Progress in Reducing Vibration Levels on NPSCuL

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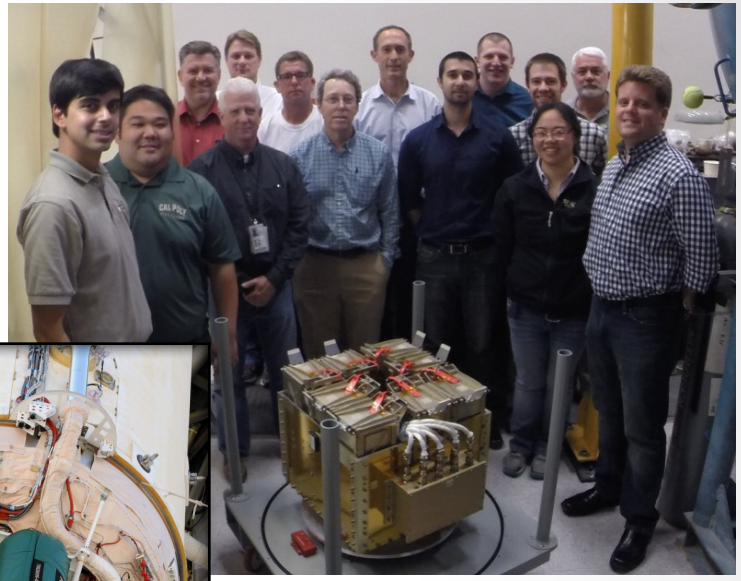
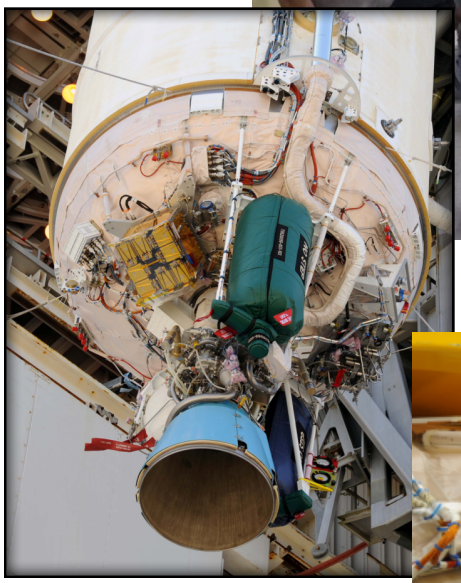
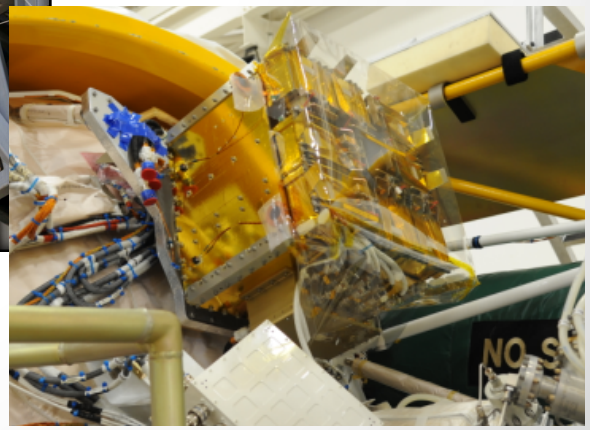
NPSCuL Overview

- NPSCuL is an ESPA-compatible payload with a capacity of 24 1U CubeSats using P-PODs and 6U dispensers
- 2 successful launches, OUTSat and GEMSat, on the Atlas V Aft Bulkhead Carrier (ABC) in 2012 and 2013
- 2 upcoming launches, ULTRASat and GRACE, in May and August 2015

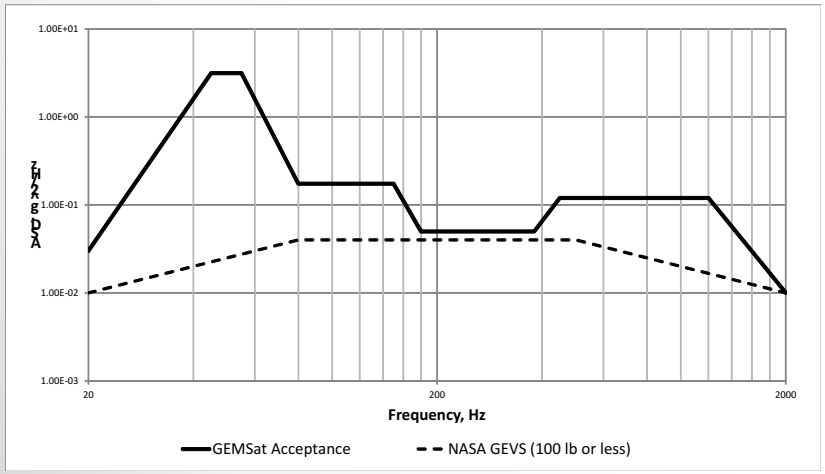






Need for Reducing Vibration Levels

- "Test-To-Insane Levels" (TTIL) methodology applied to CubeSats on NPSCuL during random vibe
  - ~15 G_{RMS} at MPE for the P-POD is considered harsh
  - Rigidly mounted, cantilevered, thin-plate structure causes amplification at P-POD interface
- Discourages more sensitive and complex payloads from gaining access to space via ABC
  - Current environment is considered "coach-class"



X-Axis G_{RMS} (Worst-Case)

Level	Base (Input)	P-POD Interface*
Acceptance (MPE +0dB)	7.6	15.1
Protoqual (MPE +3dB)	10.7	21.4
Qual (MPE +6dB)	15.2	30.3

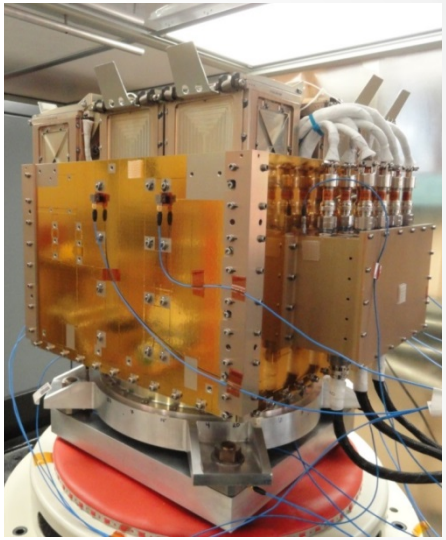
*Envelope of OUTSat acceptance test data (Flight P-PODs and CubeSats)

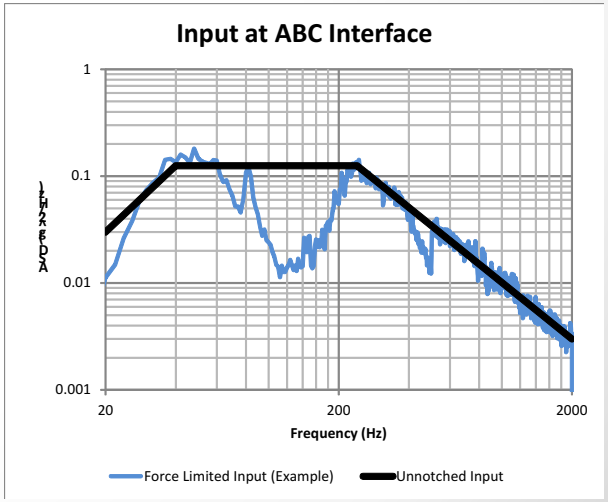
Progression of Vibration Reduction Methods for NPSCuL

- Implemented force-limited vibration testing (FLVT) to minimize over-test caused by test set-up
  - Effective in reducing the resonance at the fundamental frequency
- Redesigned NPSCuL to increase stiffness
  - Moves fundamental frequency from ~50 Hz to ~75 Hz
  - Increased stiffness results in reduced benefit from FLVT in overall G_{RMS} for the ABC input
- Obtain lower input from LV provider
  - No flight data for full test frequency range available to create test envelope

FLVT on NPSCuL

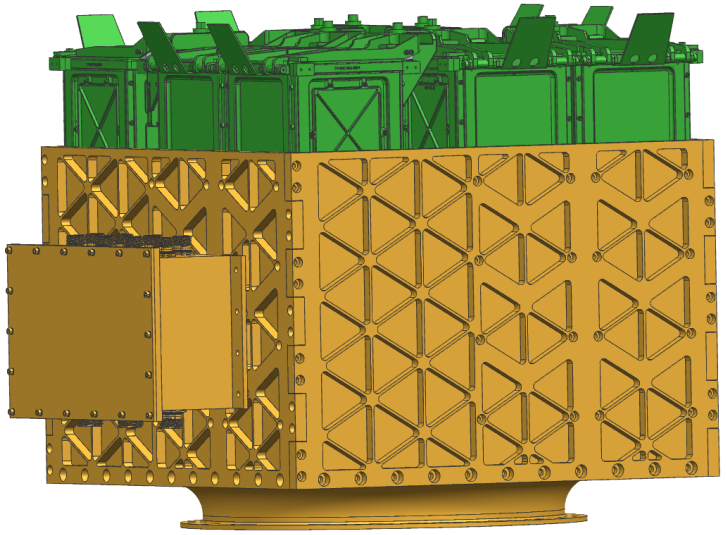
- Semi-empirical method is used to calculate force limit per NASA-HDBK-7004B
  - Has been repeatedly shown to be the least conservative method while still meeting test requirements
- Results in a notch in the acceleration input at the fundamental frequency
- Force roll-off is assumed after fundamental frequency to 500 Hz
- Does not provide relief past the force-limited range
  - Test data shows there is a significant amount of energy above 500 Hz at the P-POD interface
  - Not a mechanism, and is not intended to be, for changing the resonant properties of the system

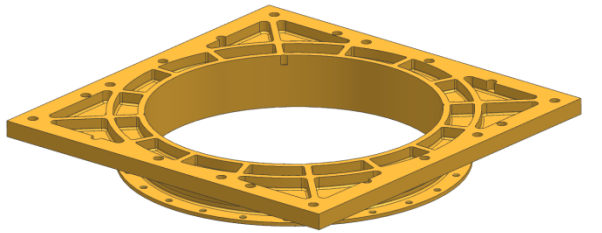




Redesigned NPSCuL - Isogrid

- Isogrid techniques were utilized to reduce amplification by increasing stiffness without increasing overall mass
  - Moves fundamental frequency from ~50 Hz to ~75 Hz
- NPSCuL adapter ring and base plate were unified into a single part to reduce amplification from "rocking" modes
- Increased stiffness results in reduced benefit from FLVT in overall G_{RMS} for the ABC input
- No significant change in G_{RMS} between isogrid and baseline NPSCuL when using FLVT set-up

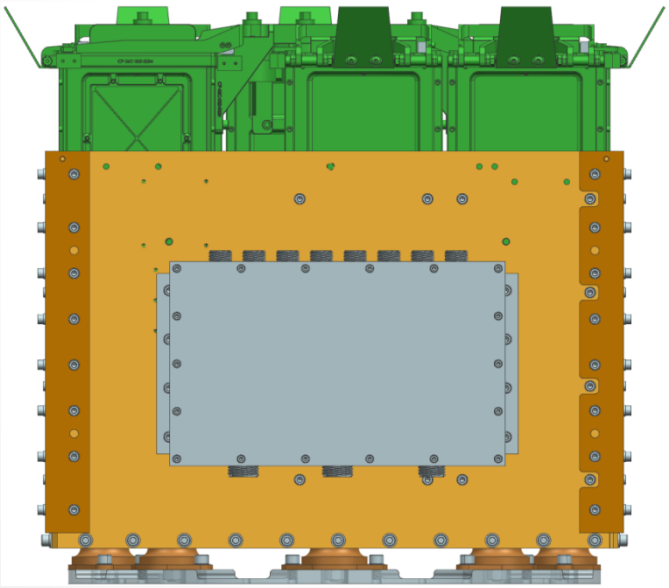


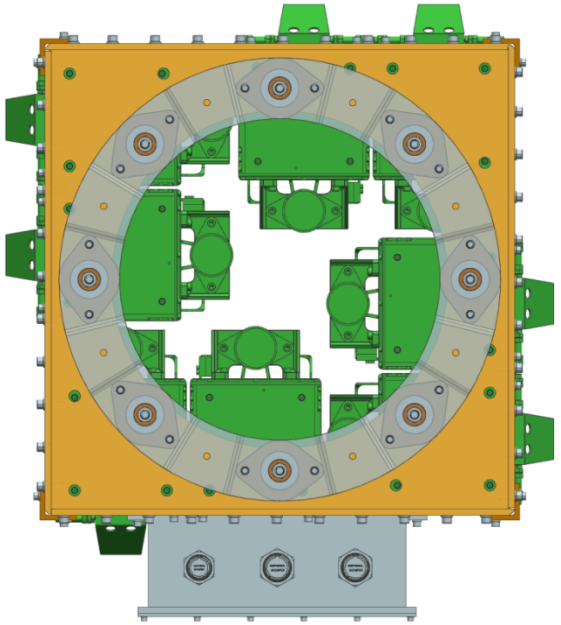


***Reference:** Kaushish, V., "Force limited vibration testing and subsequent redesign of the Naval Postgraduate School CubeSat launcher," Monterey, CA: Naval Postgraduate School, 2014.

Next Step – Isolators on NPSCuL

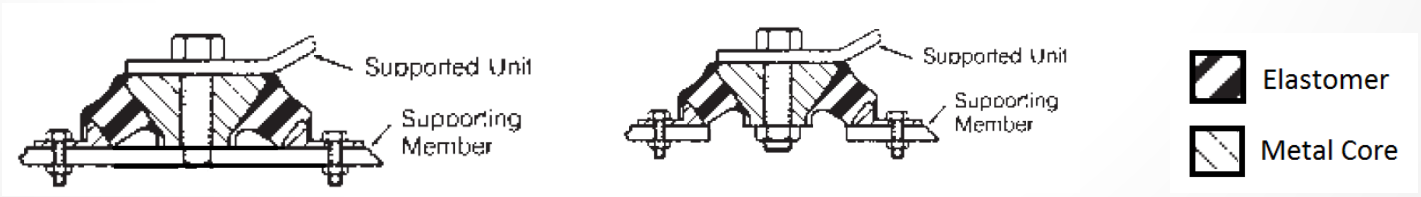
- Implement isolators with FLVT to reduce P-POD environment on NPSCuL
- Eight (8) COTS isolators incorporated between adapter ring and baseplate
- Attaches to the LV interface using eight (8) of the 24 fastener locations on the 15" ESPA standard





Isolator Installation Configurations

- Conical broad-temperature-range (BTR) silicone isolators (LORD AM-009-14) constrained using two (2) methods
  - Method 1: Fastener that goes through supported unit is threaded into supporting member
    - Elastomer is constrained in compression, tension, and shear
    - Effectively lowers the CG of NPSCuL by 0.9" with little reduction in joint stiffness
  - Method 2: Typical installation for true isolation behavior
    - Elastomer is allowed to deflect as intended by vendor
    - Generally recommended for use in compression only
    - Significant change to joint stiffness and lowers the CG
    - Use in tension is assessed on a case-by-case basis

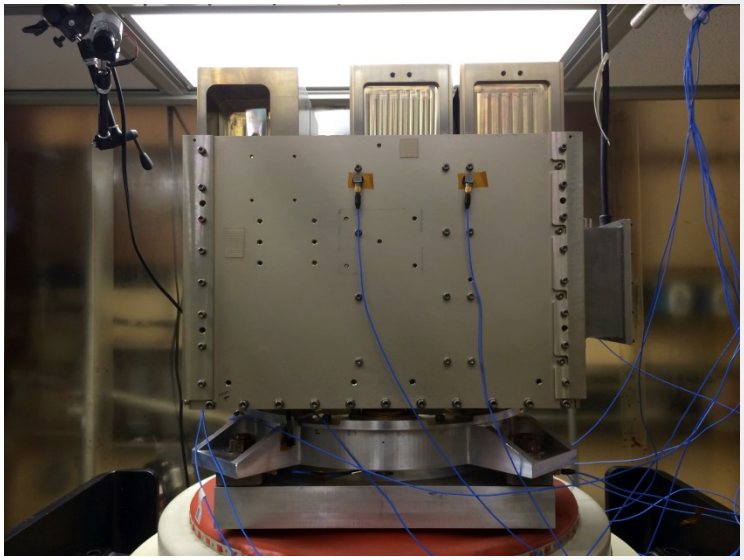


Method 1

Method 2

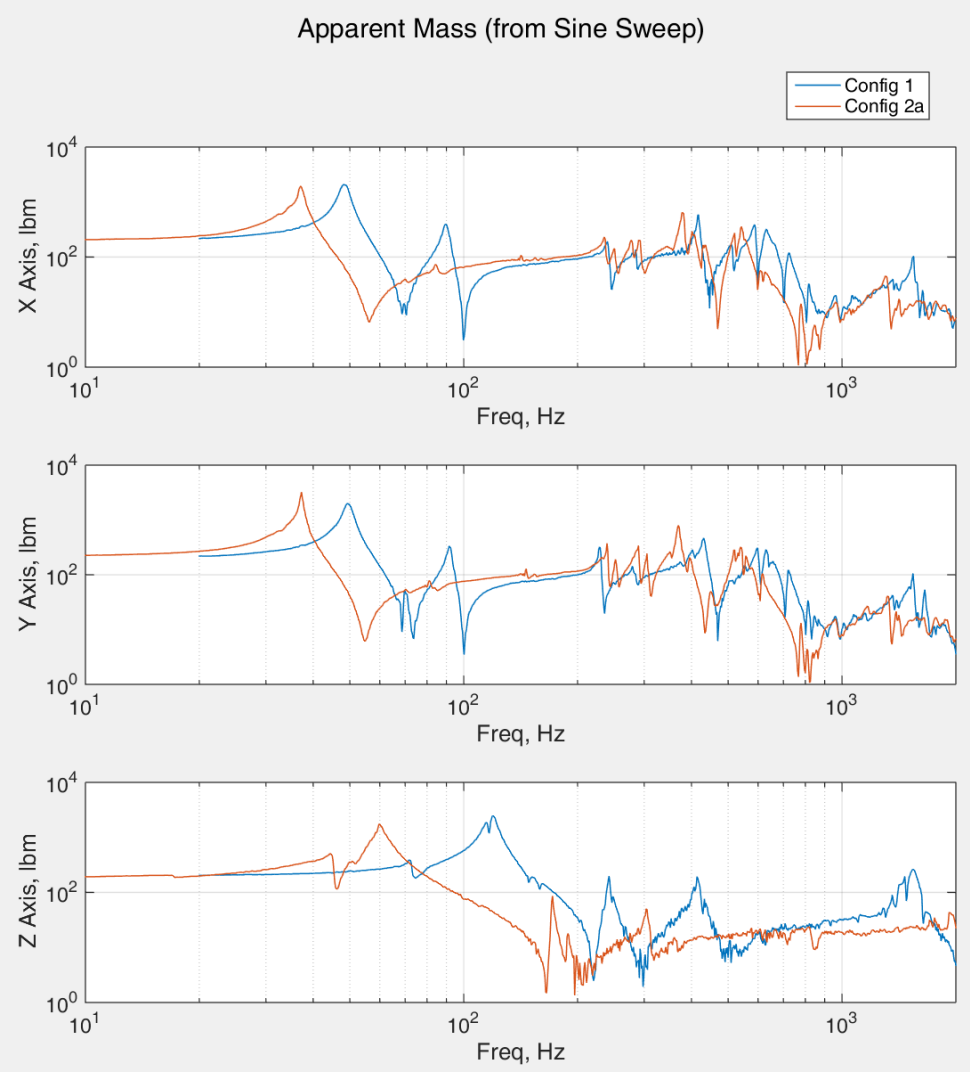
Isolator Test Set-Up

- All NPSCuL configurations, integrated with 8 P-POD Mass Models (P2M2s) and a SAD EDU, were subjected to the following tests in each axis
  - Fixed-base 0.5 G sine sweep, 20-2000 Hz
  - Un-notched and force-limited ABC levels, 7.6 Grms random acceleration input (MPE)
    - FLVT is still necessary to reduce conservatism during test
- Configurations are referred to as follows:
  - Config 1: Baseline (no isolators, original NPSCuL structure)
  - Config 2a: Baseline with constrained isolators (Method 1)
  - Config 2b: Baseline with isolators, typical installation(Method 2)



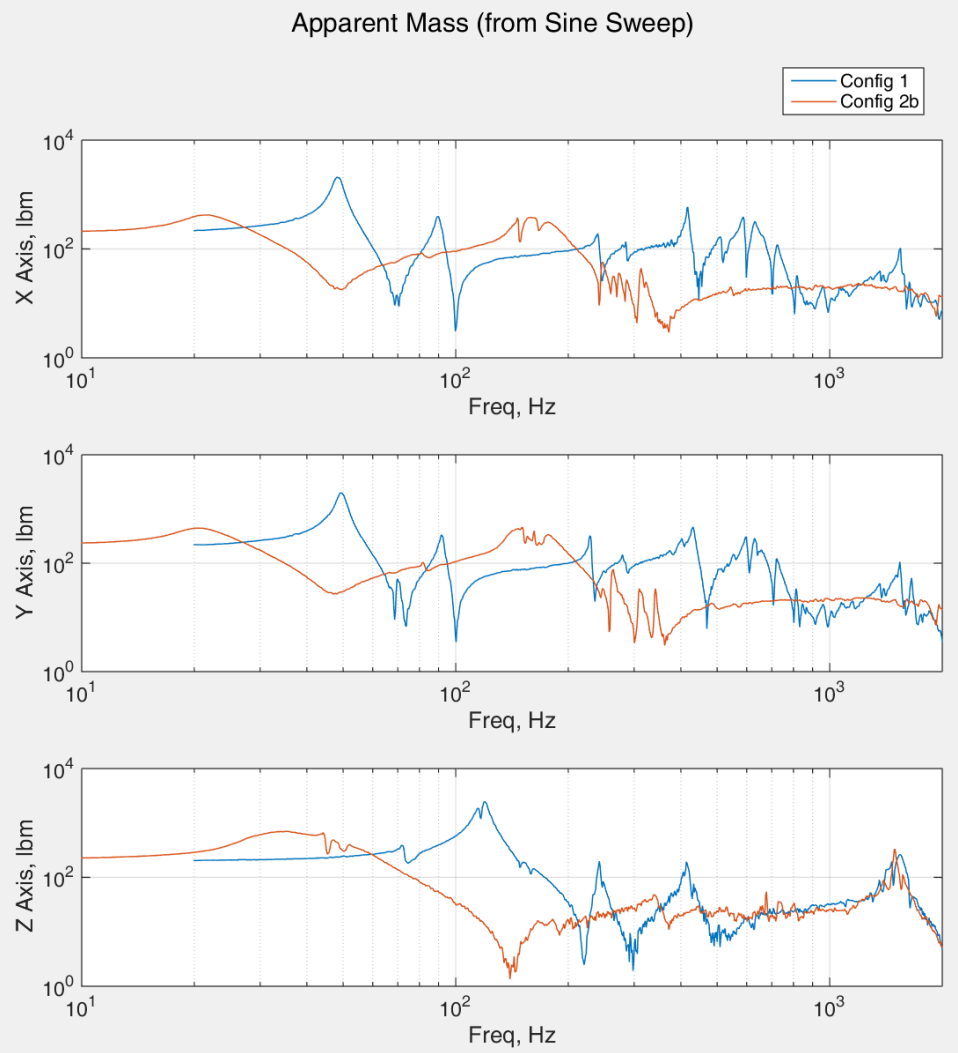
Dynamic Properties of Constrained Configuration

- Isolator system is not effective in lateral directions when constrained
  - First fundamental frequency in X, Y axes shifted lower by 15 Hz
    - Most likely attributed to a lower CG
- Isolators behave as expected in Z axis
  - Indicative of much lower response after the 1st fundamental mode



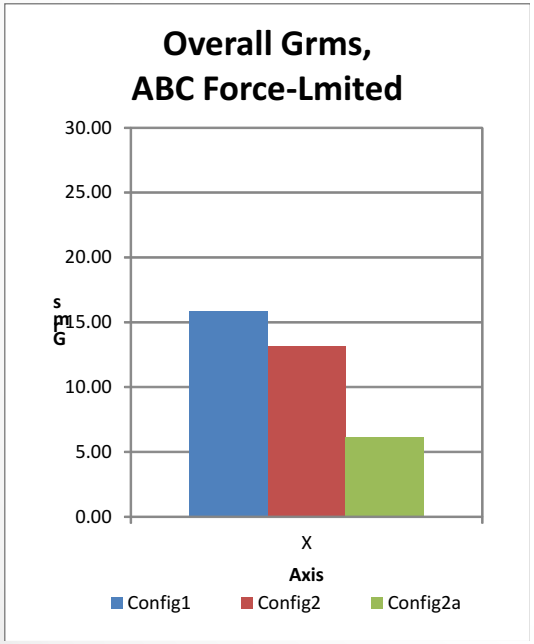
Dynamic Properties of Typical Installation Configuration

- Typical behavior for base-mounted isolators on a box-like structure
  - Results in two (2) distinct modes in each axis and no amplification of higher order modes
- Isolation system appears to produce a tuned-mass damper effect
  - Anti-resonance of isolated system occurs at fundamental frequency of baseline NPSCuL
- Peak at 1560 Hz in Z-axis is an FLVT plate mode
- Lower apparent mass results in lower response in all axes



Performance Summary

- Significant reduction in P-POD interface environment with isolated NPSCuL
  - Lower CG only contributes ~30% of total G_{RMS} reduction
- Qualification G_{RMS} levels would be less than current acceptance G_{RMS}



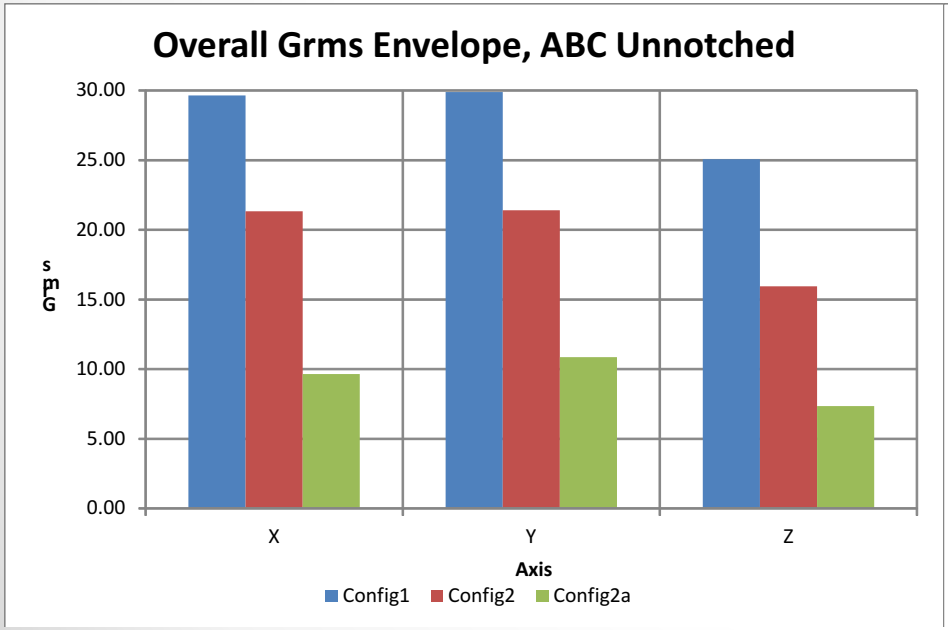
X-Axis G_{RMS} (Worst-Case)

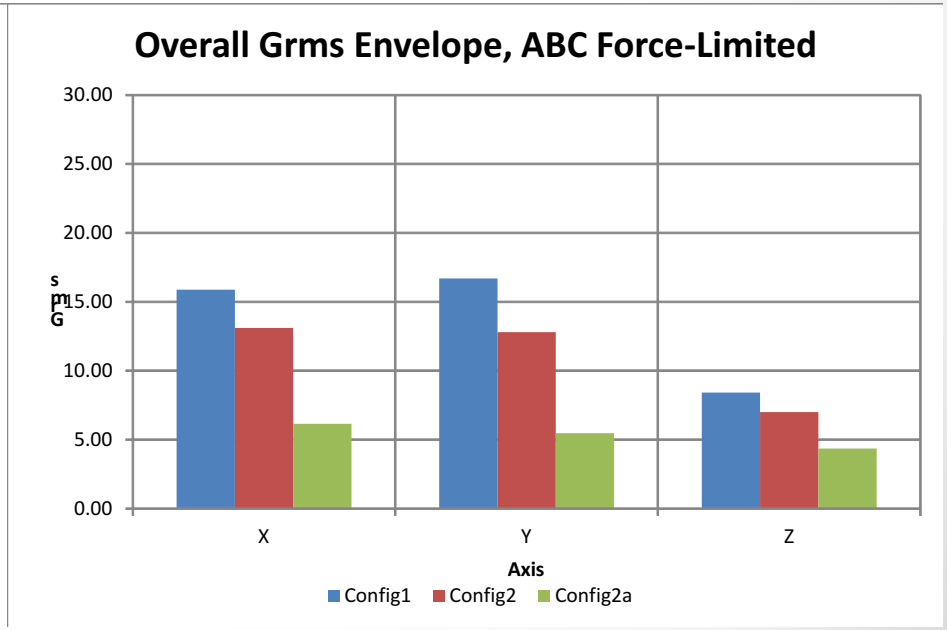
Level	Base (Input)	P-POD Interface, Config 1	P-POD Interface, Config 2b
Acceptance (MPE +0dB)	7.6	15.9	6.2
Protoqual (MPE +3dB)	10.7	22.5	8.8
Qual (MPE +6dB)	15.2	31.8	12.4

*Envelope of development test data (P2M2s)

Combined Effects of FLVT and Isolation

- Isolation system alone is effective in reducing G_{RMS}, but conservatism is still further reduced with FLVT
- Force-limited vibration test setup is still beneficial and plays an integral part in reducing the P-POD response





Benefits for the CubeSat Community

- Provides a COTS isolation system for NPSCuL and CubeSats
  - Isolation system for larger satellites (greater than 500 lbs) exist, but are often mission-specific
  - Applicable to other ESPA-class spacecraft of similar size
- Cost of NPSCuL isolation system is ~$2000 for 35-85% reduction in random vibration environment
  - Considerable cost reduction over existing industry customized spacecraft isolation for similar performance*
- Proposed isolation system is compatible with ESPA and PSC MLB interfaces and can be easily altered for use with any ESPA-class interface
  - Main design parameters include mass and mounting configuration on LV

***References:**
Wilke, P., Johnson, C., Grosserode, P., Sciulli, D., *Whole-Spacecraft Vibration Isolation on Small Launch Vehicles,* Smart Structures and Materials 2000, Damping and Isolation, 2000.
Johnson, C., Wilke, P., Pendleton, S., *SoftRide Vibration and Shock Isolation Systems that Protect Spacecraft from Launch Dynamic Environments*, 38th Aerospace Mechanisms Symposium, 2006.

Conclusion and Path Forward

- Effective and low-cost solution to provide a "first-class ride" to space for CubeSats and small spacecraft
  - Investigating other COTS isolators of comparable size that can be used in tension, compression, and shear without compromising isolator effectiveness
  - Typical isolator installation configuration in tension with current isolator may be investigated
- Qual test will be performed with final isolator selection