

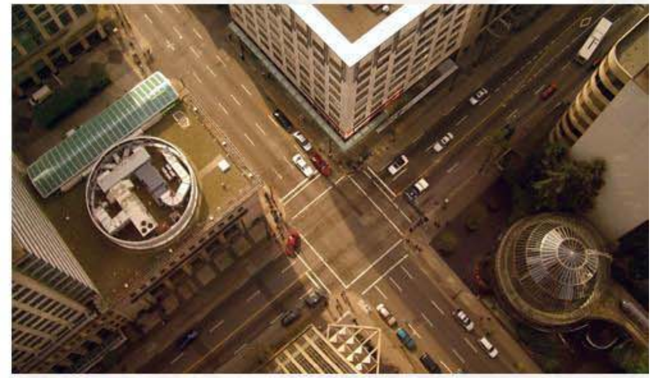

Moog CSA Engineering

ESPA CubeSat Accommodations and Qualification of 6U Mount (SUM)

10th Annual
CubeSat Developer's Workshop
25 April 2013

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Summary

- ESPA background
- ESPA CubeSat accommodations
- ESPA SUM qualification program
- Other Moog CubeSat activities
  - CubeStack adapter for Minotaur
  - NASA/Ames NLAS adapter
  - MultiPayload Sequencer
  - Athena MultiPayload Adapter
  - Moog ISP propulsion
  - 27U Mount for ESPA 24” port

ESPA History

- 1995: Adapter concept originated at DoD Space Test Program (STP)
- 1998: STP/AFRL Memorandum of Agreement
  - Contract award to CSA for EELV adapter to utilize excess launch capacity for secondary payloads
- 1999-2001: CSA ring design and fabrication
  - ESPA structure developed under Air Force Research Lab SBIR contract to CSA with financial and technical support from STP
  - CSA subcontracted to Boeing and Lockheed Martin for design loads, qualification requirements, support for test design
- 2002: ESPA qualification testing
  - Static test facility at AFRL developed by CSA
- 2007: STP-1 ESPA first flight
  - First Air Force Atlas EELV
- 2008: Memo by Secretary of Air Force on ESPA
  - CSA ESPA option configurations developed under NASA SBIR
- 2009: First NASA ESPA on Atlas V lunar mission LRO/LCROSS
- 2010: ESPA Standard Service Critical Design Review
- 2012: ESPA SUM (6U Mount) qualified for flight
- 2013: First ESPA mission on Falcon 9

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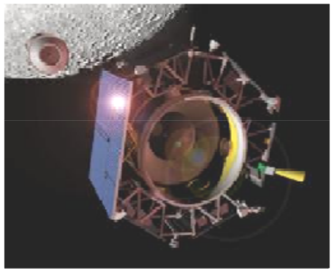
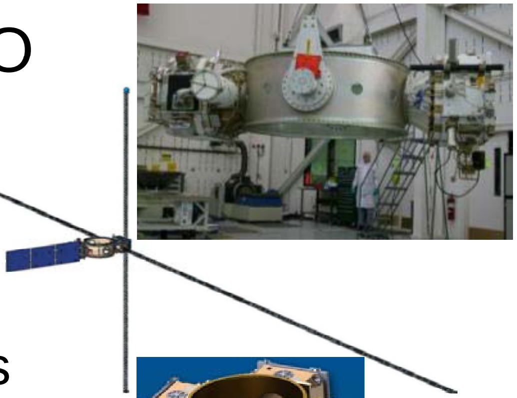
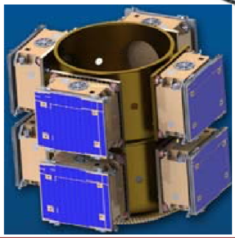
ESPA Programs

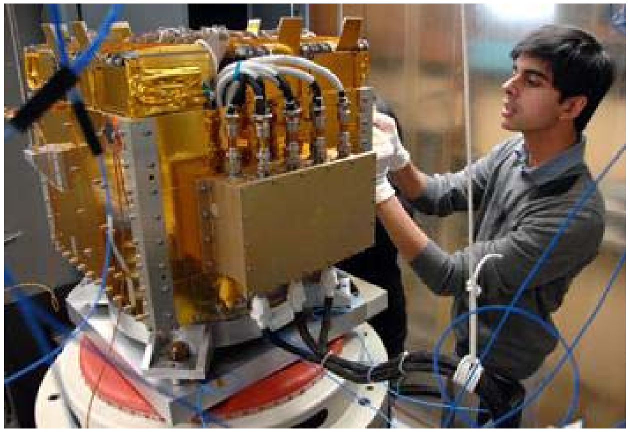
- STP-1 March 2007 Air Force mission launched six spacecraft
- LCROSS June 2009 NASA lunar impactor mission
  - ESPA “shepherding spacecraft” with on-board propulsion guided Centaur impactor to lunar surface
  - ESPA craft itself was secondary impactor
- AFRL DSX ESPA is hub of free-flyer in MEO
  - STP-2 launch on Falcon Heavy
- EAGLE ESPA in development by AFRL
  - Orbital Sciences prime contractor: propulsive ring with hosted and flyaway payloads
- ORBCOMM Generation 2 constellation launch
  - First SpaceX ESPA mission, first ESPA constellation



ESPA Secondary Payloads

- ESPA can carry six secondary payloads up to 400 lb each while supporting primary spacecraft to 20,000 lb
  - Designed to use excess launch capacity on Atlas V and Delta IV
  - Compatible with Falcon 9 and Antares
- NPSCuL packages up to eight P-PODs as secondary payload with ESPA 15” interface
  - Naval Postgraduate School adapter for CubeSats
  - Maiden launch in summer 2012 on Atlas V Aft Bulkhead Carrier

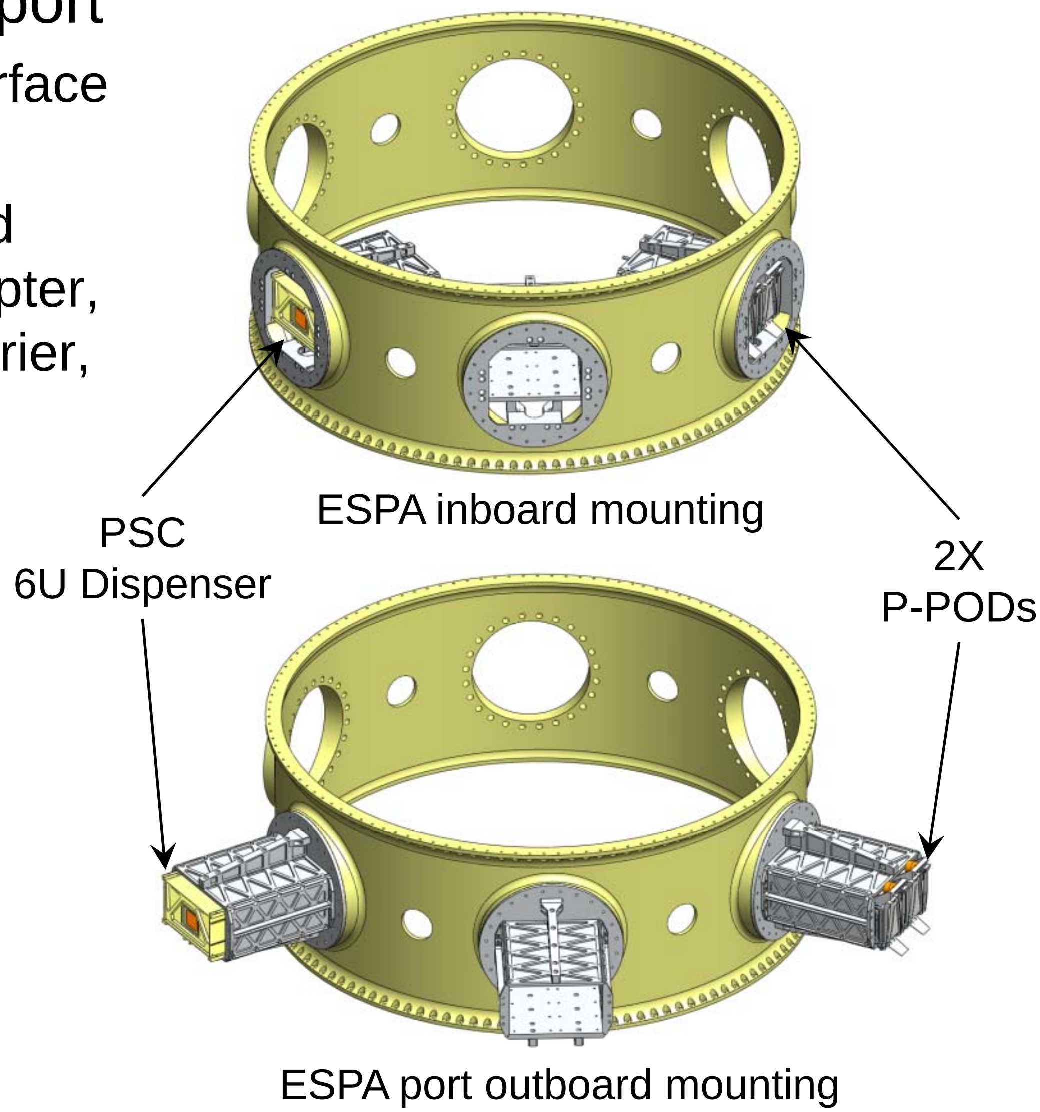


NPSCuL in test
courtesy *www.nps.edu*

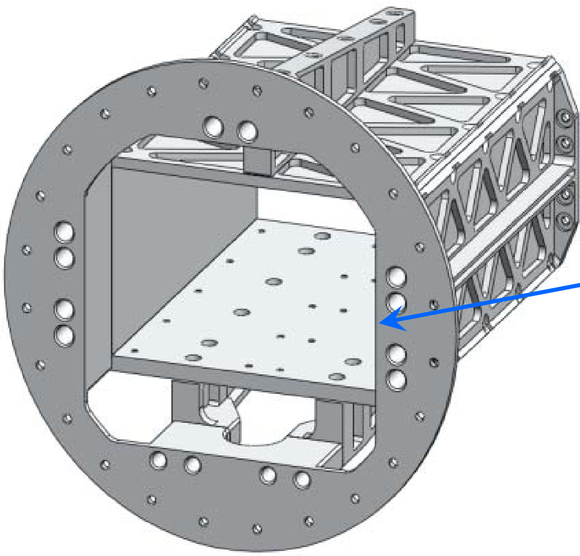
- ESPA 6U Mount developed to utilize interior of ring
  - Qualification program funded by NASA Launch Services Program
  - Design allows inboard and outboard mounting on ESPA port

ESPA Six U Mount

- SUM mounts on ESPA port
  - Standard secondary interface 15” bolt circle
  - Compatible with standard Athena II Rideshare Adapter, Atlas V Aft Bulkhead Carrier, CubeStack
- Holds two P-PODs or one 6U dispenser
  - Inboard or outboard mounting on port
- Enables increased capacity for ESPA
  - Six 400-lb satellites <u>and</u> twelve 3U satellites

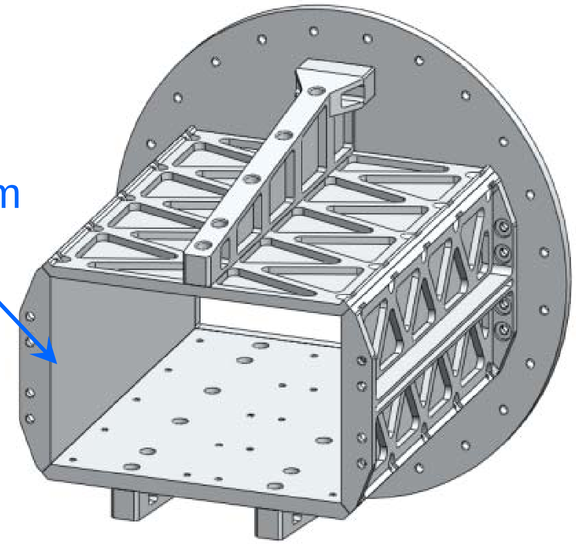


SUM Inboard and Outboard Assemblies



ISO VIEW
INBOARD MOUNT
29.0 lbs

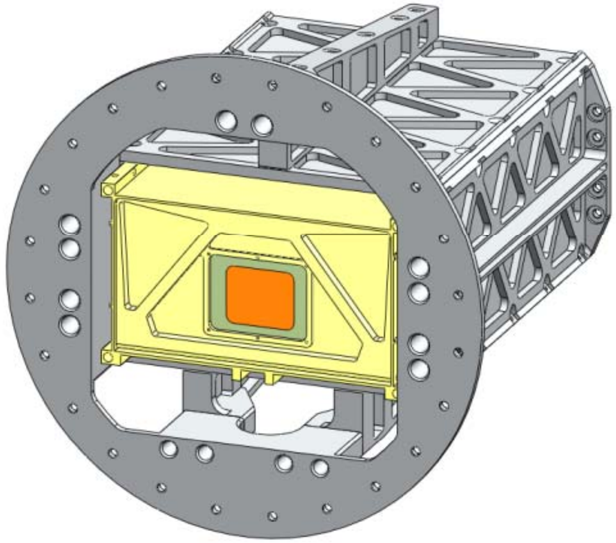
CubeSats deploy from front or rear of SUM

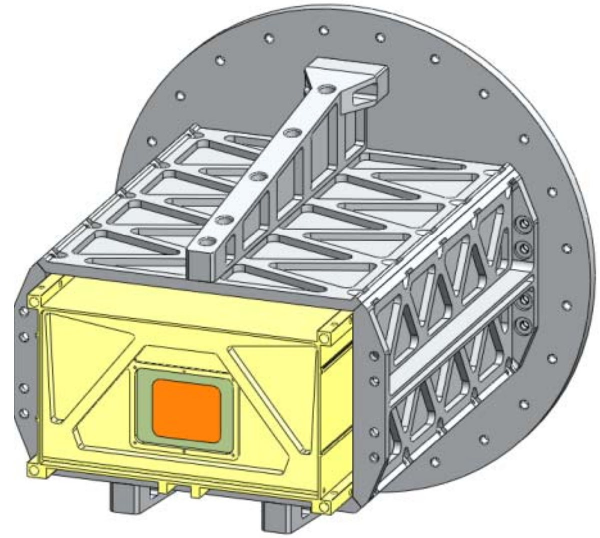


ISO VIEW
OUTBOARD MOUNT
28.3 lbs

SUM with CubeSat Dispensers

PSC 6U Dispenser

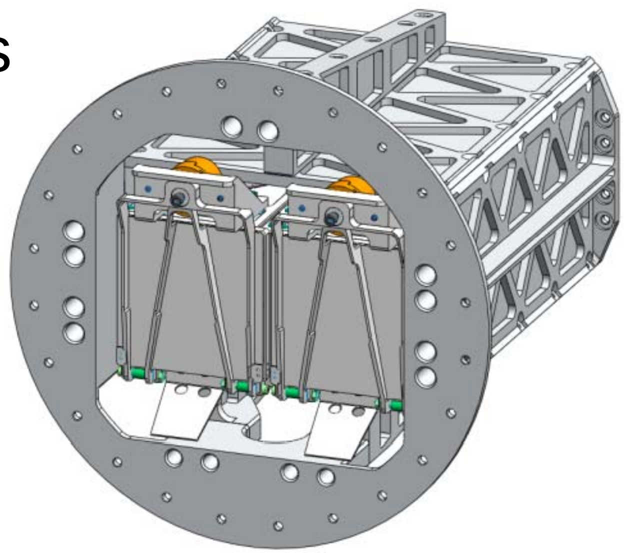


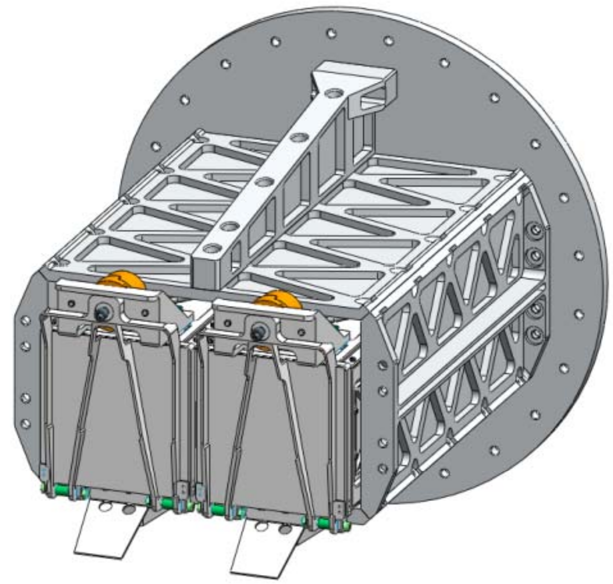


INBOARD MOUNT

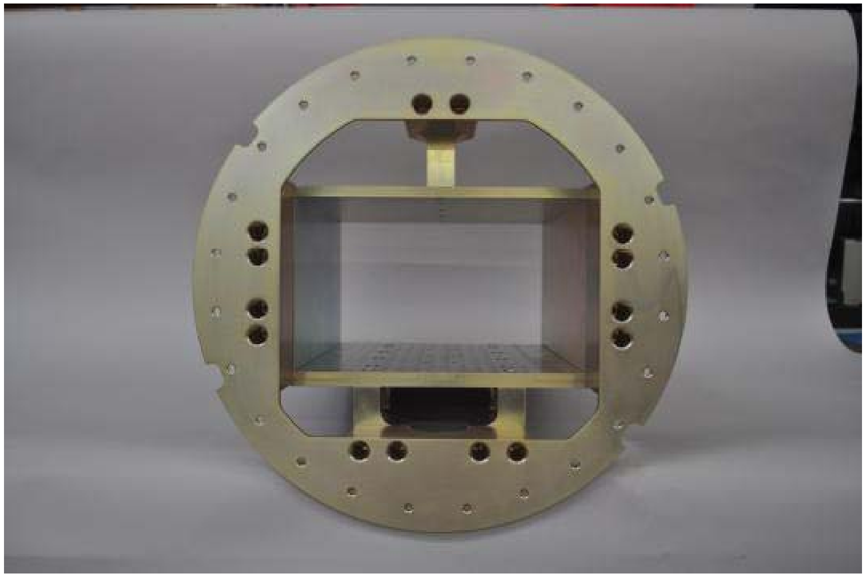
OUTBOARD MOUNT

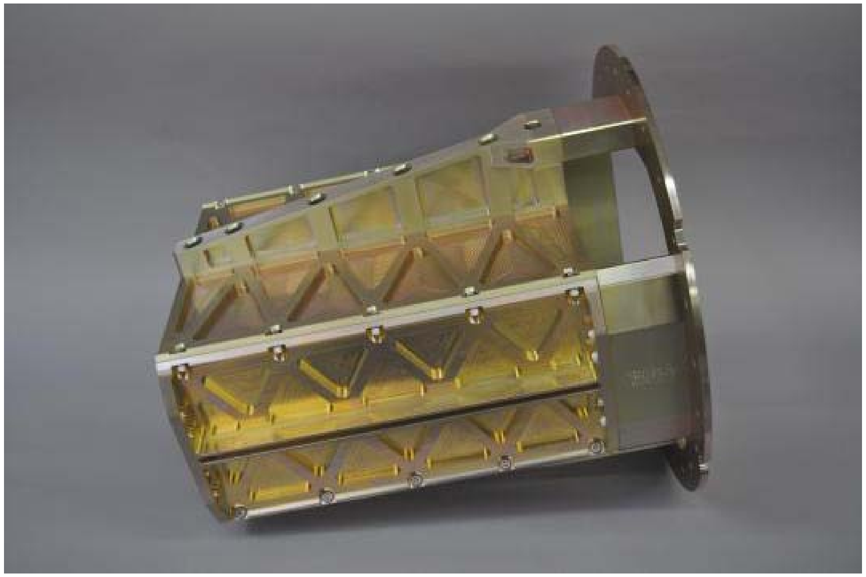
P-PODs

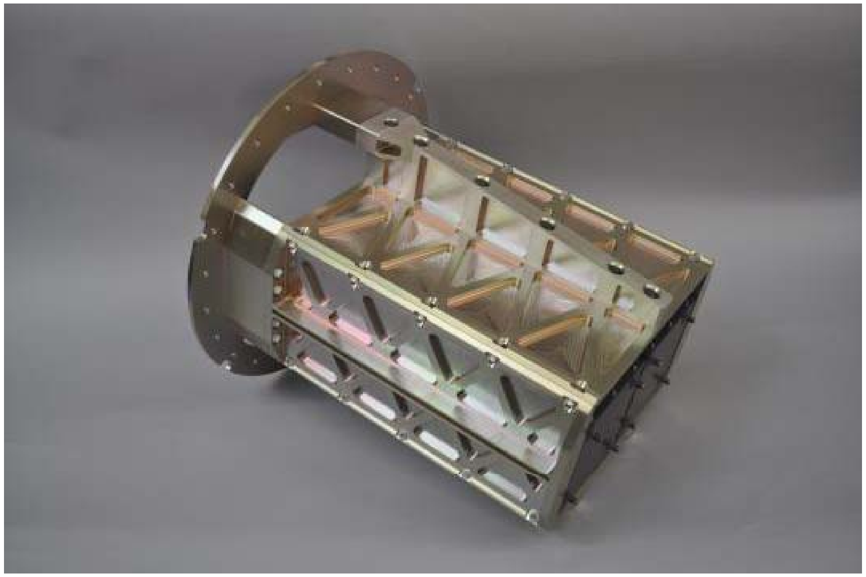




SUM Assembly, Inboard Configuration







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SUM Qualification Program Overview

- Design and analysis performed to ESPA Rideshare User's Guide (RUG) requirements
  - Structure stiffness target 120 Hz minimum fixed-base frequency
- Stiffness-driven design demonstrated positive strength margins with no-test safety factors
  - Qualification was achieved by analysis
- Workmanship test performed to RUG vibration environment +3 dB
  - All mode frequencies were >120 Hz
  - Comparison of response spectra before and after full-level runs demonstrated structure integrity

SUM Qualification by Analysis

- Combined static/random analysis with RUG environments
  - Quasi-static load factors: 8.5g in two directions simultaneously
  - Equivalent random quasi-static load factors based on Miles equation
- Thermal loading analysis
  - Analysis demonstrated that expansion and contraction due to CTE differences over range of -30C to 70C do not result in excessive stresses
    - Temperature range from P-POD Mk III ICD since no RUG thermal profile
- Model validation/workmanship test for random vibration environment
  - Room temperature, ambient conditions

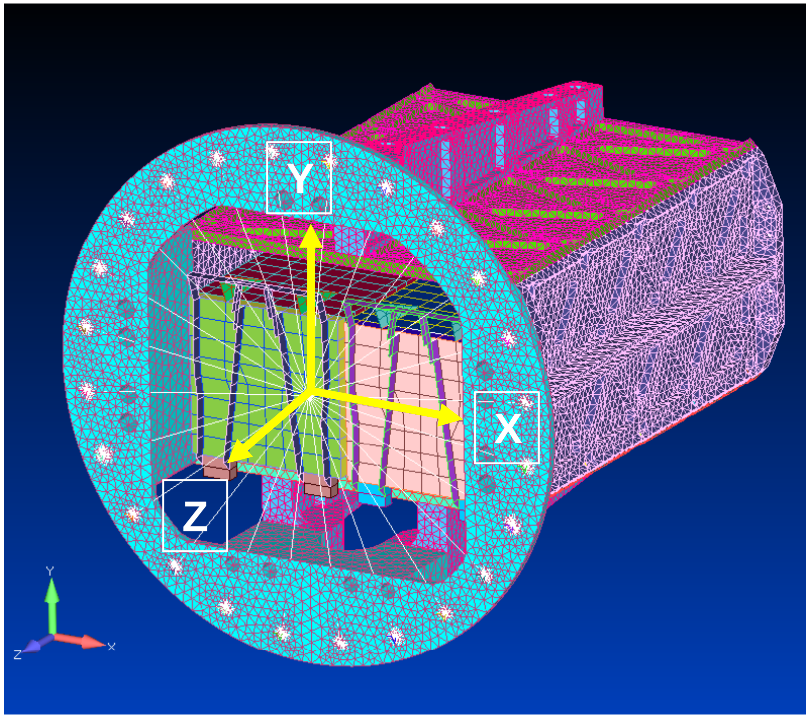
SUM Design Loads

ESPA SUM was designed for two primary load types

- Static load factors
  - Two load cases
    - -8.5g in y and 8.5g in Z direction (Case 1)
    - -8.5g in y direction and 8.5g in X direction (Case 2)
- RUG random vibration environment
  - Maximum Predicted Environment + 3 dB = 16.2 grms
  - Three primary axes
  - 60 second duration per axis
- 8.5 g quasi-static loads typically bound sine vibration
- SUM is not sensitive to shock loading

Combined Static/Random Stress Analysis

- Combined static and random vibration stress analysis performed on both SUM configurations
  - Four load cases per configuration
- Miles equation used to generate equivalent random quasi-static loads
- Safety factors for margin calculations:
  - F.S. Yield: 1.6
  - F.S. Ultimate: 2.0



Combined Static and Random Load Cases

Load Case Summary, All Loads in g										
	Direction	X, Tangential			Y, Axial			Z, Radial		
Configuration	Load Case	Static	Random	**Combined**	Static	Random	**Combined**	Static	Random	**Combined**
Inboard	1	8.5	67	**75.5**	-8.5	-22.3	**-30.8**			
	2	8.5	22.3	**30.8**	-8.5	-67	**-75.5**			
	3				-8.5	-67	**-75.5**	8.5	25.1	**33.6**
	4				-8.5	-22.3	**-30.8**	8.5	75.4	**83.9**
Outboard	5	8.5	76.1	**84.6**	-8.5	-25.4	**-33.9**			
	6	8.5	25.4	**33.9**	-8.5	-76.1	**-84.6**			
	7				-8.5	-76.1	**-84.6**	8.5	23.8	**32.3**
	8				-8.5	-25.4	**-33.9**	8.5	71.3	**79.8**

3 sigma random applied in primary axis of load, yellow highlight

1 sigma random applied in secodary axis of load, green highlight

Combined Stress Analysis Summary, Inboard

Part	ESPA Interface	Sides	Bottom Plate	Top Plate	Braces
Material	7050-T7451	7050-T7451	7050-T7451	7050-T7451	7050-T7451
Plate Thickness (in)	2-3.0	0.25-1.5	0.25-1.5	0.25-1.5	2-3.0
Sy (ksi)	59	64	64	64	59
Su (ksi)	68	74	74	74	68
Safety Factor, No Yield	1.6	1.6	1.6	1.6	1.6
Safety Factor, Ultimate	2.0	2.0	2.0	2.0	2.0

Configuration	Inboard			
Load Case	1	2	3	4
	Peak von Mises Stress (ksi)			
ESPA Interface	31.6	32.1	26.8	27.7
Sides	31.2	24.2	10.7	8.2
Bottom Plate	34.3	29.0	20.3	10.2
Top Plate	18.9	13.2	8.1	5.6
Braces	33.0	31.3	19.3	21.0
	Margin on Yield			
ESPA Interface	0.17	0.15	0.38	0.33
Sides	0.28	0.65	2.74	3.88
Bottom Plate	0.17	0.38	0.97	2.92
Top Plate	1.12	2.03	3.94	6.14
Braces	0.12	0.18	0.91	0.76
	Margin on Ultimate			
ESPA Interface	0.08	0.06	0.27	0.23
Sides	0.19	0.53	2.46	3.51
Bottom Plate	0.08	0.28	0.82	2.63
Top Plate	0.96	1.80	3.57	5.61
Braces	0.03	0.09	0.76	0.62

Highlighted cells have edited stress values

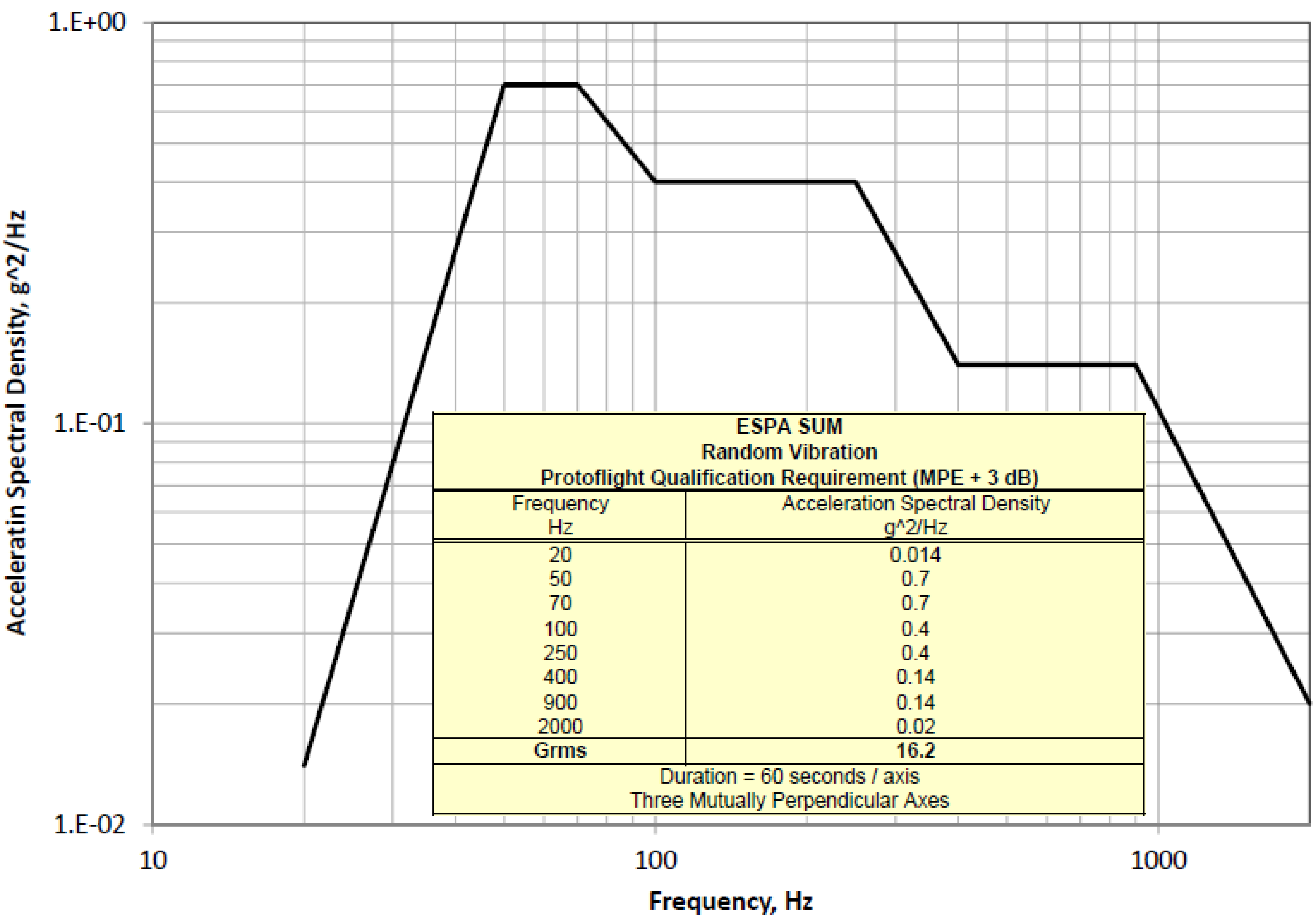
Model artifacts due to NASTRAN RBE2 rigid elements removed from stress contour

All margins are positive

Vibration Test Objectives

- Subject test article to ESPA RUG MPE + 3 dB three axis random vibration environments (protoflight qualification)
- Testing performed in two configurations
  - With two “Test PODs”
    - Equivalent to two P-PODs and two 12.7 lb (5.8 kg) 3U spacecraft simulators
  - With one PSC 6U dispenser and a 25.4 lb (11.5 kg) 6U spacecraft mass simulator

Random Vibration Spectrum

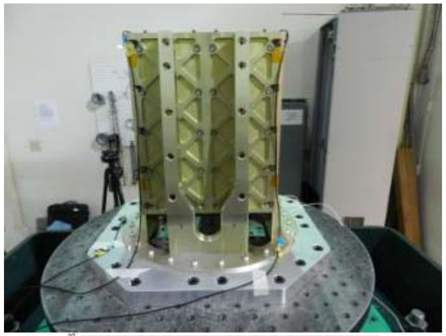


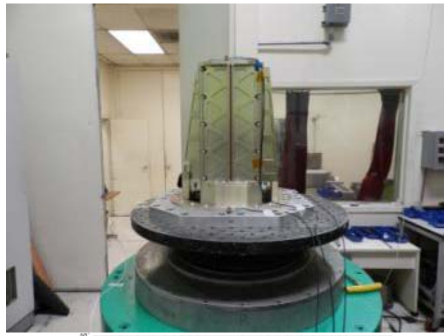
ESPA SUM
Random Vibration
Protoflight Qualification Requirement (MPE + 3 dB)

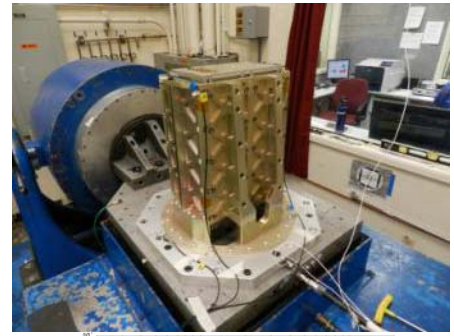
Frequency Hz	Acceleration Spectral Density g^2/Hz
20	0.014
50	0.7
70	0.7
100	0.4
250	0.4
400	0.14
900	0.14
2000	0.02
Grms	**16.2**

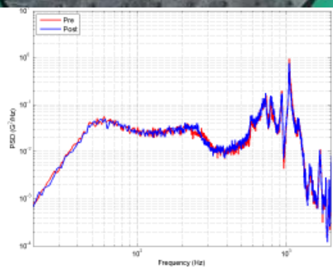
Duration = 60 seconds / axis
Three Mutually Perpendicular Axes

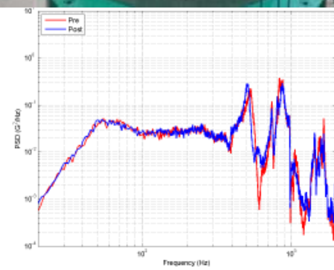
SUM Random Vibration Test Configurations

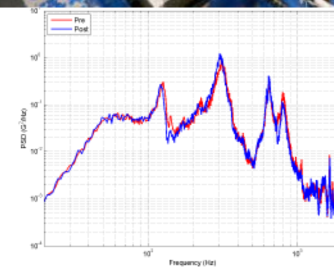


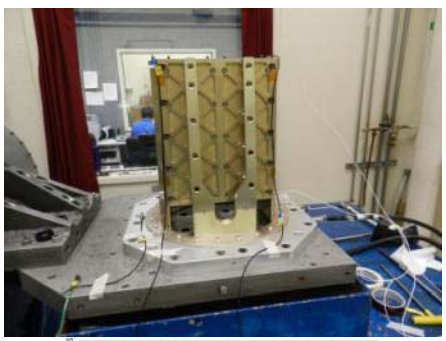


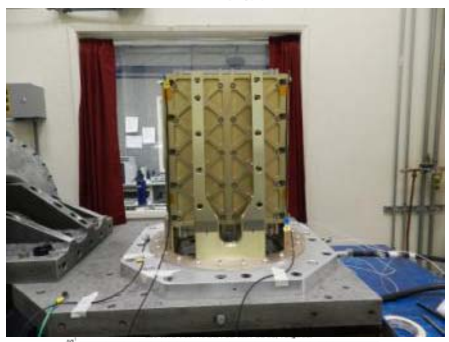


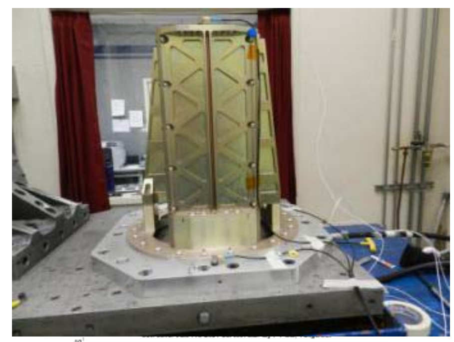


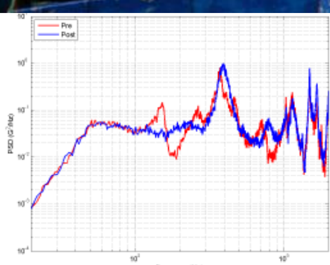


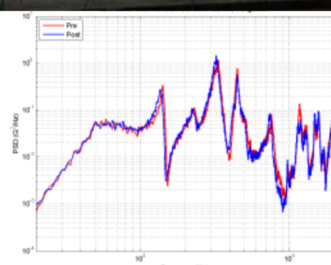


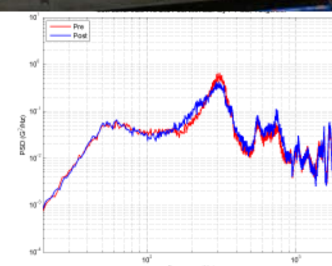












SUM Measured Mode Frequencies

Configuration	Measured Frequency
PSC 6U Tangential	138 Hz
PSC 6U Thrust	123 Hz
PSC 6U Radial	502 Hz
Cal Poly P-PODs Tangential	153 Hz
Cal Poly P-PODs Thrust	315 Hz
Cal Poly P-PODs Radial	216 Hz

Vibration Test and Design Success Criteria

- Test success criteria
  - Applied appropriate vibration environment for correct duration ☑
  - Acquired good quality data to verify vibration input and ESPA SUM responses ☑
- Design success criteria
  - Withstood ESPA RUG MPE + 3 dB vibration environment with no observed significant degradation
    - Pre- and post-test characterization runs at -12 dB performed before and after 0 dB full level runs for each test configuration ☑
    - Visual inspection for yielding and joint slip ☑

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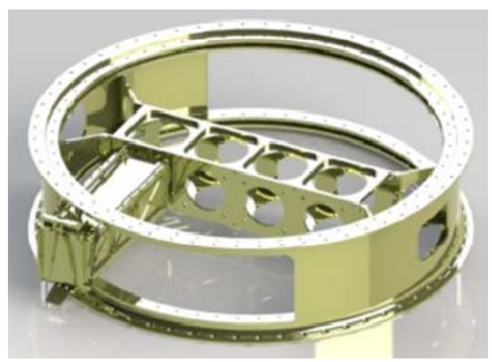
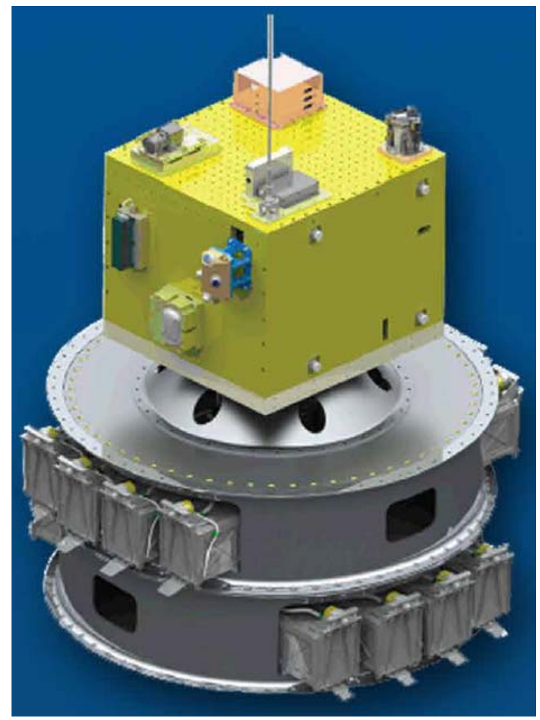
ESPA SUM Ready for Flight

- SUM design optimized
  - For compatibility with P-POD and PSC dispensers
  - For both internal and external ESPA port installation
- Analysis showed positive margins on all parts and fasteners with no-test Safety Factor of 2.0
  - Satisfied requirement for qualification by analysis
- Dynamics did not change significantly throughout test
  - Comparison of response spectra before and after full-level runs demonstrated structure integrity
- SUM design verified for ESPA RUG environment + 3 dB

CubeStack

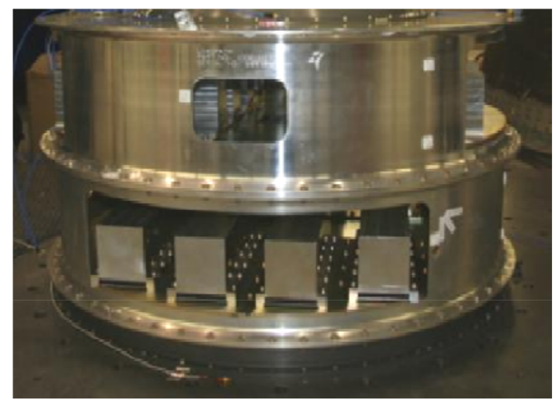
- CubeSat adapter by LoadPath and Moog CSA developed under contract to AFRL Space Vehicles Directorate
  - Eight 3Us, or four 6Us, or combinations of 3Us and 6Us
  - Qualification program completed 2012
- Dual CubeStack manifested on ORS 3 in September 2013
  - Air Force Minotaur 1 to test space-based rocket tracking technology and autonomous flight termination system
  - Co-manifested with STPSat 3
- Second generation design
  - Bulkhead design eliminates lower deck
  - Weight reduced by 15%-20%
  - Improved access for integration





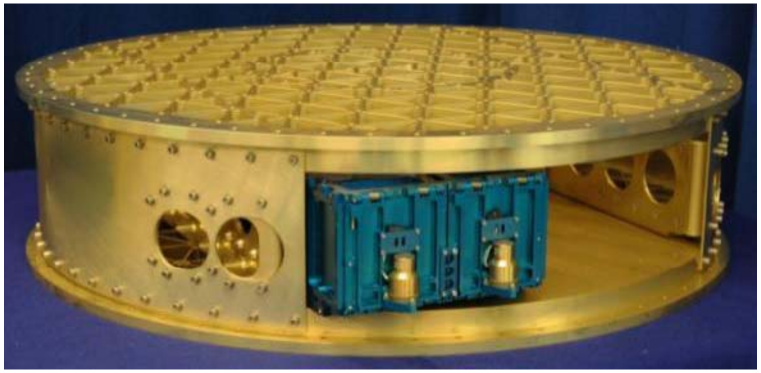
CubeStack Testing

- Qualification testing completed in 2012
- Random vibration testing of ORS 3 flight-like payload stack
  - March 2013 test
  - Two proto-flight CubeStacks populated with CubeSat dispenser mass simulators (max mass condition)
  - 105-lb primary spacecraft simulator
- Modal survey performed for finite element model tuning
  - Refined FEM modal frequencies within 4% of measured frequencies
  - Reduced model uncertainty factor resulted in CLA net CG load factors that do not exceed component test levels



NLAS Adapter

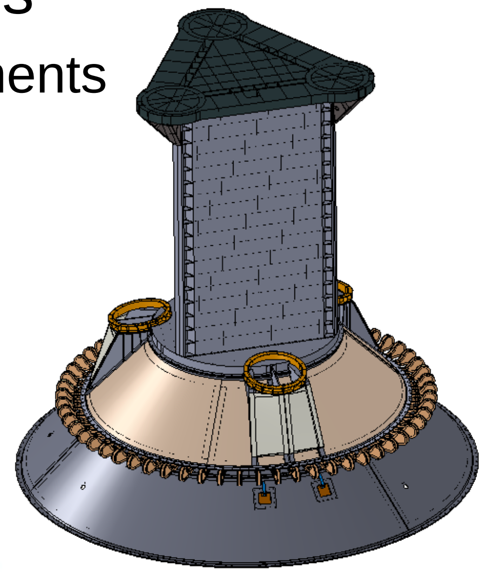
- Nanosat Launch Adapter System (NLAS) by NASA Ames
  - Includes prototype “wafer” adapter, 6U dispenser, sequencer
- Adapter prototype design by NASA/Ames Research Center
  - Final design, fabrication, and test by CSA in 2010
- Manifested on ORS 4
  - Super Strypi launch 2013 to utilize excess lift capacity for CubeSats
  - University of Hawaii HiakaSat as primary payload
  - 13 CubeSat secondary payloads

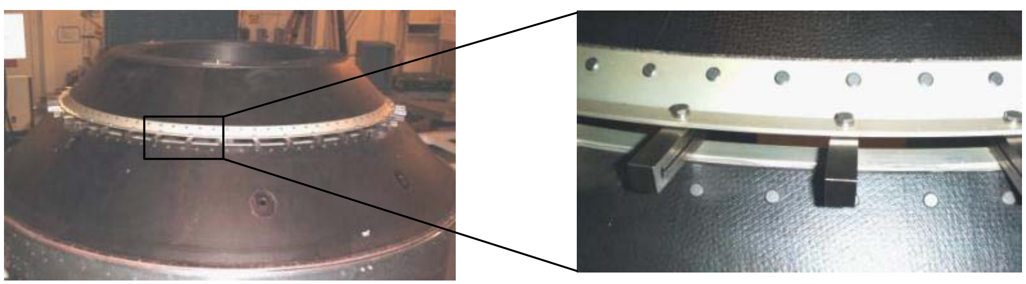


Athena Commercial Rideshare

LOCKHEED MARTIN

- Athena IIc annual launches for small satellites
  - Lockheed Martin and ATK heritage rocket components
- Moog CSA payload accommodations
  - Modular multi-payload adapter
    - 4-9 rideshare satellites, 110-440 kg spacecraft
    - CubeSat accommodations
  - SoftRide isolation of adapter and payloads
    - Reduced launch environments
    - Vehicle has similar dynamics with various payload stacks
  - Coupled loads analysis for environment predictions





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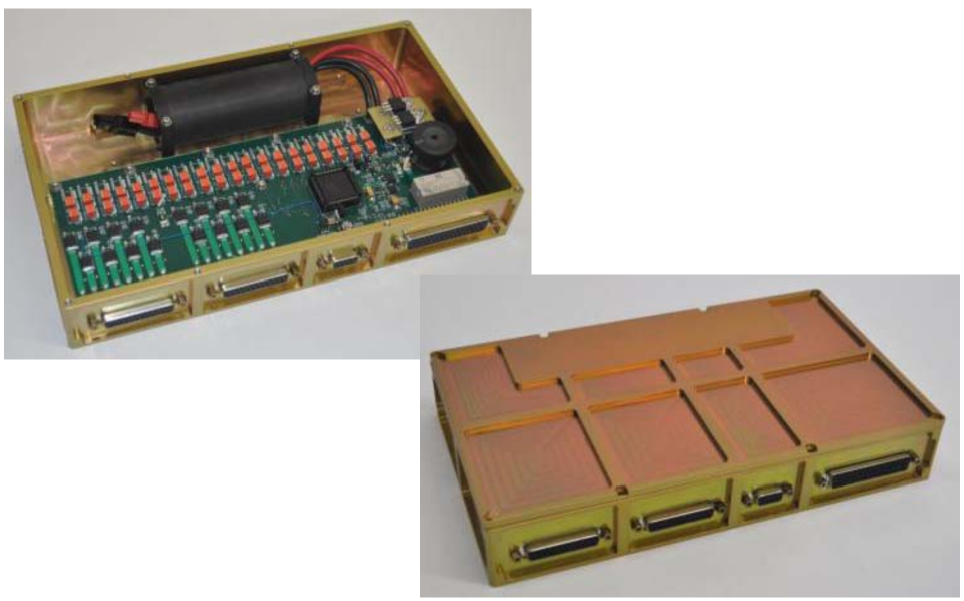
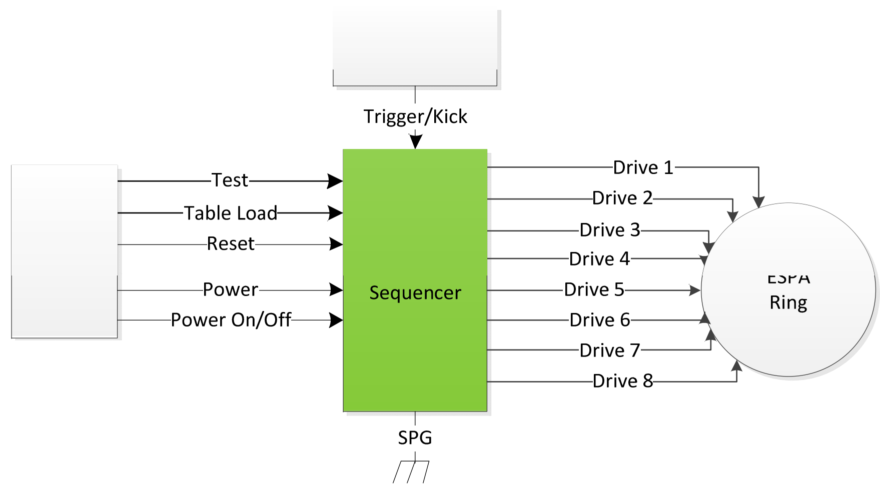
Moog CubeSat Deployment Sequencer

- Moog IRAD multi-payload sequencer
  - Modular architecture
  - Compatible with P-POD, PSC, SNC, RUAG systems
- Redundant high-current output signals to drive eight spacecraft release mechanisms

- Recent Moog acquisition of Broad Reach Engineering enhances development plan
  - Adopting Broad Reach board set and architecture
  - Flight heritage
  - Modularity for addition of sensor and telemetry interfaces





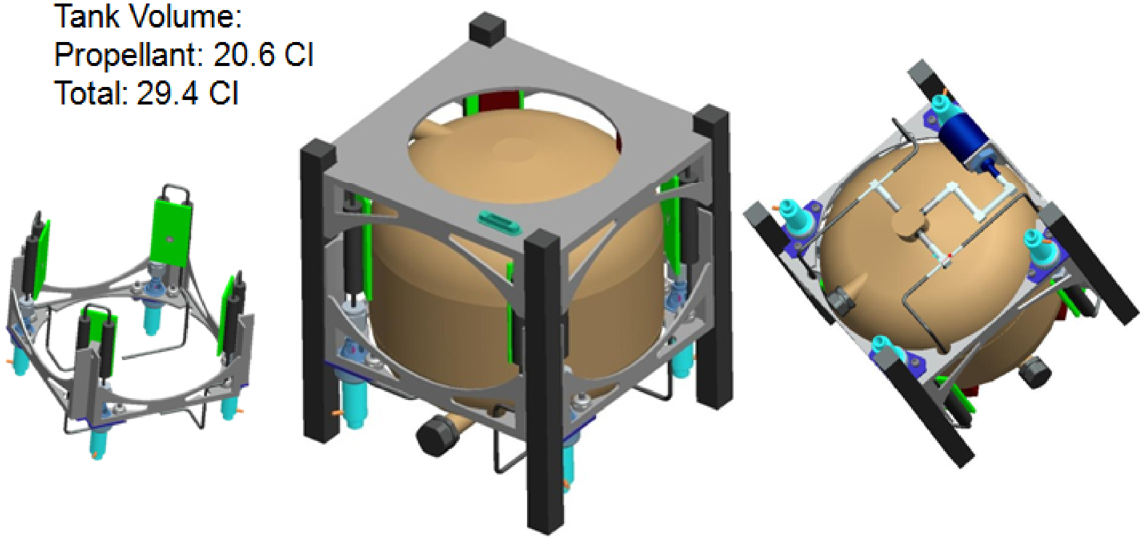
Moog ISP CubeSat Propulsion

- Recent acquisition of AMPAC In-Space Propulsion (ISP) by Moog Space and Defense Group enables in-house CubeSat propulsion concepts
  - Moog ISP facilities at Niagara Falls (New York), Dublin (Ireland), Cheltenham and Wescott (England), Chatsworth (California)
- Hydrazine CubeSat propulsion system using Moog-ISP heritage components
- Concept for ¼U configuration w/ no operating pressure
  - Massachusetts Institute of Technology electrospray thrusters
  - Moog avionics, tank, manufacturing, propulsion system experience
- Cold gas propulsion components

Hydrazine Cubesat Propulsion System

Concept - 1U System

Tank Volume:
Propellant: 20.6 CI
Total: 29.4 CI



Performance

Operating Press	100-400 psia
System Mass (dry)	1.2 kg
System Mass (wet)	1.65 kg
Thrust Level	0.1 lbf
No. of Thrusters	4
Chamber Pressure	250-80 psia
Average Isp	245 sec
Total Impulse (1U)	1130 N-sec
Power (@12 Vdc)	15 watts

Status

- Moog-ISP Conceptual Hydrazine Design is complete
- Minor tank and thruster development is required
  - scaling sizes downwards
- Suitable for 6U+ cubesats
- Estimate 9 – 10 month development cycle
- Estimate recurring 8 month fabrication cycle from scratch

Contact Information:
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716-731-6266
jcolvin2@moog.com

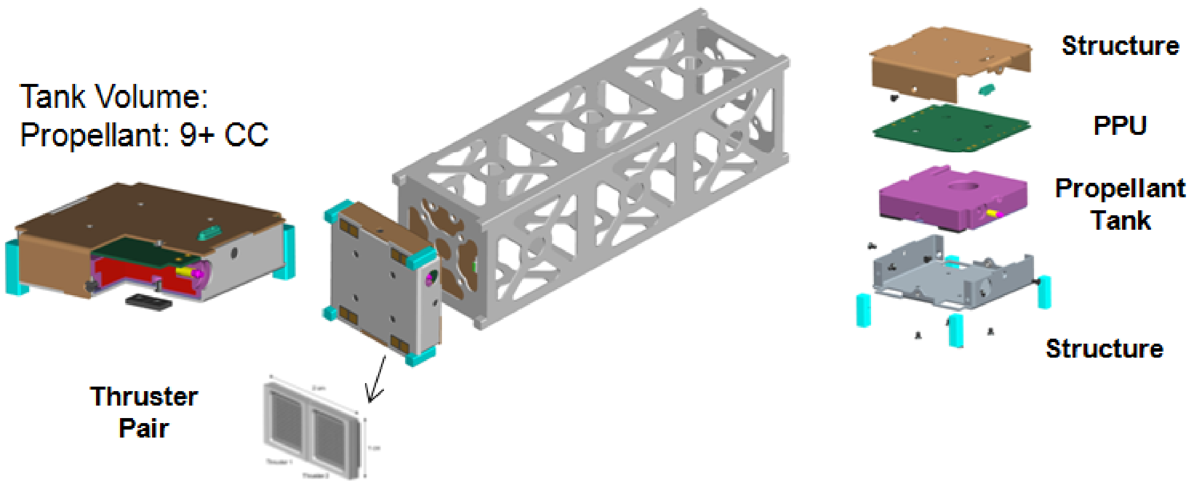
TRL

Component	Current TRL	Heritage TRL
Propellant Tank	2	9
Thruster	2	4
Valve	2	2
Pressure Transducer	3	9
Filter	1	1
Fill/Vent Valve	2	6
Fill/Drain Port	9	9
Tank / Line Heater	3	9
Catalyst Bed Heater	3	9

Electrospray Cubesat Propulsion System

Concept – ¼ U System

Tank Volume:
Propellant: 9+ CC



Performance

Operating Press	15 psia
System Mass (dry)	0.53 kg
System Mass (wet)	0.56 kg
Thrust Level (ea.)	150 µN
No. of Thrusters	4 pairs
Average Isp	> 3500 sec
Total Impulse (1/4 U)	500 N-sec
Power (@5 Vdc)	7 watts

Status

- Moog-ISP Conceptual Electrospray Design is nearly complete
- Tank and thruster development is required
- Suitable for 3U or larger cubesats
- Estimate 15 – 18 month development cycle
- Estimate recurring 10 units in 2 months once tooling, procedures and people are in place

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TRL

Component	Current TRL	Heritage TRL
Propellant Tank	3	3
Thruster	3	4
Fill/Drain Port	9	9
Tank Heater	9	9
PPU	4	4

Moog Dublin Cold Gas Propulsion

- High pressure regulator
  - Could be used to store and regulate cold gas for lightweight all-in-one unit
  - Inlet tube could store 250bar GN2
  - Outlet tube could include thruster valve

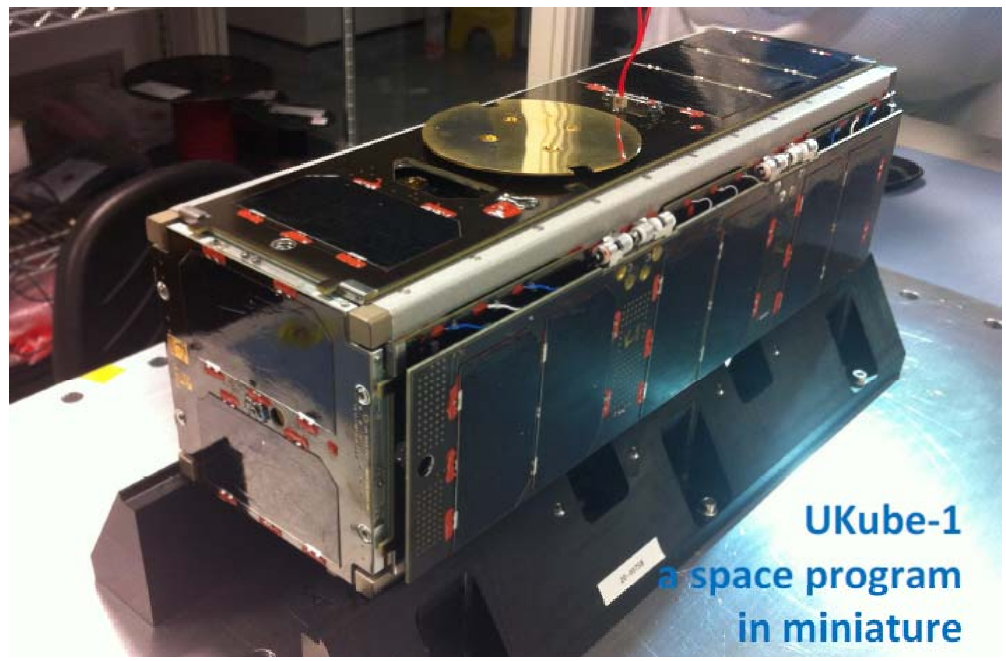
(Regulator used on Prisma)

- MEMS cold gas regulator
  - Combination high pressure regulator including MEMS components
  - Pressure transducer
  - Pressure isolation valve
  - Pressure relief valve
  - MEMS filtration

(developed in partnership with NanoSpace)

CubeSat Program Management

- Ronan Wall in Moog Dublin was founding PM for UK's national CubeSat program for over 2 years
  - Astrium PM service provided to UK Space Agency
- Four Tech demo, science and outreach payloads
- Launch due Q3 2013
- Dublin also provides structural and mechanical design & manufacture support



Conclusion

- ESPA SUM qualification program completed and flight units available
- CubeSat "Wafer" adapters to launch on ORS 3 and ORS 4
- Future work
  - 2nd generation CubeStack design and propulsion module
  - CubeSat propulsion components and modules
  - 27U Mount for ESPA 24" port