Developing a Standard Test Program for CubeSats

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ABSTRACT

Developers of CubeSats and other miniaturized satellites often lack the schedule and budget to devise and implement an extensive environmental test campaign. CubeSat projects have become increasingly common at Jet Propulsion Laboratory (JPL) over the past few years, revealing the need for a standard CubeSat test program to maximize the likelihood of mission success while meeting project cost and schedule constraints. In this paper, we describe our efforts to develop a general protoflight test program for CubeSats in low-Earth orbit (LEO) and compare this test program with a typical test program for non-CubeSat LEO satellites and instruments. We investigate the effectiveness of the CubeSat test program—both as a design and workmanship screen and as a standard needing minimal project-specific tailoring—and discuss potential areas for improvement.

I. INTRODUCTION

CubeSats are small satellites that conform to the standardized CubeSat design specification, which controls the form factor (size, shape, and mass), center of gravity location, and other features. Dispensers provide attachment to a launch vehicle and release the CubeSat at the appropriate time; dispenser options include hard-mounted dispenser such as the Poly-Picosatellite Orbital Deployer (PPOD) or soft-stowed dispenser such as the NanoRacks CubeSat Deployer (NRCSD). CubeSats can be placed on a variety of launch vehicles and can be released and maneuvered to a variety of trajectories, including LEO, lunar orbit, and Mars flyby. Mission duration can vary from 90 days to several years.

The small, standardized CubeSat platform makes development of these spacecraft more affordable, which allows developers of CubeSats to take greater risks than developers of other satellites and instruments. CubeSat projects often develop and demonstrate new technologies, making extensive use of deployables, consumables, and commercial, off-the-shelf components. Over the past few years, JPL has built and delivered a variety of CubeSats and CubeSat payloads, including those listed below.

- ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics): technology demonstration to achieve arcsecond-level line-of-sight pointing error and highly stable focal plane temperature control
- DHFR (Defense Advanced Research Projects Agency [DARPA] High-Frequency Research Space Testbed), radio (receiver and antenna): technology demonstration to observe high-frequency (5–30 MHz) signals from ground transmitters
- RainCube (Radar in a CubeSat): technology demonstration to validate a new architecture for Ka-band (26.5–40 GHz) radars and an ultra-compact, lightweight, deployable Ka-band antenna

- TEMPEST-D (Temporal Experiment for Storms and Tropical Systems–Demonstration), radiometer: technology demonstration to reduce risk for a future constellation of five-channel millimeter-wave radiometers

Non-CubeSat projects have the resources to devise and implement extensive environmental test campaigns to maximize the likelihood of mission success; CubeSat projects do not. Instead, the standard JPL environmental assurance approach must be tailored for these projects based on their risk posture (i.e., their willingness to accept risk), development schedule, budget and funding profiles, hardware pedigree (e.g., inherited, new design, commercial), and other considerations. In doing so, we have developed a standard environmental test program specifically for LEO CubeSats.

II. DEVISING A GENERAL TEST PROGRAM FOR LEO CUBESATS

At JPL, an environmental requirements document (ERD) is written for each project regardless of the mission destination, duration, or complexity. The ERD defines the project's formal environmental assurance program; describes the expected natural, self-induced, and mission activity induced environments occurring during the mission; and specifies requirements for all formal assembly-, subsystem-, and system-level environmental tests and analyses. Included in the ERD is a test and analysis matrix, which identifies the level of assembly hardware will be tested at and the method of verification for environment (i.e., test and/or analysis).

Our efforts to develop a general protoflight test program for LEO CubeSats began with simplifying the ERD for a general non-CubeSat LEO spacecraft or instrument to create a pair of CubeSat ERD templates (one for CubeSats utilizing a hard-mounted dispenser and one for CubeSats utilizing a soft-stowed dispenser). ERDs for LEO missions typically specify the following environments:

- Ground: temperature, humidity, and vibration
- Pressure: maximum depressurization rate
- Dynamics: random vibration, acoustic noise, shock
- Thermal: worst-case hot and cold temperatures for each assembly
- Natural space: radiation, solid particles, plasma/charging
- Electromagnetic: conducted and radiated emissions and susceptibility limits

We left the standard LEO ground and pressure environments largely intact and focused our tailoring on the dynamics, thermal, natural space, and electromagnetic environments.

Dynamics Environment

Because CubeSats can be placed on a variety of launch vehicles, we specify conservative random vibration levels based on NASA General Environmental Verification Standard (GEVS) and shock levels assuming a Falcon 9 launch vehicle with a 937 mm clampband separation system because this shock environment envelopes that of several other launch vehicles. Given the CubeSat size and form factor, we do not consider the acoustic environment to be applicable.

Thermal Environment

Rather than specify a particular thermal environment in the templates, we include an empty temperature requirements table to be populated with project-specific temperature limits based on CubeSat thermal models and JPL institutional margin.

Natural Space Environment

We describe the LEO proton and heavy ion fluxes to inform part selection; because CubeSats have such short mission lifetimes, we do not consider cumulative effects (total ionizing dose, displacement damage dose, orbital debris, and micrometeoroids).

Electromagnetic Environment

While we typically limit assembly emissions and susceptibility to reduce the risk of serious incompatibilities at the system level, CubeSat developers simply do not have the resources—schedule, budget, mass, power—to build the quantity or complexity of instruments typical of non-CubeSat LEO projects. For these small projects, verifying compliance with emissions and susceptibility limits at the assembly level is cost prohibitive and less likely to reveal true incompatibilities (e.g., because limits may not reflect the actual sensitivities of newly-developed hardware). Rather than impose such limits, we provide guidance for minimizing electromagnetic interference and rely on self-compatibility testing at the integrated CubeSat level.

III. IMPLEMENTING THE CUBESAT TEST PROGRAM

Both CubeSat ERD templates specify a protoflight test program the integrated CubeSat level to qualify the design and screen for workmanship defects; testing at the assembly level is recommended but not required.

Environmental Test Sequence

At JPL, projects establish the sequence of environmental tests based on hardware design and materials, hardware sensitivity to each environment, and environmental characteristics and effects. While non-CubeSat projects establish their environmental test sequences based primarily on technical considerations, cost- and schedule-constrained CubeSat developers may base their test sequence decisions on logistical and other non-technical considerations. In our experience, maturity of pretest analysis, availability of suitable test venues, and availability of critical support equipment (e.g., NanoRacks-provided vibration test fixture) have factored into test sequence decisions.

The recommended test sequence is electromagnetic compatibility (EMC) testing followed by dynamics testing followed by thermal testing. Performing EMC testing prior to dynamics and thermal testing is advantageous because hardware can be reworked to correct EMC failures without invalidating the dynamics or thermal tests. Performing dynamics testing before thermal testing is more flight-like, and thermal testing may uncover intermittent failures that developed during dynamic testing. For CubeSats, however, deployables such as solar arrays and antennas make this test sequence problematic: Deployables need to be exercised at the hot and cold temperature extremes, but resetting these features typically involves some level of disassembly. If vibration testing were completed before thermal testing, resetting deployables after thermal testing would likely invalidate the dynamics test.

Verification of deployables can also dictate a need for assembly-level testing. For example, verification of antenna deployment after CubeSat-level random vibration testing would have required disassembly of the entire DHFR spacecraft—and, therefore, would have invalidated the vibration test—so the DHFR project performed extensive environmental testing at the antenna level and did not verify antenna deployment after the CubeSat-level vibration test (Figure 1).

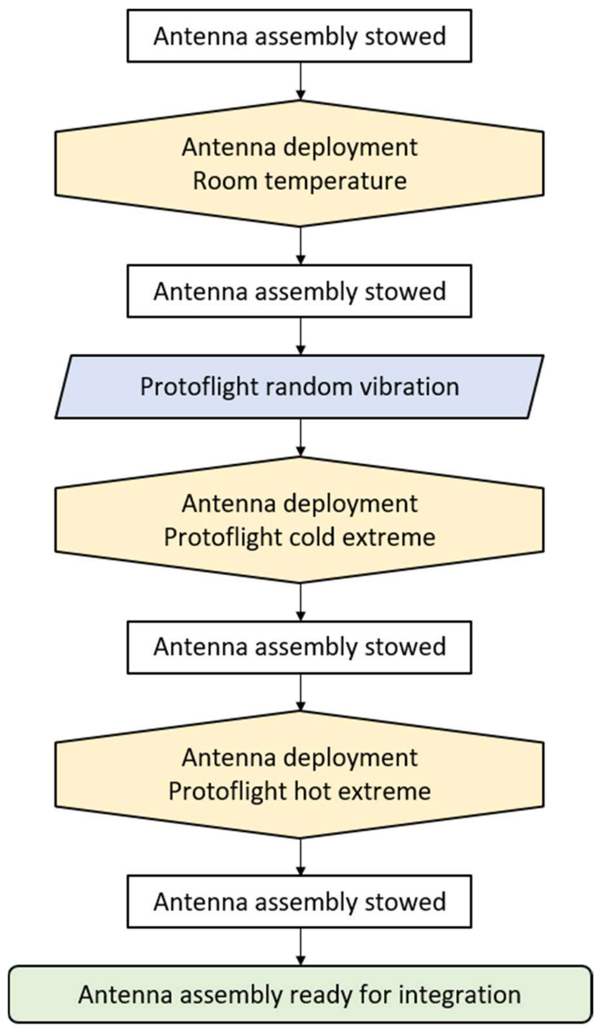

Figure 1. DHFR antenna assembly test flow. Schedule constraints precluded antenna deployment between vibration testing and thermal testing.

Dynamics Testing

All JPL-delivered CubeSats and CubeSat payloads undergo random vibration testing; CubeSat dispenser systems (and launch services providers) typically require random vibration testing at the

CubeSat level. However, JPL relies on vibration testing as a workmanship screen, and the test profiles specified in CubeSat-to-dispenser interface definition and interface control documents (IDDs and ICDs) do not always envelope JPL's minimum workmanship test profile (identical to the minimum workmanship test profile defined in GEVS). In these cases, we recommend testing to a profile that envelopes the minimum workmanship test profile and the test profile specified in the IDD or ICD. For example, NanoRacks offers CubeSat developers two options for random vibration testing of the CubeSat integrated with the NRCSD or equivalent test fixture (Figure 2):

1. Test in the soft-stow flight configuration (i.e., wrapped in NanoRacks-provided bubble wrap and foam) to the maximum expected flight plus margin
2. Test in the hard-mount configuration (i.e., bolted directly to a vibration table) to a profile that envelopes the maximum expected flight level and a NanoRacks-defined minimum workmanship level

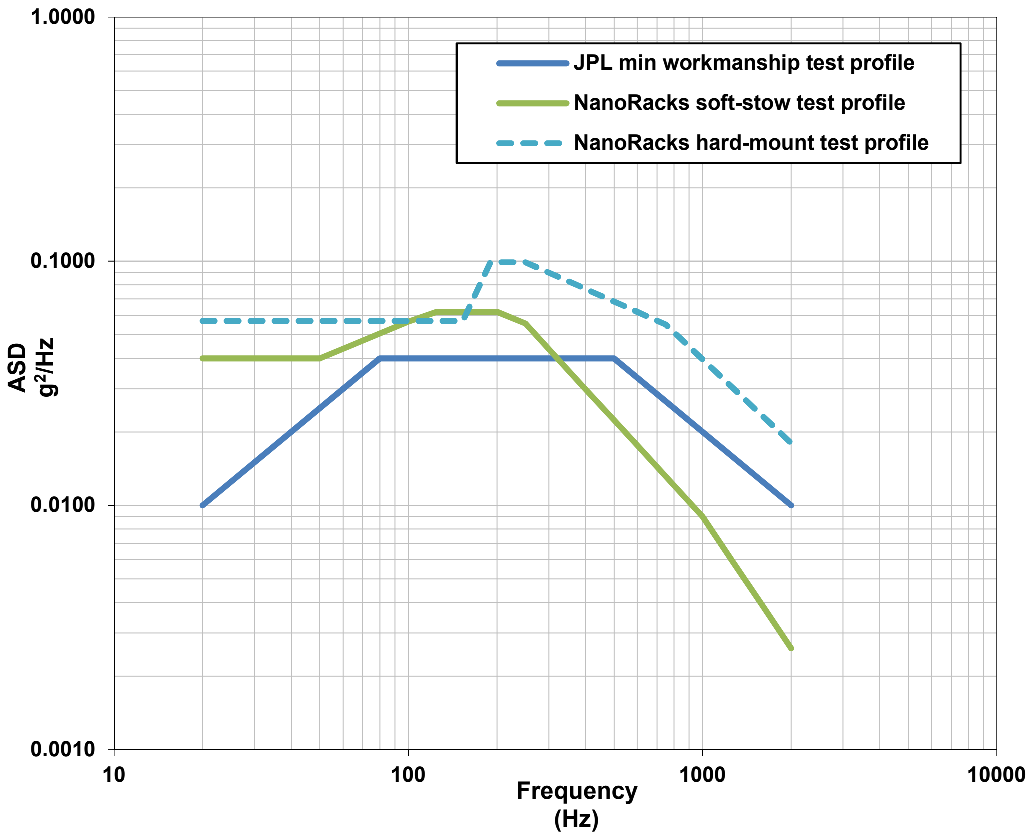

Figure 2. Random vibration test profile comparison. Prior to delivery to the CubeSat bus provider, the RainCube payload was tested to a profile that envelopes the NanoRacks soft-stow test profile and the JPL minimum workmanship profile.

To date, we have not shock tested any LEO CubeSats or their payloads at JPL. In part, this is because shock testing is not required for CubeSats utilizing a soft-stowed dispenser as they do not experience significant mechanical shock; in part this is because JPL does not treat shock testing as a workmanship screen. Without a precedent for shock testing as a workmanship screen, CubeSat developers are reluctant to risk over-testing their hardware, particularly when the launch vehicle or dispenser system—or both—are unknown.

Thermal Testing

In addition to vibration testing, all JPL-delivered CubeSats and CubeSat payloads undergo thermal testing. Testing at the payload or assembly level is straightforward, but when testing at the integrated CubeSat level, it is not always possible or desirable to test the entire system with full protoflight margin. In particular, batteries present a challenge because exposure to temperatures beyond their allowable flight temperatures can result in permanent performance degradation.

One option is to use a flight-like engineering model (EM) or spare flight battery during the system-level test and then replace it with the flight battery prior to vibration testing. This approach is advantageous because the end-to-end performance of the entire system can be verified over the full protoflight test range. For example, the ASTERIA project used a spare flight battery during thermal testing of the integrated CubeSat. To verify startup after release from the dispenser at worst-case conditions, the bus was powered on at the margined cold extreme with a low starting battery voltage. At colder temperatures, the battery impedance is greater, resulting in large voltage drops and rises when loads are powered on and off. When the battery under-voltage limit was violated due to the low starting voltage and large voltage drop when the bus was powered on, the power system entered a continuous reset loop. After the test, the turn-on sequence and certain system parameters were modified to preclude this happening during flight.

Another option is to qualify the CubeSat bus, battery, and payload separately, then test to flight acceptance temperatures at the integrated CubeSat level. This approach requires more thermal tests than would be needed if an EM-type battery were used during system-level testing. It avoids disassembly to replace the battery after the test; however, unlike more traditional projects, CubeSat projects typically perform vibration testing *after* thermal testing, so such disassembly would not invalidate any dynamics tests, and workmanship would be verified after reassembly.

Electromagnetic Compatibility Testing

Although not required, we strongly recommend an early self-compatibility check for risk reduction, particularly if a FlatSat—a breadboard or EM CubeSat bus—is available. For example, the TEMPEST-D spare instrument was temporarily assembled (minimal fasteners, no torqueing, no staking/thread locker) and integrated with the EM bus for compatibility testing while the flight instrument went through vibration and thermal testing. The test revealed several grounding issues that were corrected during assembly of the flight bus.

IV. FINDINGS AND CONCLUSIONS

By tailoring the standard JPL environmental assurance approach, we developed a standard environmental test program for LEO CubeSats. Over the past few years, we have applied this program to several CubeSats and CubeSat payloads and found it to be an effective design and workmanship screen that increases the likelihood of mission success while being responsive to project risk posture, schedule and budget constraints, and other considerations. Our experience with ASTERIA, DHFR, RainCube, TEMPEST-D, and other projects suggests a few areas for improvement, including developing a standard vibration environment that envelopes as many launch vehicles and dispensers as possible and streamlining the standard JPL thermal test profile to make assembly-level testing more affordable without compromising its effectiveness.

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BIOGRAPHY

Gabriella Seal is an environmental requirements engineer and mission assurance manager at the Jet Propulsion Laboratory, where she has worked since obtaining her B.S. in Mechanical Engineering from the California Institute of Technology in 2013. Experience and projects include mission assurance management for TEMPEST-D and Surface Water and Ocean Topography (SWOT), environmental requirements engineering for Mars Helicopter, and instrument assembly/integration/test engineering for Deep Space Atomic Clock (DSAC).