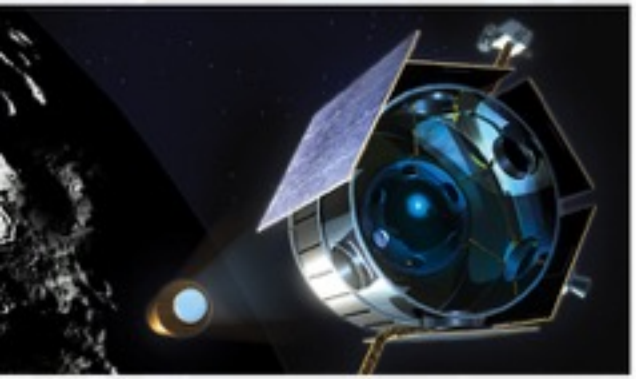
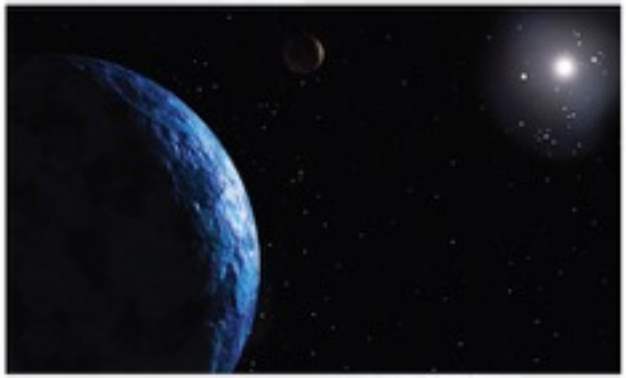


Moog Capabilities for Small Satellites
CubeSat Launch and Deployment Accommodations

13th Annual CubeSat Developer's Workshop

Joe Maly and Marissa Stender

MOOG
SPACE AND DEFENSE GROUP

Outline

- Moog Space Access and Integrated Systems
- Payload adapters and CubeSat accommodations
- Vibration and shock isolation for CubeSats
- Orbital Maneuvering Vehicles (OMVs) for customized satellite deployment
  - Propulsive ESPA for Atlas V and Falcon 9
  - Nano-Launch OMV for new class of launchers

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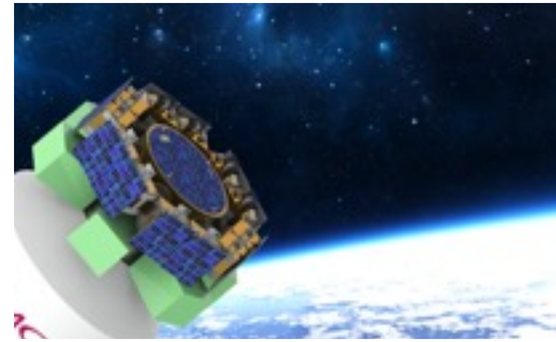
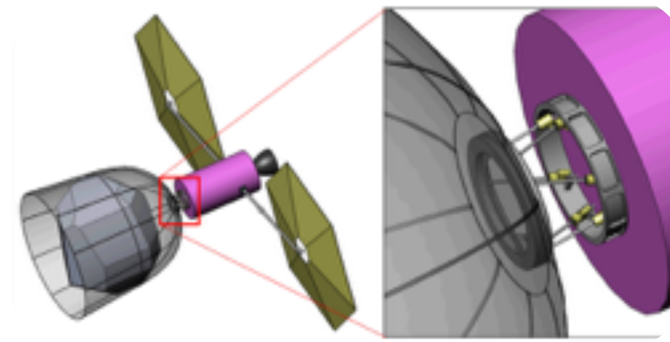
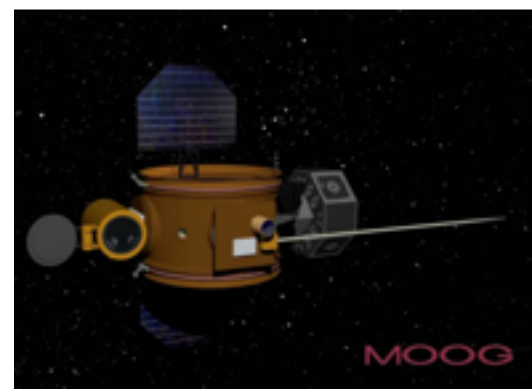
Moog Space Access and Integrated Systems

CubeSat and OMV work is mainly supported by Moog personnel in Golden, CO, Mountain View, CA and Chatsworth, CA







- Moog Integrated Systems provides a focal point to harness the breadth and depth of Moog capability
  - Mission architecture/design
  - Launch strategy
  - Spacecraft systems engineering
- The IS group works with customers at the initial stages to identify and optimize technical, cost, risk and programmatic trades
- Moog has supported trades and developed concepts for:
  - Commercial GPS-RO Weather constellation
  - Commercial Broadband Satellite Mega Constellation
  - NASA Asteroid Return Mission
  - Non-traditional Mars Mission
  - Numerous mission concepts based on an Orbital Maneuvering Vehicle (OMV)

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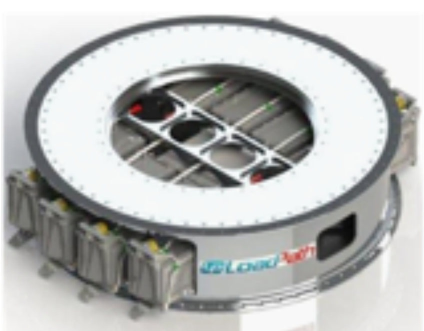
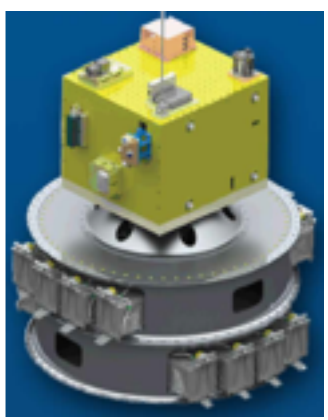
Moog Secondary Payload Adapters For Rideshare

- ESPA: Moog flagship adapter product (up to 300kg secondary payloads)
  - Atlas V, Delta IV, Falcon 9 heritage
- Moog has partnered on the development of nanosat deployers
  - Cubestack and NLAS Wafer adapters:
    8x 3U, 4x 6U (or combinations)
  - FANTM-Ride: ESPAsat-sized box, 3U & 6U spacecraft with additional space for central microsat

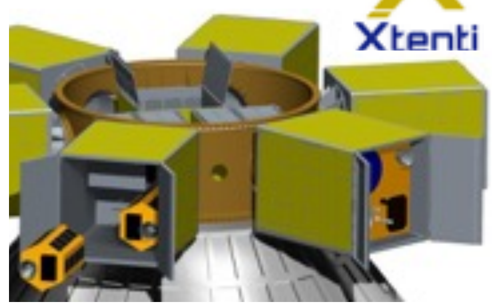

Photo Credit: ORBCOMM

LoadPath

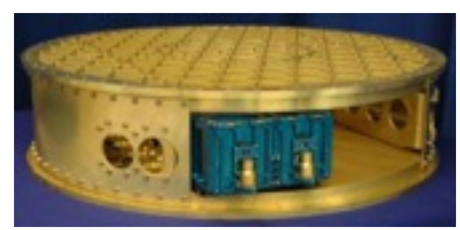




Xtenti



NASA
Ames Research Center



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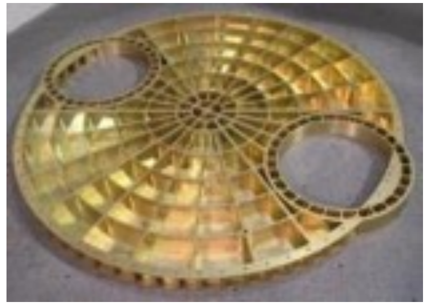
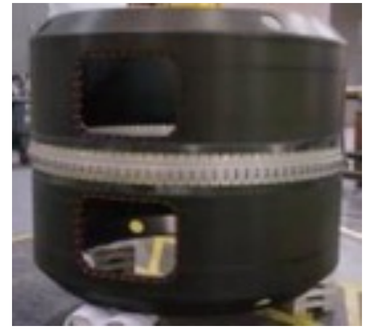
Moog Growing Family of Adapters

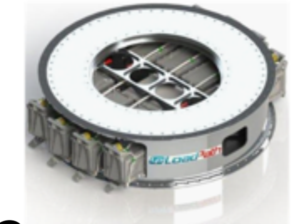
ESPA



Flat Plate Adapters



CASPAR



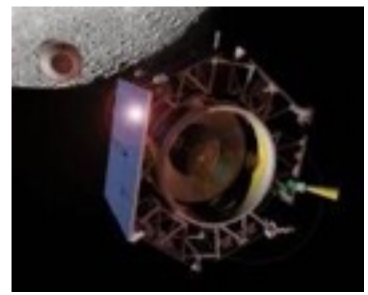
CubeSat Wafer

ESPA 6-15-24 LCROSS

SL ESPA 15

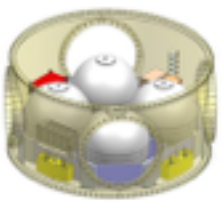
SL ESPA 24

ESPA SUM

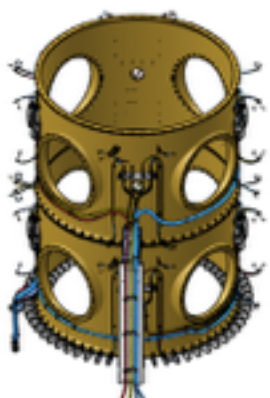


ESPA as Bus: LCROSS

ESPA 4-15-24 DSX



ESPA 4-24-32 SPECIAL OMEGA



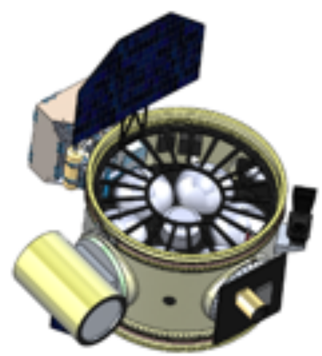
2x ESPA 4-24-42 ORBCOMM

ESPA 2-15-24-4PT EAGLE

ESPA 5-24-42 SHERPA

ESPA n-d-h

n=number of ports, d=port diameter (inches), h=ring height (inches)



OMV

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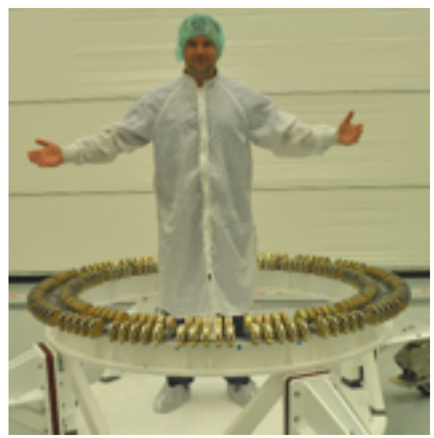
ORBCOMM Generation 2 (OG2) on ESPA

ESPA Dispensers for OG2 constellation deployment

- M2M communication for transportation and distribution, heavy equipment, oil and gas, maritime and Government customers
- Seventeen OG2 satellites launched on two Falcon 9 missions July 2014 and December 2015

ESPA rings at Moog CSA in Mountain View



SoftRide installed at SpaceX SLC-40

photo credit ORBCOMM

Moog engineers assembling dispenser stack

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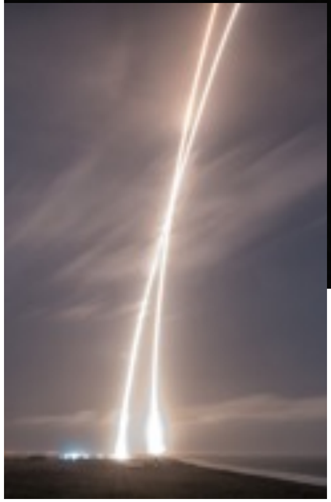
OG2 Mission 2 Payload Stack and Deployment

- ESPA Grande stack with eleven OG2 satellites
- Deployment in Low Earth Orbit after rocket landing at Cape

photo credit ORBCOMM

SpaceX SLC-40 at Cape Canaveral

ESPA Dispenser deploys satellites on orbit



Falcon 9 launch
and landing
21 December 2015

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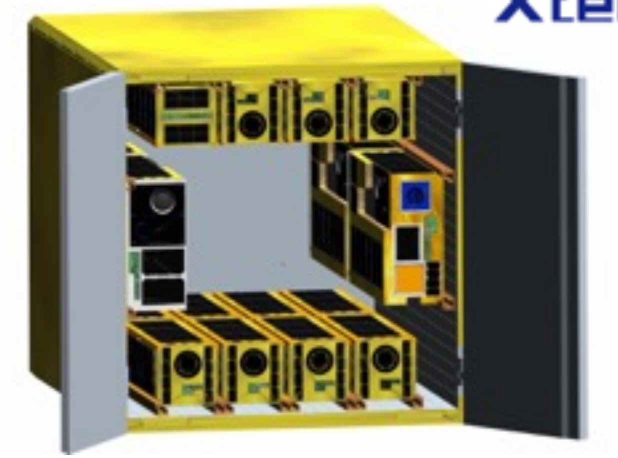
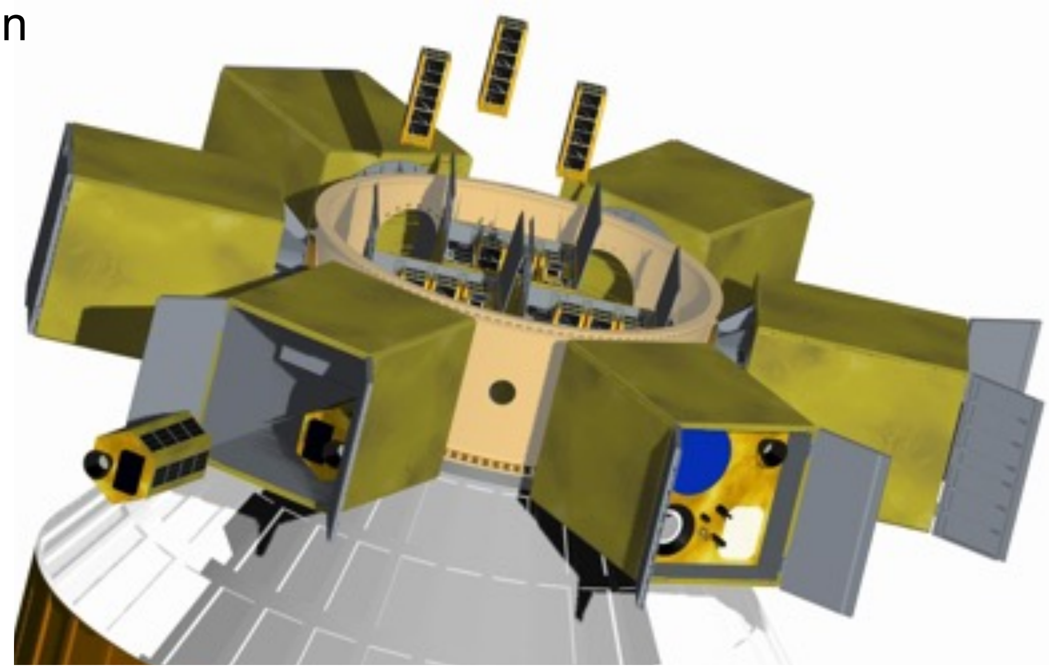
FANTM-RiDE™

Configurable enclosure for multi-manifest missions

- Collaboration between Xtenti and Moog CSA
- Mix and match CubeSats with microsats and other nanosats in ESPAsat-sized box (610 mm x 610 mm x 812 mm)
  - FANTM-RAIL: CubeSat deployer in development
    - 3U and 6U spacecraft two deep along interior walls, leaving space for central microsat
  - Compatible with multiple launch options
- Mass tuned for flexible integration schedule
  - No need for last-minute coupled loads analysis
- Integration services provided by Xtenti





www.fantm-ride.com

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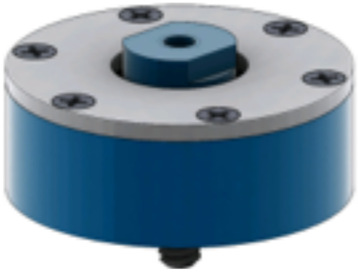
Vibration/Shock Isolation for CubeSat Launch

- Presentation at Small Satellite 2015* showed cyclic loading contributes significantly to CubeSat failures
  - Accelerations due to random vibration and shock
  - Thermal loading
  - Pressure, vacuum, humidity cycling
  - Assembly cycles
- Vibration isolation can be used as low-pass mechanical filter to greatly reduce accelerations on payload
  - Whole spacecraft vibration isolation has reduced dynamic environments for satellites on 36 launches since 1998
    - Moog CSA SoftRide has flown on vehicles ranging from Terrier Orion and Minotaur to Delta IV Heavy
- New isolator design for CubeSats developed for shock isolation of industrial equipment
  - ShockWave (patent pending) isolators



* *Methods to predict fatigue in CubeSat structures and mechanisms,* Holemans, Azure, Hevner, Planetary Systems Corp., 12th Annual Summer CubeSat Developers' Workshop

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ShockWave Isolators for CSDs

- 2nd generation CubeSat dispensers feature fixed mounting of payloads within enclosure
  - Fixed mounting provides linear behavior during shock and vibration loading, enabling dynamic testing and finite element analysis
  - Planetary Systems Corporation's Canisterized Satellite Dispensers (CSDs) will be used for Exploration Mission 1 (EM-1) payloads
- Moog ShockWave isolators were tested as part of PSC's 6U CSD qualification testing
  - Significant mitigation measured in sensitive frequency ranges for CubeSats
- ShockWave product sheet in development
  - Lookup table to set isolation break frequency based on isolator stiffness and number of isolators
  - Pricing compatible with CubeSat program budgets

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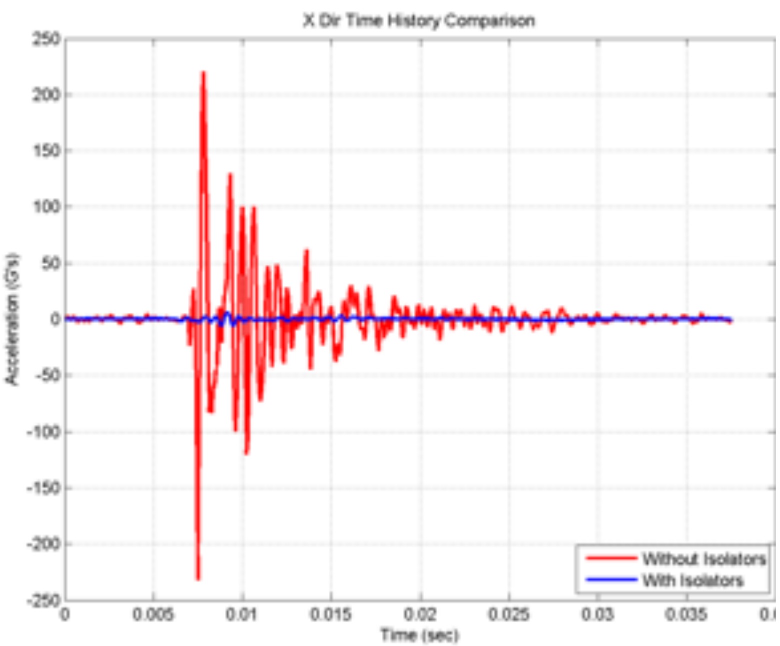
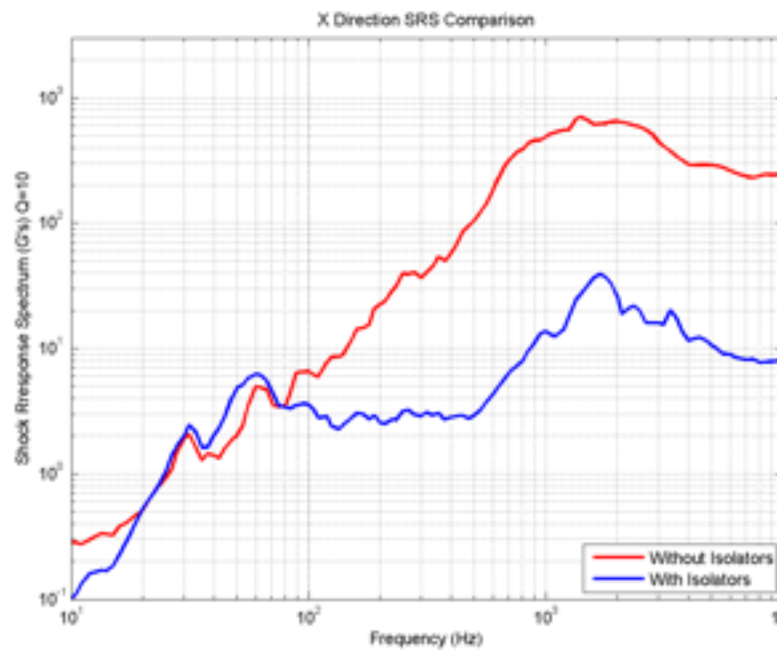
ShockWave Test Results

Testing performed in 2015 for industrial application

- 40x reduction in shock loads
- Peak acceleration < 10 Gs





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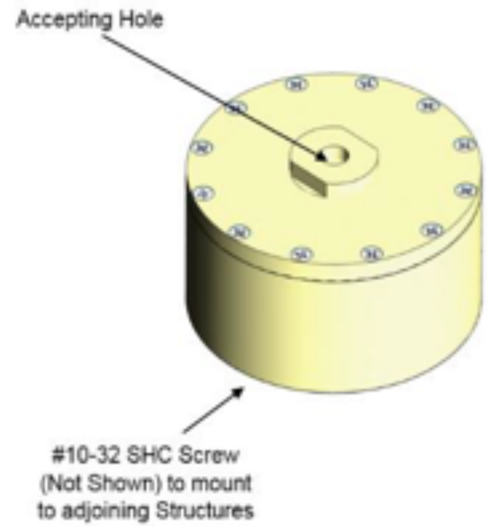
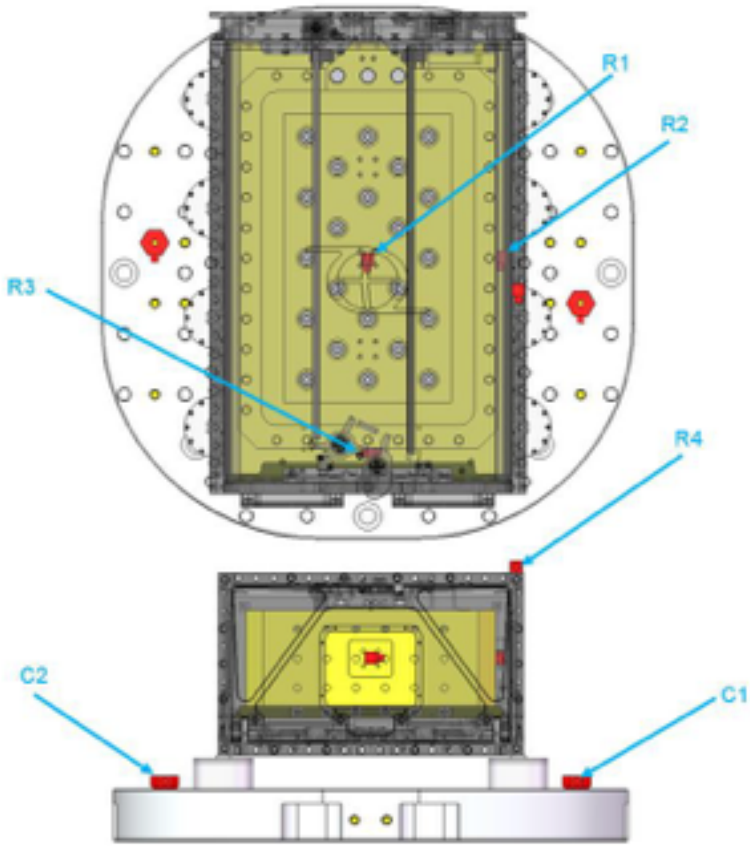
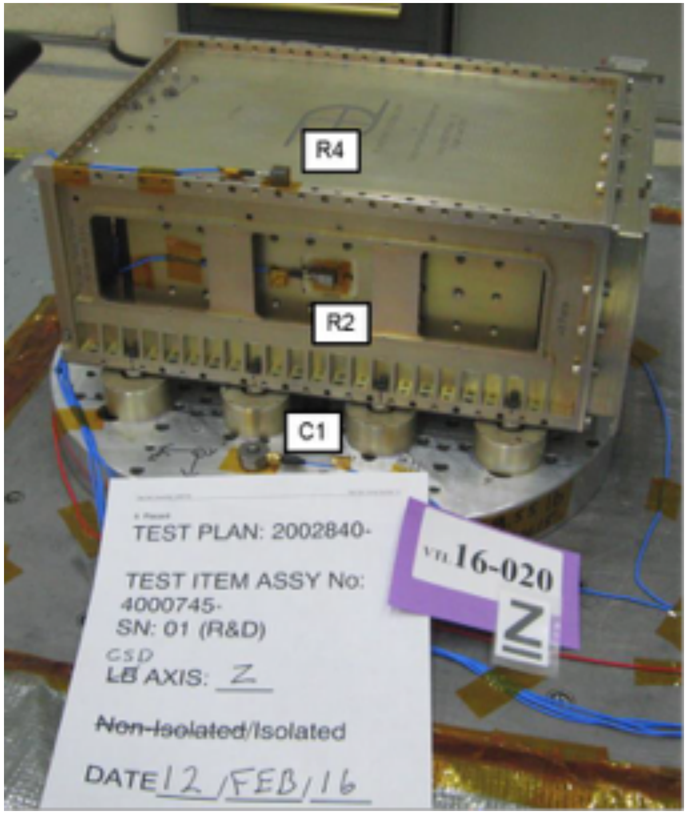
ShockWave Testing at PSC



6U CSD mounted to vibration table with eight ShockWave isolators

- Accelerometer locations C1 thru R4 shown





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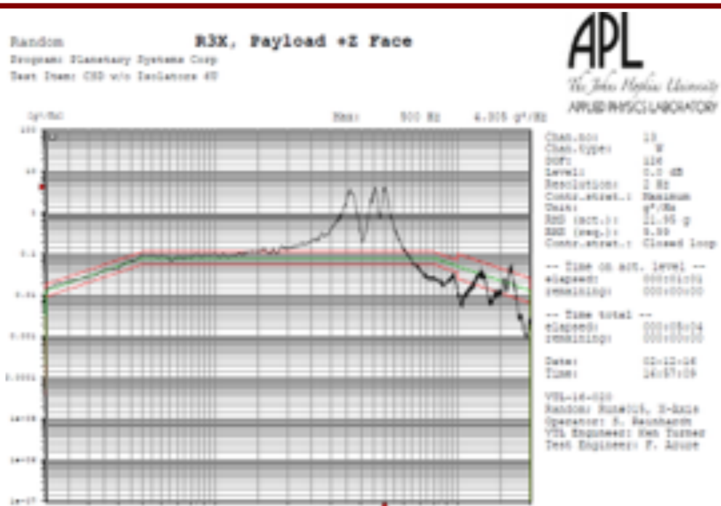
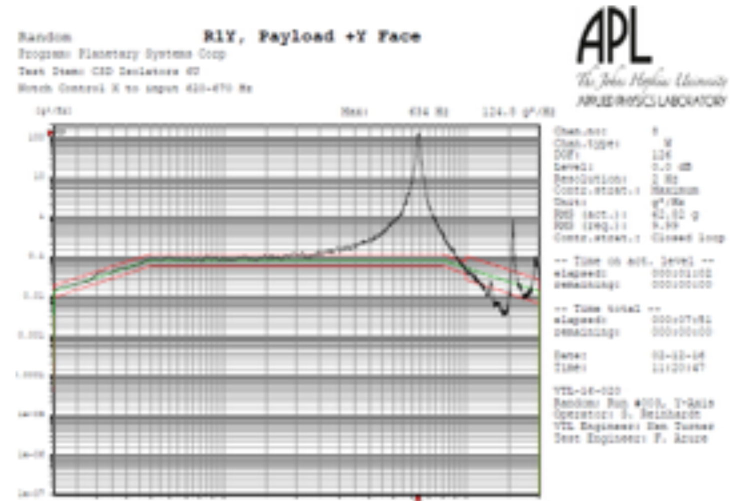
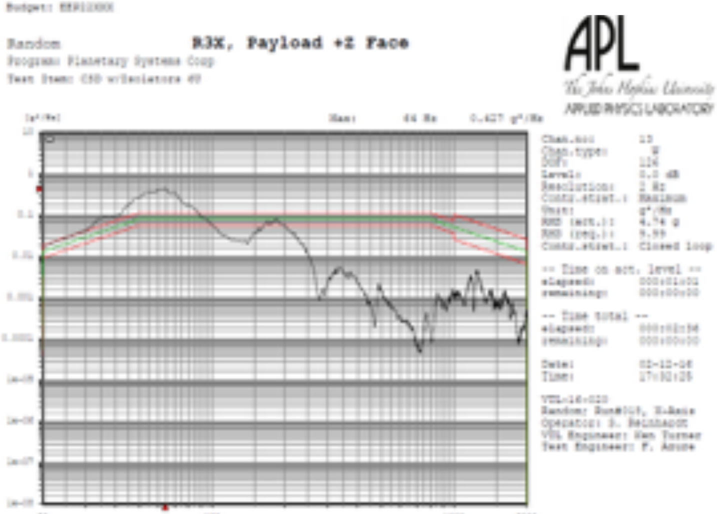
Isolators reduce g RMS levels by factor of 13!



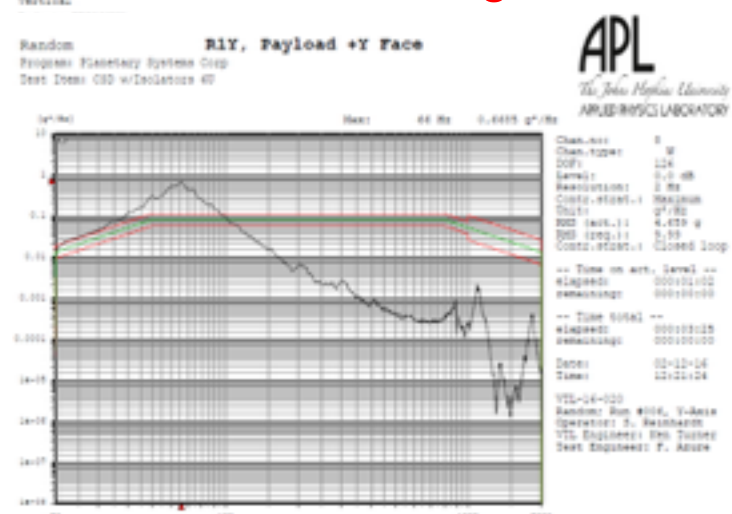
no isolators 21.9 g RMS



no isolators 62.8 g RMS



with isolators 4.7 g RMS



with isolators 4.7 g RMS

Isolators are cheap insurance against mission failure

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Orbital Maneuvering Vehicle Update

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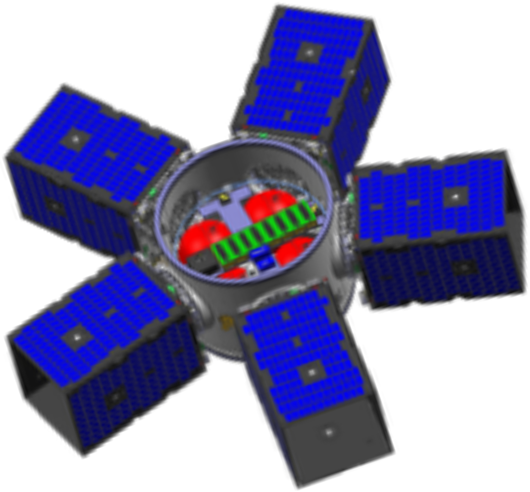
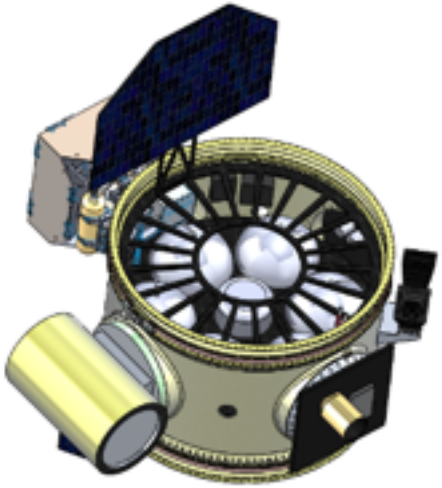
OMV Architecture

- The OMV architecture is based on a breadth of capabilities from across Moog's Space and Defense group
- The goal is to provide a baseline capability that can be expanded and upgraded to meet each specific mission's requirements including:
  - Flexible avionics architecture (variable redundancy, hosted payload ability)
  - Modular power system for a range of load configurations and mission durations
  - Highly adaptable propulsion architecture balancing cost, performance and versatility
- Notional Flight Readiness: Late 2018



Small Satellite Deployment Concept



ELLIE: Earth-Sun L1 Mission (Moog/ AMES/Langley Team)

Stand-alone Propulsion Module + ESPA

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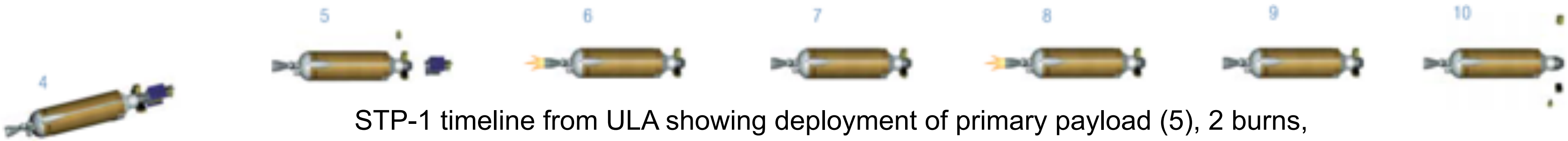
Typical Operations & Orbits

- An OMV, or a passive ESPA ring, can be launched in multiple configurations
  - Individual entity below Primary Payload
    - Example: STP-1 launch (see graphic)
  - As part of a larger stack of ESPA rings
    - Moog integrated a three-stack ESPA configuration for launch on a SpaceX Falcon 9 return-to-flight in December 2015
- An OMV can act as a tug or a hosted payload platform
  - For launches to sun-synchronous orbit (SSO), an OMV can provide altitude and the small inclination changes required to maintain sun-synchronous inclination
  - For longer duration missions, the OMV can remain on-orbit to provide all the necessary capabilities to power a payload and downlink data


Photo courtesy USAF


Photo courtesy ORBCOMM



STP-1 timeline from ULA showing deployment of primary payload (5), 2 burns, then deployment of secondary payloads from ESPA ring (10)

Image from www.ulalaunch.com

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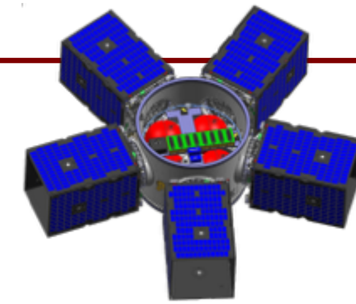
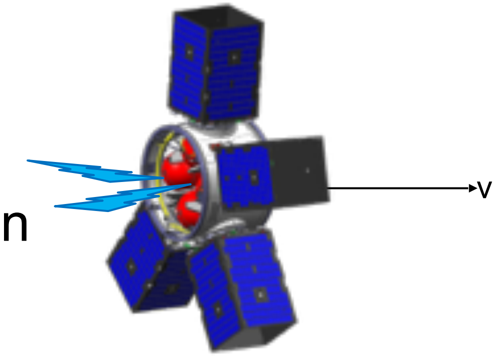
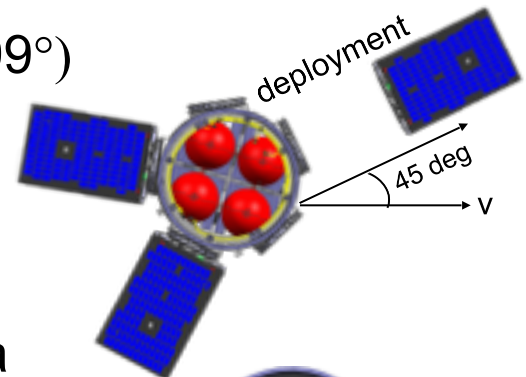
Notional LEO Rideshare CONOPs



Timeline

- OMV Drop-off at 450 km SSO
- Detumble
  - Deploy Initial Payload(s)
    - Slew to +/- 45° off of velocity vector to minimize chance of recontact
- Increase Altitude and Change Inclination to maintain sun-synchronous orbit (550 km/97.59°)
  - Deploy Payloads
- Repeat maneuvers and deployments (650 km/97.99°)
- Deorbit OMV





CONOPs delta-V requirement: ~325 m/s

Expanded CONOPs: Add phasing maneuvers within a single orbital plane for constellation delivery

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Mission Simulation

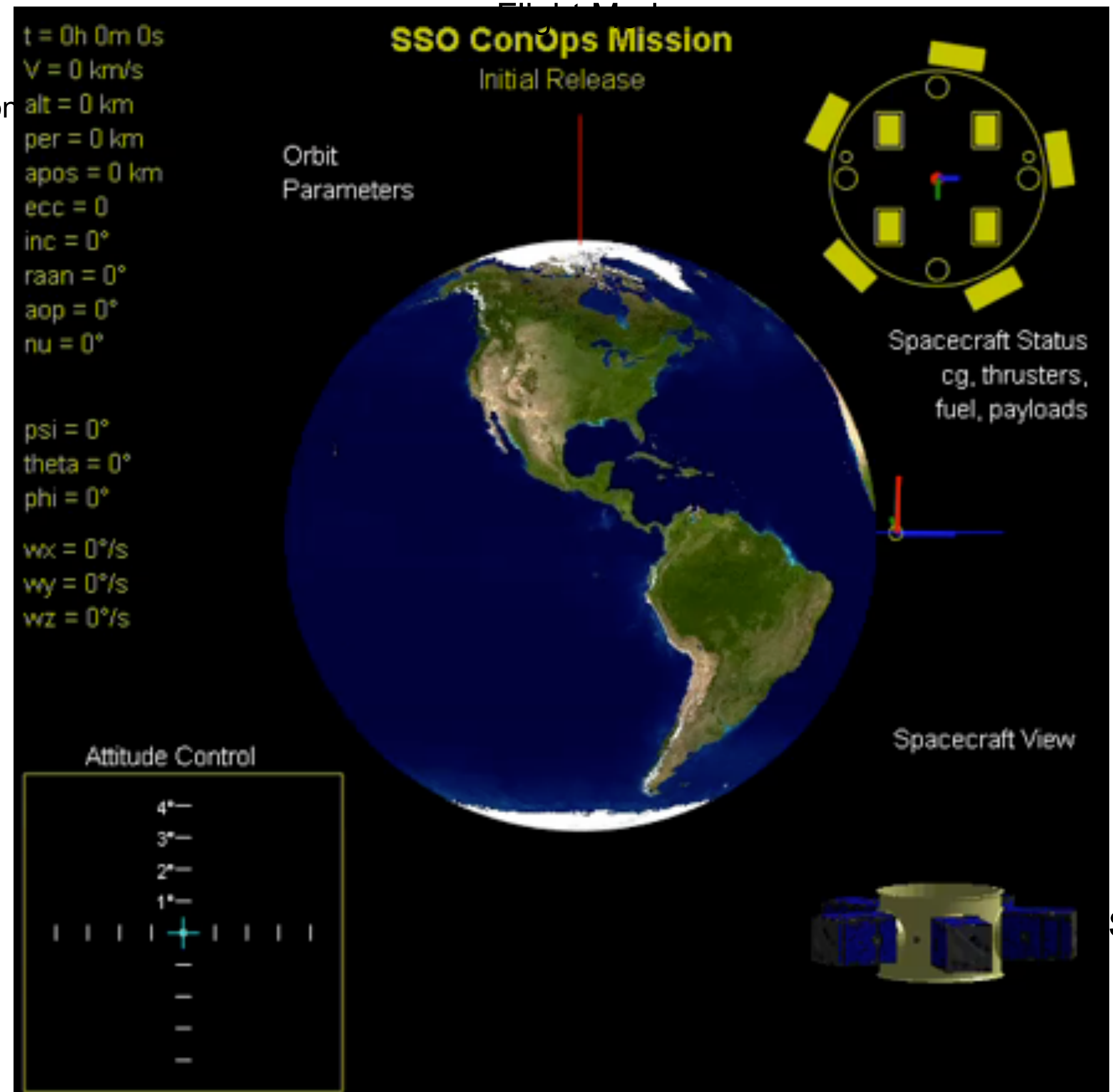
116:1 time speedup

- 3.9 hour mission in 2 minutes

Orbital parameters

Sun synchronous orbit = high (97°) inclination

Pointing accuracy reticule



Spacecraft status icon

- Thruster activity
- Fuel remaining
- Payload status

Flight path and attitude w.r.t Earth Centered Inertial

Spacecraft 3D

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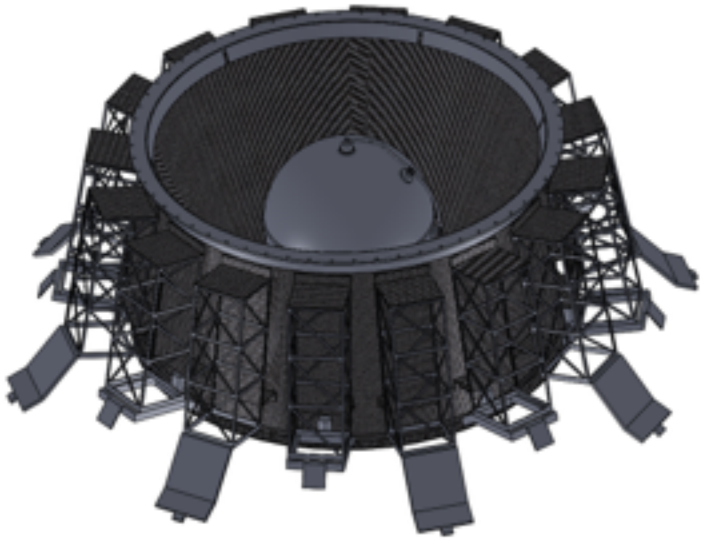
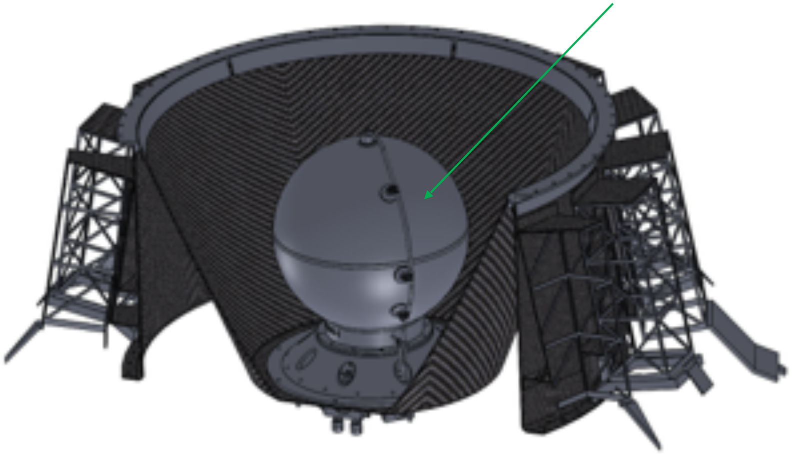
Moog Nano-Launch OMV (NL-OMV)

- Designed for a lighter primary payload & smaller diameter launch vehicle fairing
  - Delta-V >350 m/s fully loaded
- Minimal Mass
  - Composite Cylinder Adapter: 38.81” Bolt Circle interface, 20” Height
  - Lightweight CubeSat dispensers
    - Tyvak RailPOD (shown)
    - FANTM-RAIL
    - Teton Aerospace dispenser
- Maximized Payload Carrying Capability
  - 16 x 3U CubeSats
- Modularity
  - Flexible adapter height
  - Customizable quantity of dispensers
  - MPU tank size can be increased with no change in the pedestal adapter size
- NL-OMV is an option for small “Venture Class” launch vehicles





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Contact Info

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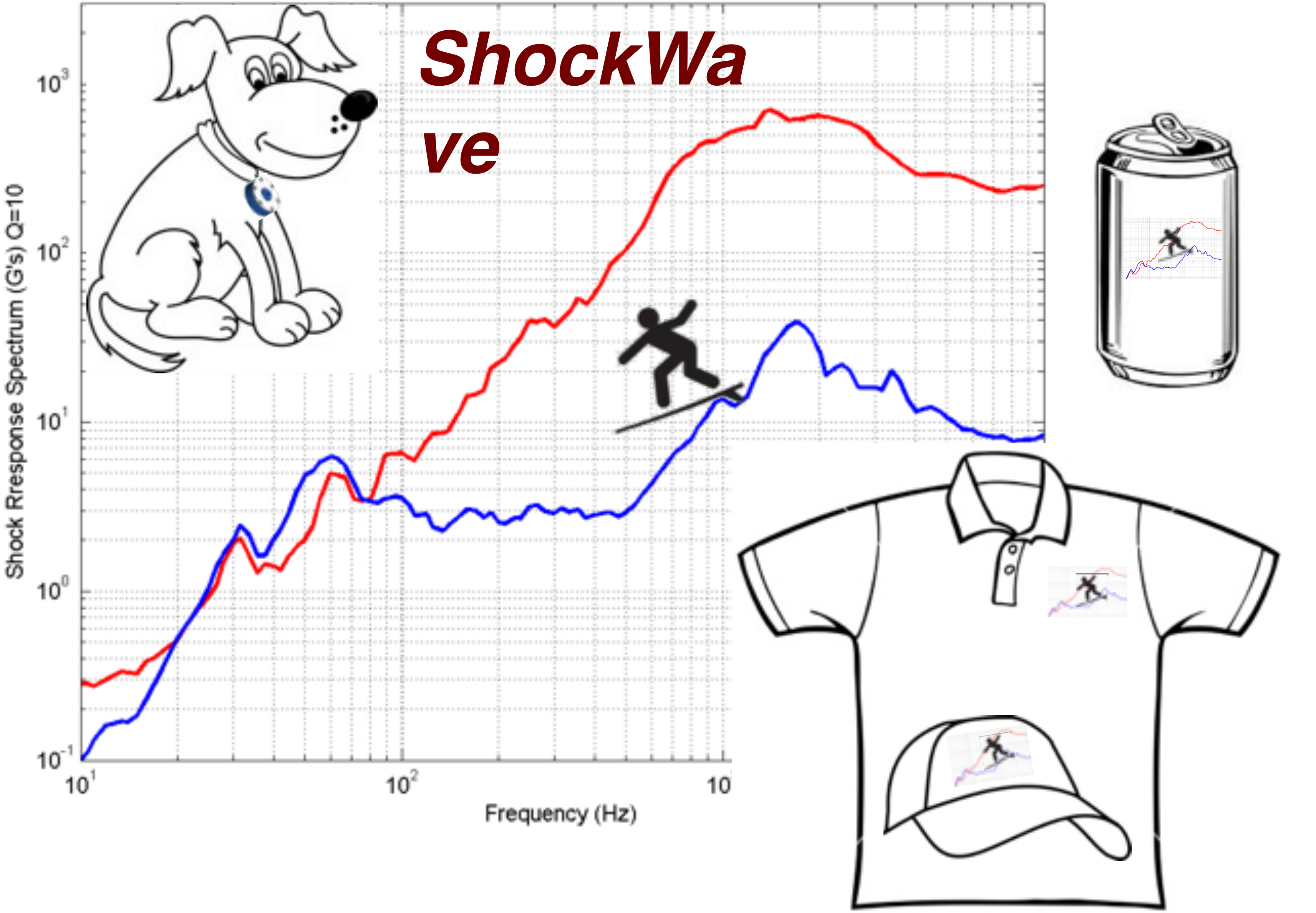

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