kernel dumps always showed they were directly caused by an invalid memory access, but the stack traces themselves varied, occasionally occurring inside SPI and I2C device drivers, with a few occurrences inside the POSIX message queue function calls. The crashes were not reproducible, and the first noticeable correlation was that enabling instrument TTE reads would eventually induce a crash. This could take anywhere from 5 minutes to upwards of an hour. However, there was no obvious culprit in the instrument flight software applicaiton.

No changes in kernel configuration parameters resulted in additional information about the crashes. Eventually a subject matter expert found references to a Xilinx forum post that had showed the same crash symptoms. This narrowed down the cause to a race condition in the I2C driver. A patch was included in the Xilinx kernel fork in 2019 and the spacecraft was running a version of the kernel from 2017 without the patch. Upgrading the toolchain versions is a nontrivial process with some of the custom driver patches needed to support the hardware, and an entire kernel cannot simply be upgraded to a newer version without upgrading other components. The fix was applied manually to the spacecraft kernel version. This resolved the kernel panic issue.

ENVIRONMENTAL TESTING

Figure 12, outlines the Environmental test flow diagram. This section will focus on the magnetic characterization and calibration, Thermal Vacuum (TVAC) test, end-to-end communications test, the performance tests, and the vibration tests.

Magnetic characterization and calibration

While the MAG is calibrated by the manufacture, it is important to quantify the calibration and compensate for

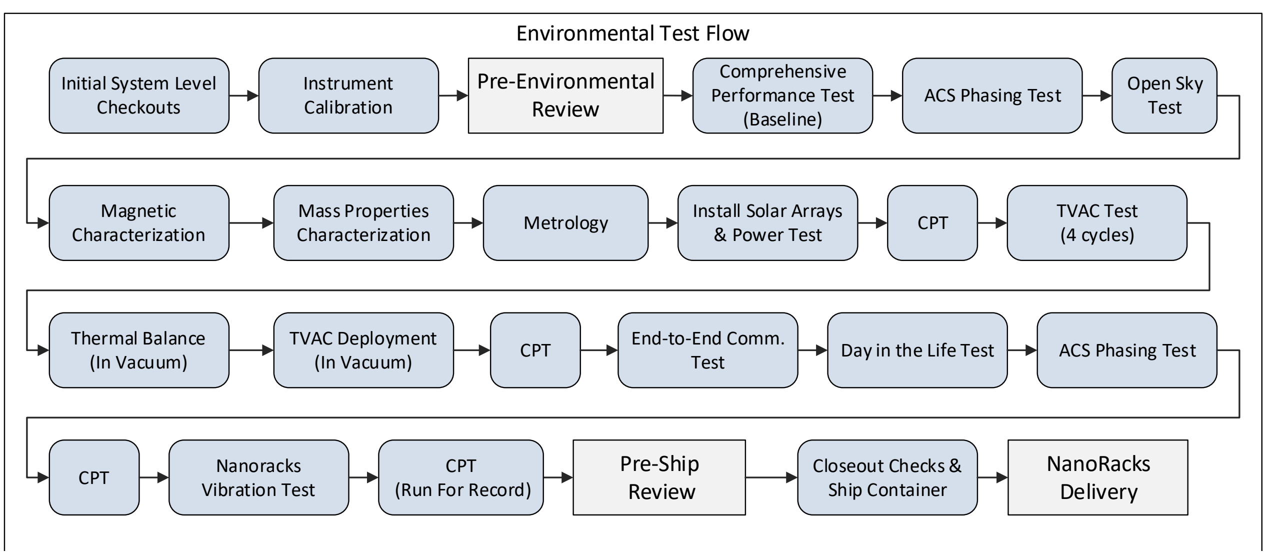

Figure 12: Enviornmental testing flow diagram.

any additional noise that is contributed by the spacecraft bus. The calibration was completed in three steps.

Figure 13: Spacecraft Magnetic Test Facility at NASA Goddard Spaceflight Center

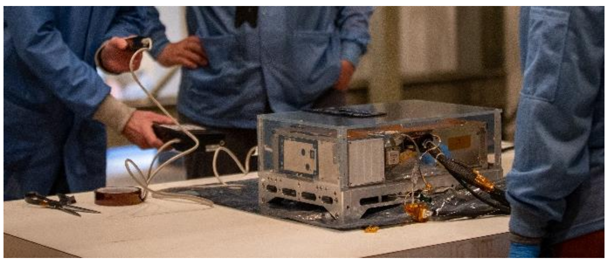

Figure 14: Magnetic Calibration at the MCF at NASA WFF (credit: NASA/Sophia Roberts)

Initial calibration of the MAG was completed with the bare unit within the Spacecraft Magnetic Test Facility (SMTF) at NASA Goddard Space Flight Center (GSFC), shown in figure 13. The sensor was connected via a wire harness and once placed in the test chamber, the ambient magnetic field was nulled. With reference magnetometers reading approximately zero nT, it was possible to determine offsets for the MAG sensor to null its field. It was found that these offsets were within a few hundred nano-Teslas, providing the baseline calibration for the MAG sensor.

Once the integration of the spacecraft was completed, a secondary calibration was completed at the Magnetic Calibration Facility (MCF) at NASA Wallops Flight Facility (WFF). Here, as shown in figure 14, the integrated spacecraft was placed within the testing apparatus and the ambient field was nulled as before. Once the spacecraft was powered and placed in a typical nominal operational state, it was possible to compare the MAG readings with the ambient reference magnetometer, which read a nulled magnetic field. It was found that the MAG, which was placed internally within the spacecraft, had readings in the range of 10s of micro-Teslas. These offsets were recorded and applied such that the spacecraft MAG would match the readings of the ambient magnetometer. A linearity test was also conducted at the MCF by varying the magnetic field within the test chamber over the range of expected magnetic field values in orbit. The data from the test was analyzed to provide a secondary linear gain tuning parameter.

A final calibration of the MAG offsets was completed at the SMTF at NASA GSFC, as solar panels had not yet been integrated on the spacecraft in the earlier test. While only some minor changes were expected with the addition of solar panels, it was found that the offsets had unexpectedly changed significantly. Due to this sensitivity, a plan was formulated to perform additional on-orbit calibration of the MAG to verify proper magnetic field readings, which are necessary to maintain adequate momentum management of the spacecraft

TVAC testing

To prepare for TVAC testing, the spacecraft needed to be in a flight-like configuration, including the solar arrays mounted, hardware installed, fasteners staked, and necessary reflective coatings cured onto the outer structure. These coatings, like silver Teflon and Kapton tape, were used to reflect and hold heat on the spacecraft, so that temperatures could be regulated during full-sun and eclipse orbits. BurstCube was then integrated with optical posts into a thermal chamber, figure 15, and oriented so that the science instrument would have a direct line to a radiation source, and so that the baseplate solar panel could deploy during the test. This deployment configuration was tested before adding thermocouples for temperature sensing, and the dome of the chamber lowered to begin the procedure. Table 2 gives the 5 stages achieved during TVAC. Figure 16, shows the TVAC testing profile.

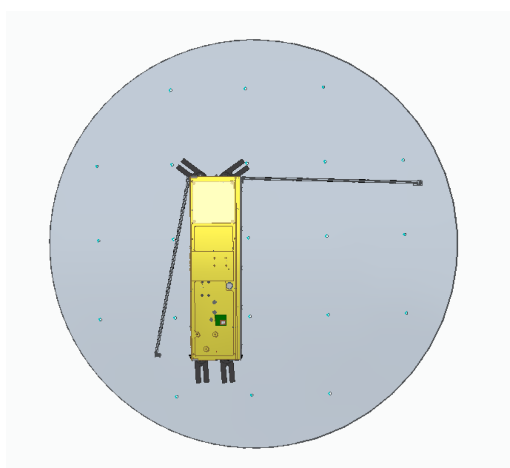

Figure 15: Rendered top down view of Burstcube in the thermal chamber for TVAC testing

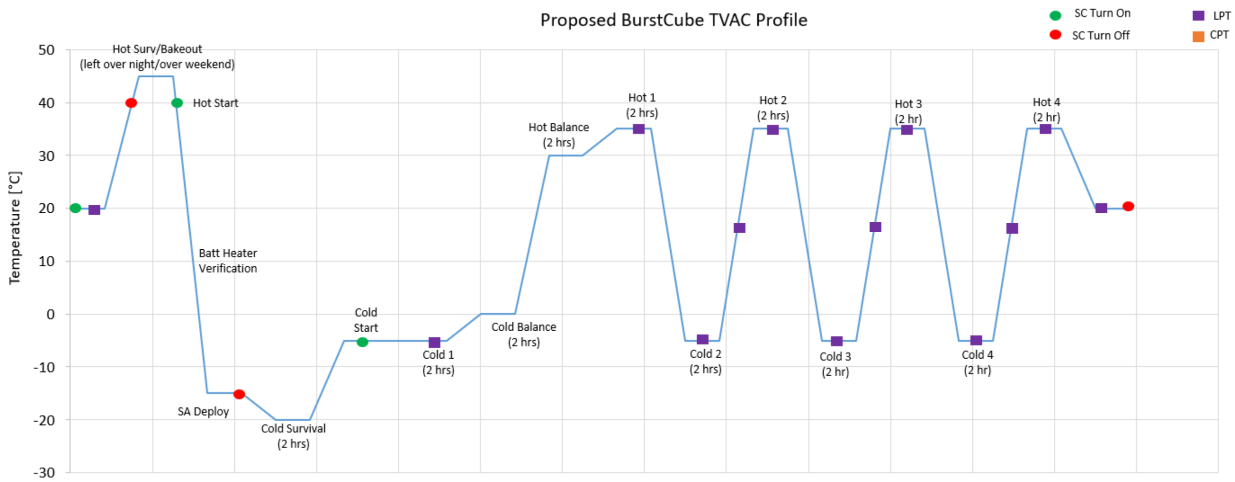

Figure 16: TVAC testing planned temperature profile

The thermal vacuum chamber used was a B4 Dynavec chamber with a shroud 32 inch diameter and a 32 inch heigh.

During TVAC testing, the instrument remained on where reasonable – in particular, at each cold/hot dwell and during various temperature ramps. 137Cs and 241Am radiation sources were placed outside the TVAC chamber and positioned close to the instrument zenith/nadir axis to obtain similar photon rates on all four detectors.

Table 2: TVAC Stages

Stage	function
Bakeout	-Remove uutgassing materials
Hot and cold balances	-Verify interface definitions and assumption used in analysis. -Provide data for thermal model correlation
Cold survival	-Verify Triggers to safe the spacecraft in cold
Cold Deployments	-Deployment of solar arrays (one partial, one pop and catch)
Thermal Cycles	-Ensure workmanship standards -Verify heater functionality -verify temperature margin at critical interfaces

The TVAC campaign was successful. No thermal issues were discovered on the spacecraft. The thermal correlations were all within acceptable model correlations. The actual thermal profile as measured duringTVAC is shown in figure 17.

End-to-end Communications test

Many CubeSats don't establish communications on their first pass as they don't have the opportunity to test their equipment in a flight-like configuration. End to end communications testing allows the exercise of the full chain of communications equipment in a controlled manner. The only difference is the use of a hardwire coaxial connection to the radio instead of instead the wireless antenna. The ground support equipment used by the compatibility team is the same model used for flight operations, and the configuration the compatibility team finalizes is passed along to the ground stations we use for flight. The compatibility team can provide the spacecraft an emulation of the same signal expected to be seen on orbit.

This was tested for both TDRSS and DTE networks. For both networks, we tested all data rates listed in the RF ICD. For each data rate, the compatibility team also decreased signal strength in steps and monitored any data loss to verify our link margins. This involved having the spacecraft powered on and sending live telemetry data over the radio. The file uplinks and downlinks were also tested to verify a maintained link integrity during periods of shifting data throughput to our different virtual channel transitions. The compatibility equipment was configured to send the data to the same servers used in flight operations to verify that ground systems can successfully send commands and decode telemetry.

Performance tests

It was mentioned previously that the NOS3 environment was leveraged for development, but it was also used for testing the fault detection and correction (FDC) involved on-board the spacecraft. An example of this included using the simulation backdoors to trigger EPS faults that were not possible without damaging the unit and ensuring the FDC acted upon them as expected and resolved the situation.

While a simulation environment has many uses, it's limitations should be known, and it shouldn't be utilized

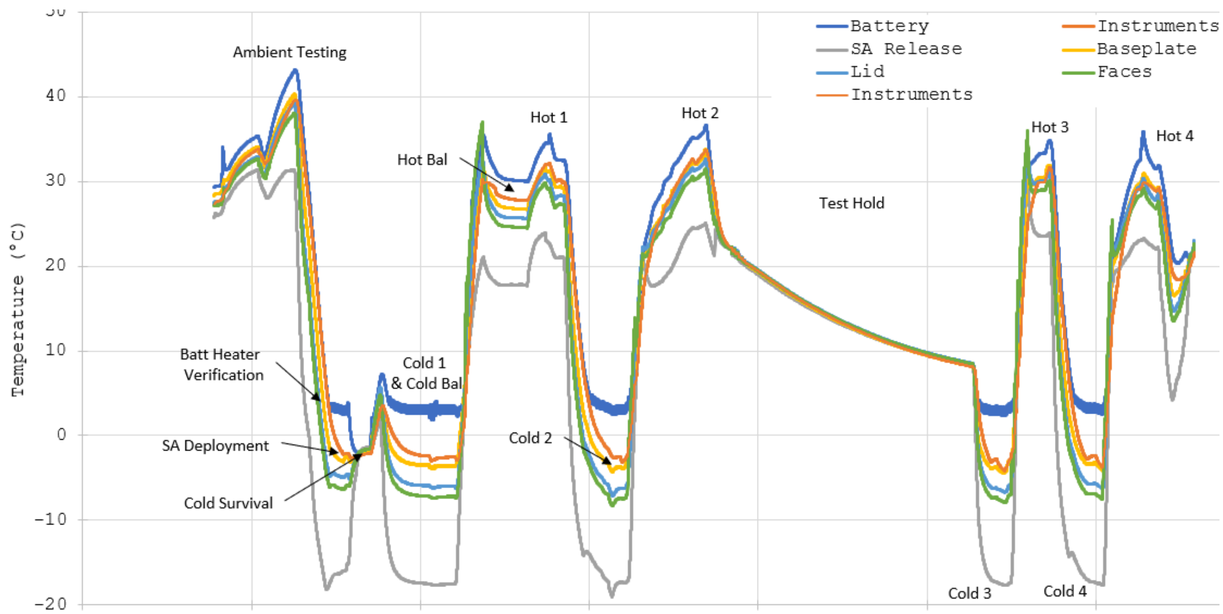

Figure 17: TVAC testing actual thermal data for battery, solar array release mechanism, lid, instrument (two locations), baseplate, and outer faces.

as a complete replacement for hardware testing where it can be avoided. BurstCube maintained a shared FlatSat with other GSFC LEO SmallSats and was a next step after the NOS3 environment. While the FlatSat was running actual hardware, it's configuration was slightly different than that of the spacecraft and not all hardware was present. Even with these changes, the additional test bed was invaluable to having a solid a baseline prior to final testing on flight hardware.

Both limited performance tests (LPT) and comprehensive performance tests (CPT) were leveraged throughout the I&T process. The limited version of the test did not require any special spacecraft configuration and could be run at the click of a button from the ground software. The comprehensive version required external stimulus and was a much more involved and detailed set of procedures to ensure that everything that could be tested on the fully assembled spacecraft, within reason, was tested.

Vibration tests

BurstCube was analyzed to 3-Sigma loads based off the launch deployer hard-mount random vibration test profile of 9.47 Grms for 60 seconds. The Miles equation was used to calculate the 3σ Von Mises and principal stress loads, and Goddard standard fastener analysis sheet was used to conclude fastener stresses based on the Finite Element Analysis. Due to this detailed analysis, BurstCube was determined safe for the launch provider loads.

BurstCube was random vibration tested twice, once when BurstCube was fully integrated for flight, and again after a late-stage configuration change. Each time, BurstCube was tested to the Voyager Space Nanoracks Soft-Stow test profile of 5.76 Grms for 60 seconds per axis, a softer load than the previous analysis. To perform the test, BurstCube is integrated to the launch provider test deployer—a replica of the actual launch deployer—and bubble wrapped and strapped down to the vibration table, as it would be for launch. A sine sweep test, table 3 includes the test specifications, was also performed before and after each axis so that the profiles could be compared and capture any physical spacecraft breakage. BurstCube was tested for functionality before and after the vibration test to ensure no internal damage to the components or hardware was due to the vibration test.

Table 3: Vibration testing low-level sine sweep

Charteristic	Target
Frequency Range	20-2000 Hz
Sweep Rate	2 oct/min
Input Amplitude	0.25 g-pk

BurstCube had another successful random vibration test after a de- and re-integration of the rotary release mechanism near the end of integration. This test was also conducted in the same manner as above, including the pre- and post-functionality testing. Once again, this test was successful, proving the BurstCube structure was ready to withstand the launch loads.

LESSONS LEARNED

Cataloguing the lessons learned on any project is a valuable exercise. Listed here are several broad lessons that the team has compiled specifically for the Phase D portion of this mission.

Early and substantial subsystem involvement

It is crucial to have all subsystems involved in AI&T at the outset. It allows for a more realistic schedule and expectation for validation and verification. This can also allow different subsystems to have better communication when troubleshooting issues between subsystems. Such as flight software having access to exact hardware setups. Having high level systems understanding of the system and interfaces across the subsystems allows for a smoother validation and verification process.

As part of this, documentation, (written, photographic, and screen recording) is incredibly valuable later during integration. Referencing prior work can reveal the causes of issues later on.

Test as you fly

FlatSats and engineering units should be as flight-like as possible, ideally with the ability to simulate missing hardware. Testing on flight hardware and/or the integrated spacecraft is much slower than testing on an engineering setup. This allows diagnostics and pre-tests to move much quicker as it removes the important barriers to working with flight hardware.

Prepare for disassembly

BurstCube integration repeatedly proved the need for simple component and subassembly de-integration. Due to unforeseen issues, such as component failure, board modifications, or additional testing needs, multiple subassemblies needed to de-integrate from the flight unit for modification. Without a design that allowed for quick de-integration, BurstCube would not have been able to modify subsystems without a major schedule and cost impact.

For example, when the science instrument needed an internal board replaced, the instrument unit was designed in a way so that it could be directly lifted from the spacecraft based with minimal contact to other components, making it simple to remove from the top-level spacecraft assembly. And when a subassembly, such as the instrument, is composed of multiple units, it should be comprised of standalone units where possible. For example, ensuring that each individual SQD is light-tight saves the need to retest at the integrated instrument level.

And as part of this lesson, it is valuable to build into the schedule time for issues to arise and be tested and corrected. This can save more time and money in the long run than expecting the entire schedule to proceed without issue.

Design for flight and testing

Components and assemblies should be selected and designed for their mission environment but also for the testing environment. Components need to be able to withstand testing and flight conditions. For example, the instrument originally had a one-way valve to depressurize the interior when deployed from the ISS. This selection ignored the testing reality that during TVAC , the instrument would eventually have to be repressurized. Using this valve could have at least damaged the light tightness of the instrument and at most caused a rapid depressurization that damaged the electrical components of the instrument.

Economy of scale

While CubeSats are the champions of lowering the barriers to orbit entry, it is vital to remember that not all systems scale the same. During component selection, understanding the component trade offs between vendors or in house builds are crucial down the line. Higher quality components may be more expensive, but they may be more reliable through robust testing. Components and ground system equipment don't just need to survive orbit, they need to survive testing as well.

Subsystems such as FSW, ADCS algorithms, and instrument FSW, are not linearly simpler or miniaturized versions of larger spacecraft counterparts. A CubeSat has to perform in many of the same functions of those full-sized satellites. Having similar bus designs across multiple missions does help to lower the development cost, but when missions have very different requirements and science objectives, there will be unique issues to those missions.

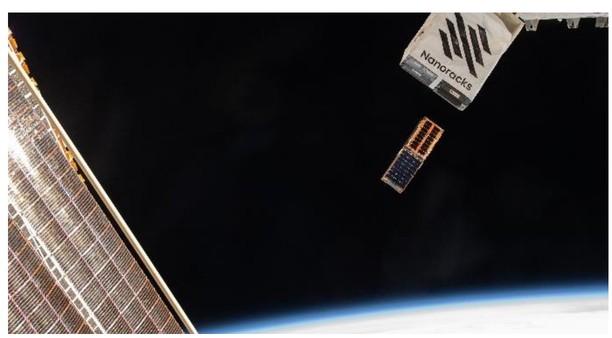

Figure 18: BurstCube (the Cubesat down and to the left) being deployed from the ISS with SNOOPI. (Credit: NASA/Matthew Dominick)

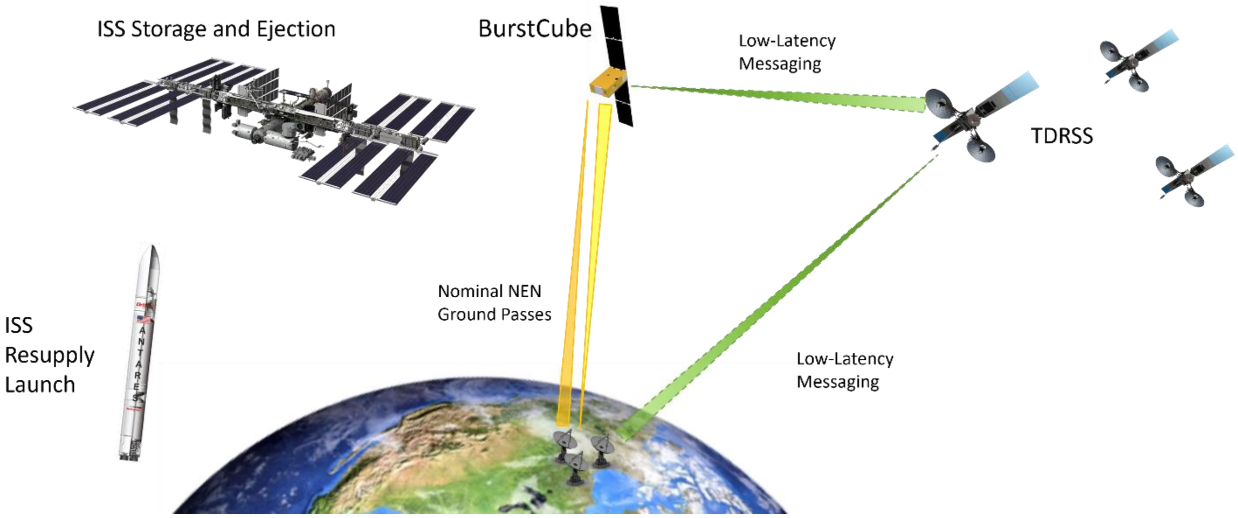

Figure 18: BurstCube concept of operations

EARLY MISSION OPERATIONS

BurstCube was launched to the International Space Station (ISS) on SpaceX CRS-30 on March 21,2024. It was successfully deployed from the ISS on April 18 with its sister mission SNOOPI, another NASA GSFC SSPO CubeSat. Figure 18 shows a photo from the deployment.

As of June 2024, the BurstCube team is making significant progress on commissioning the science instrument. The team has powered on the detectors, enabled science data production, and analyzed both low- and high-resolution data. The final step in instrument commissioning is to enable triggering, which will allow the team to obtain alerts at any time in BurstCube's orbit rather than waiting for scheduled passes to downlink data. Figure 19 shows the concept of operations for the mission.

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