Smaller Satellites, Bigger Return

A Custom Rideshare Payload Adapter for Greenhouse Gas Monitoring Microsatellites Launched in Tandem

Kevin Guan (kev.guan@mail.utoronto.ca)

Eric van Velzen (eric.vanvelzen@mail.utoronto.ca)

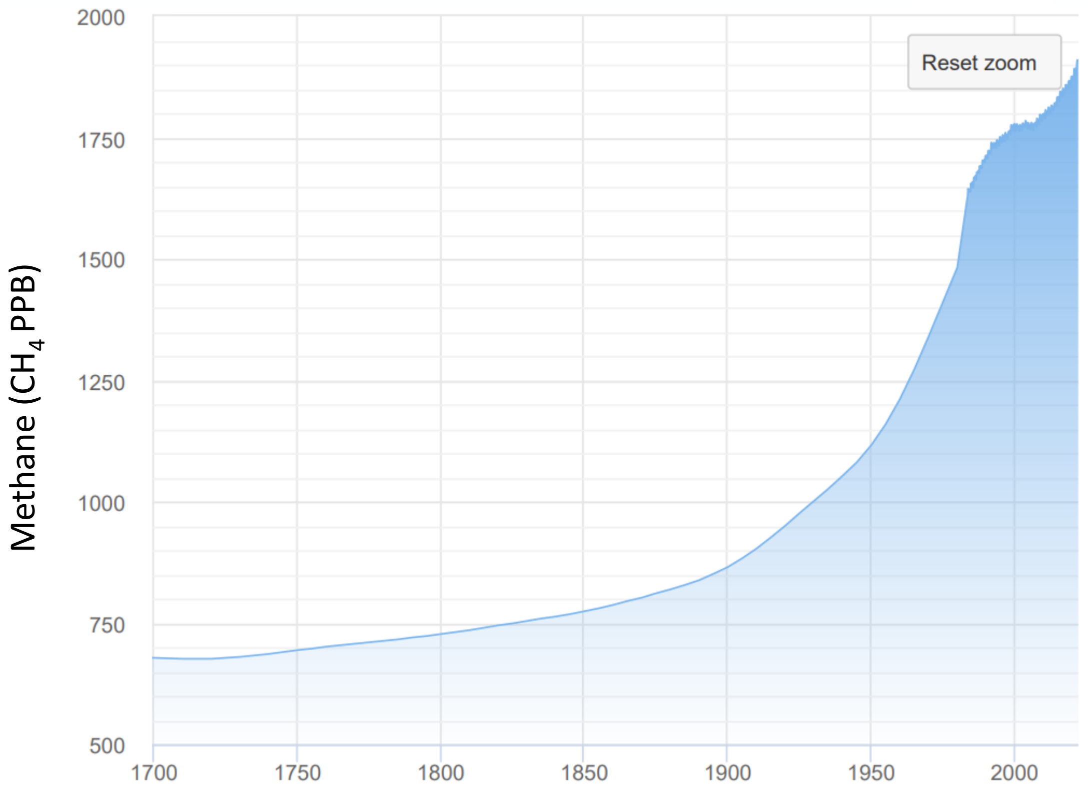
Space Flight Laboratory (SFL)

University of Toronto Institute for Aerospace Studies

August 10, 2022

Greenhouse Gas and Global Warming

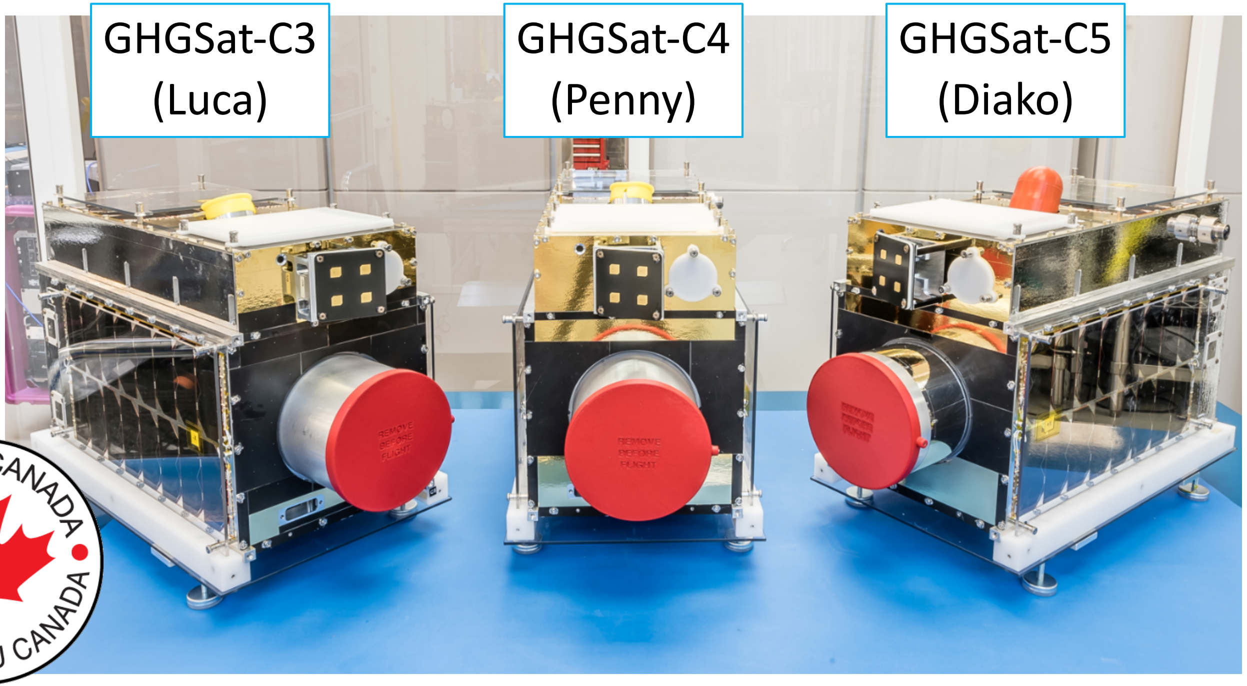
- Global mean surface temperature has risen: in 2020 was 1.2 degrees warmer than pre-industrial baseline (1850-1900).
- Methane is second biggest contributor to global warming after CO2, and is 25 times as potent at trapping heat.
- Detecting methane is a critical to addressing global warming.



Global Methane Levels from year 1700 to 2020
[Source: 2 Degrees Institute]

GHGSat Constellation Mission

- Constellation developed for *GHGSat Inc.* to provide remote-sensing of atmospheric methane.
- GHGSat-C3/C4/C5 are latest three microsatellites in the growing constellation.

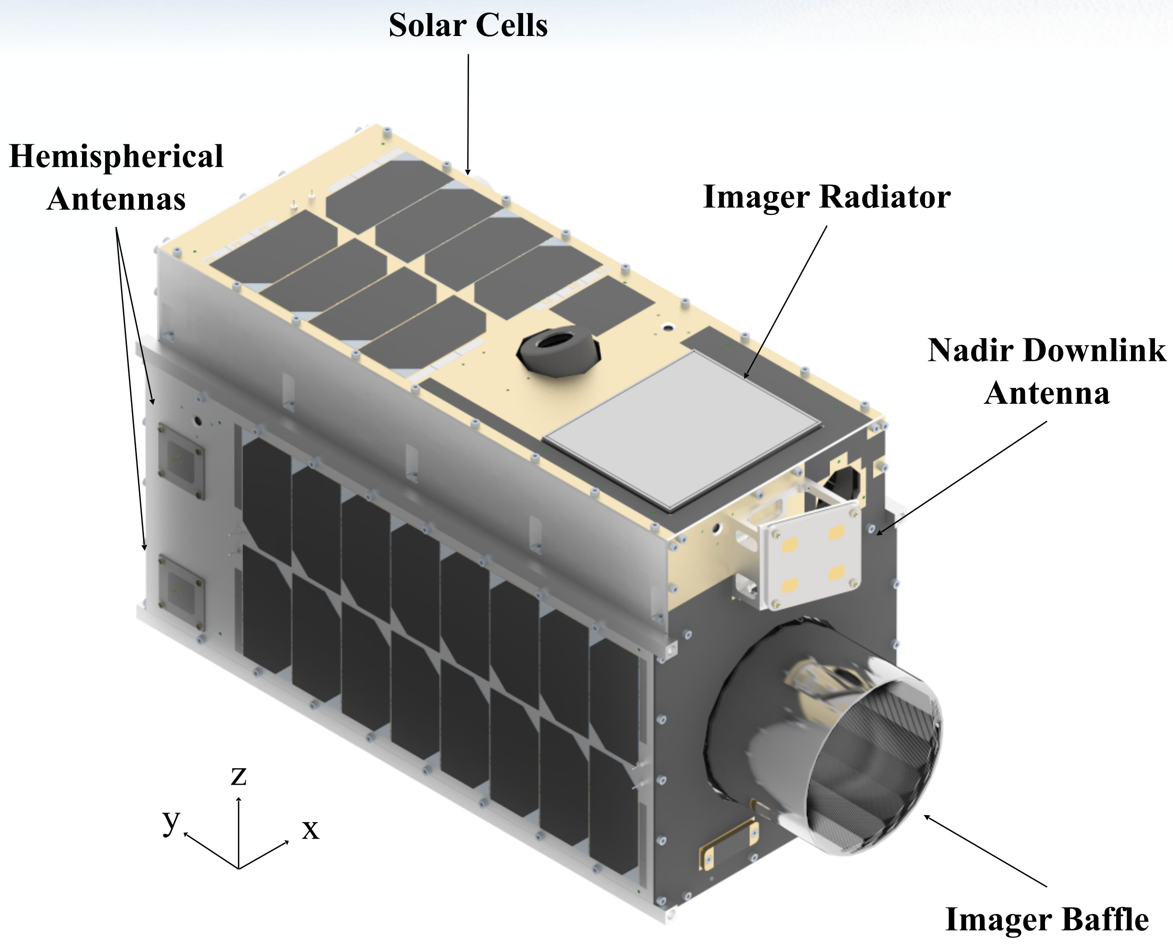


Picture of GHGSat-C3, GHGSat-C4 and GHGSat-C5 [Source: GHGSat Inc.]

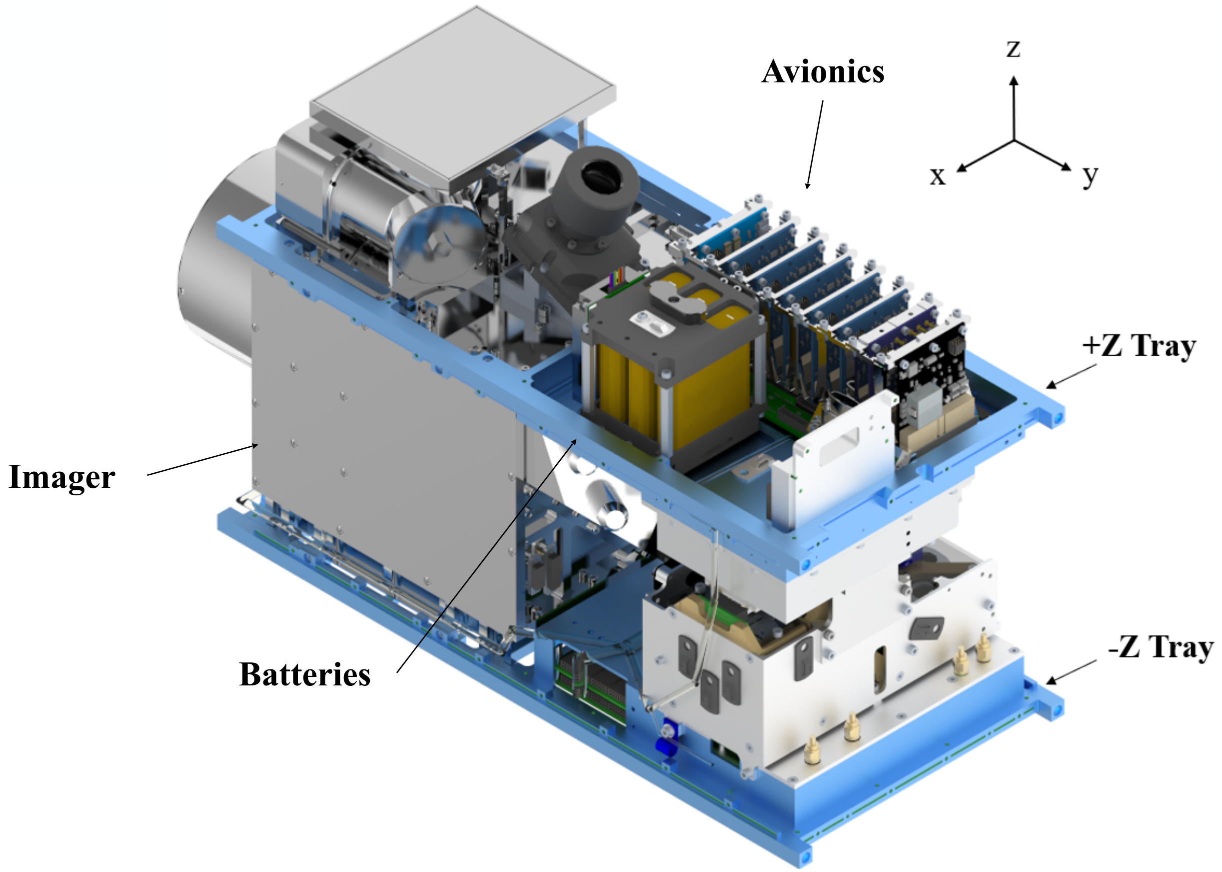
GHGSat Constellation Mission Patch

NEMO Spacecraft Bus

NEMO: <u>N</u>ext-generation <u>E</u>arth <u>M</u>onitoring and <u>O</u>bservation

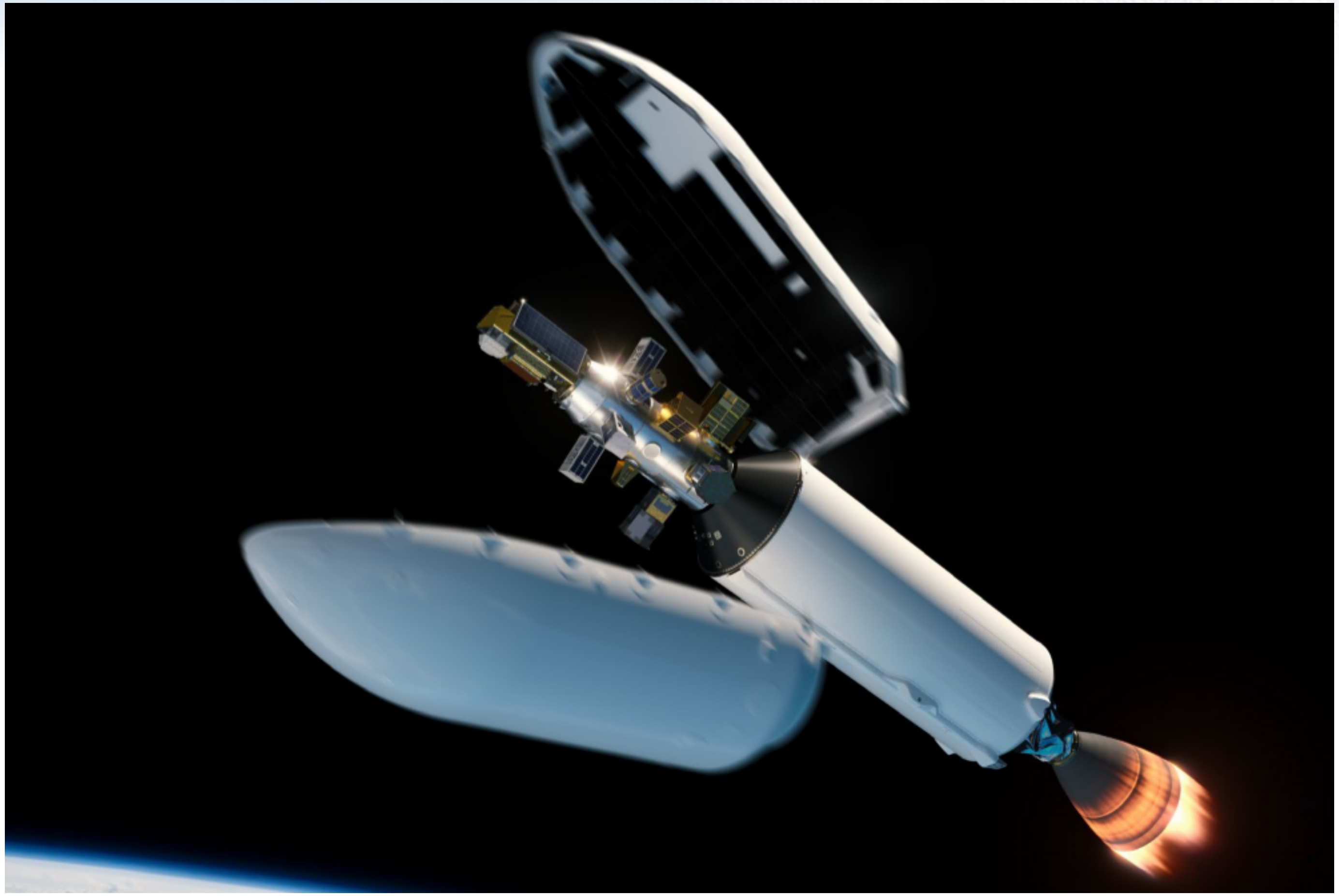


3D Rendering of GHGSat Spacecraft

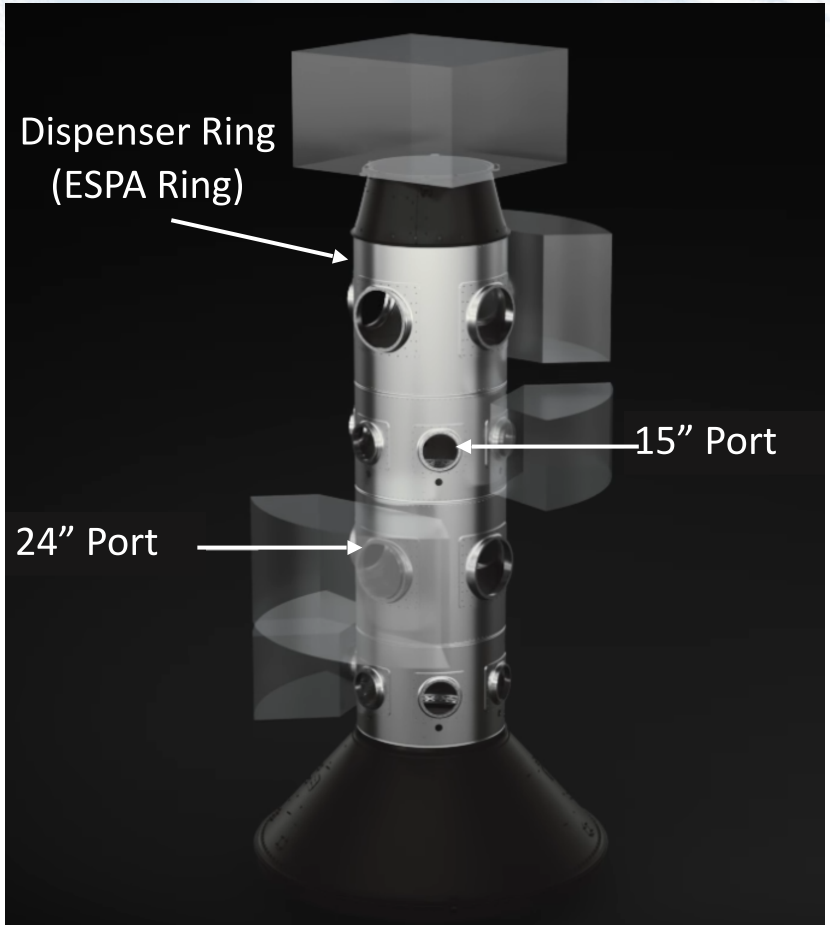


3D Rendering of GHGSat Spacecraft Tray Assembly

Launch Opportunities for Small Satellites



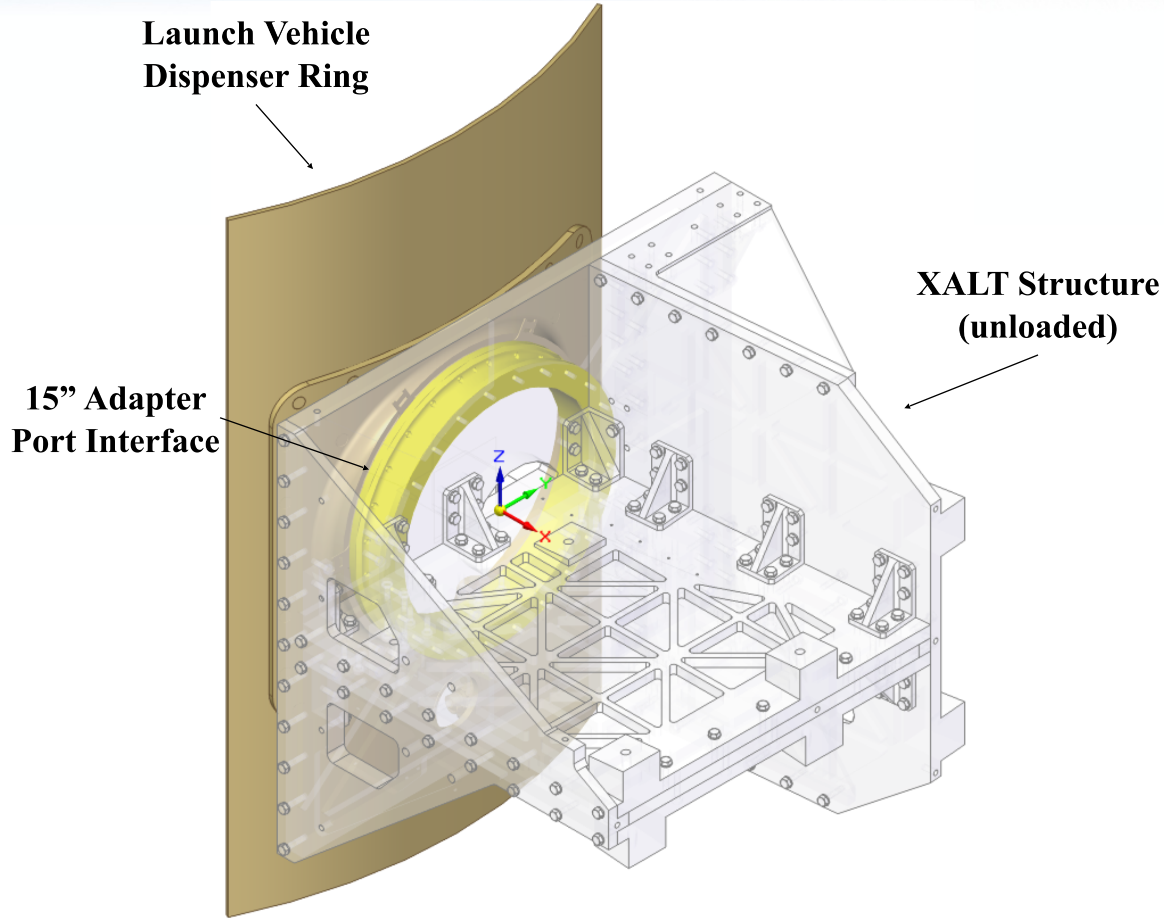
Rendering of Falcon 9 Second Stage and Payload Fairing Separation
[Source: SpaceX]



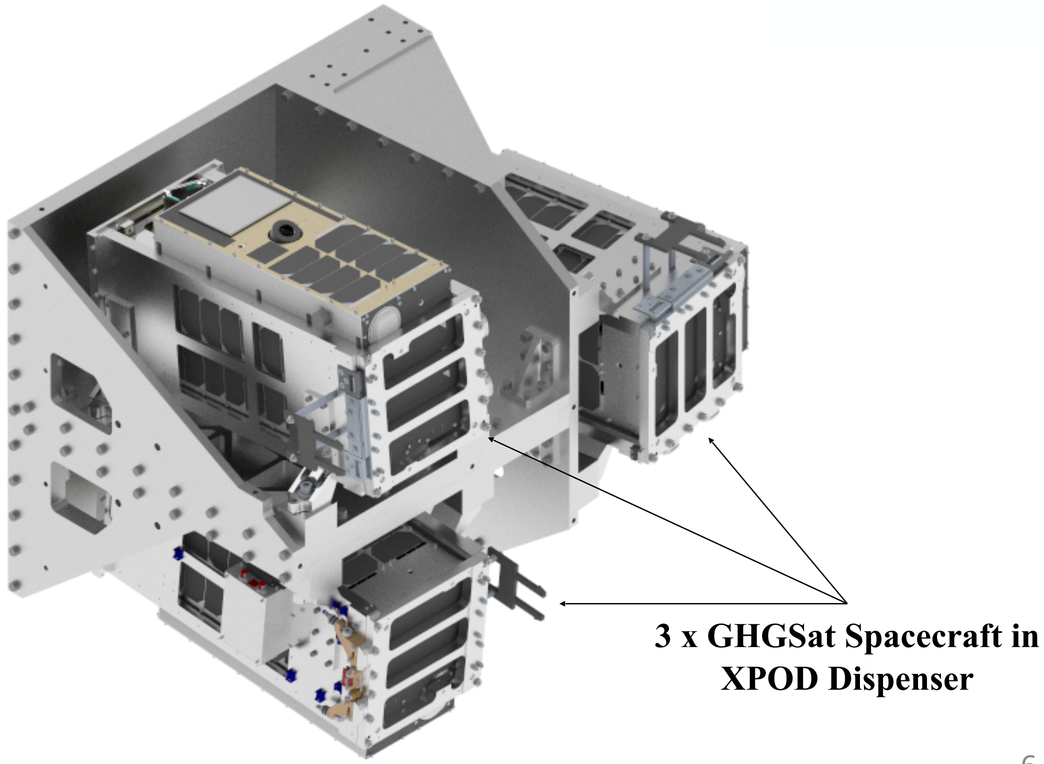
Falcon 9 Dispenser Ring Stack
[Source: SpaceX]

Custom Adapter for GHGSat-C3/C4/C5

XALT – XPOD Adapter for Launch in Trio



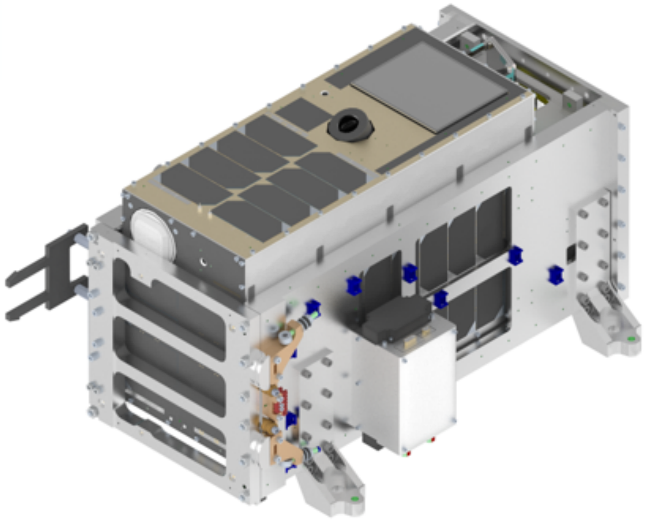
View of XALT mounted on the SpaceX 15" Interface Ring



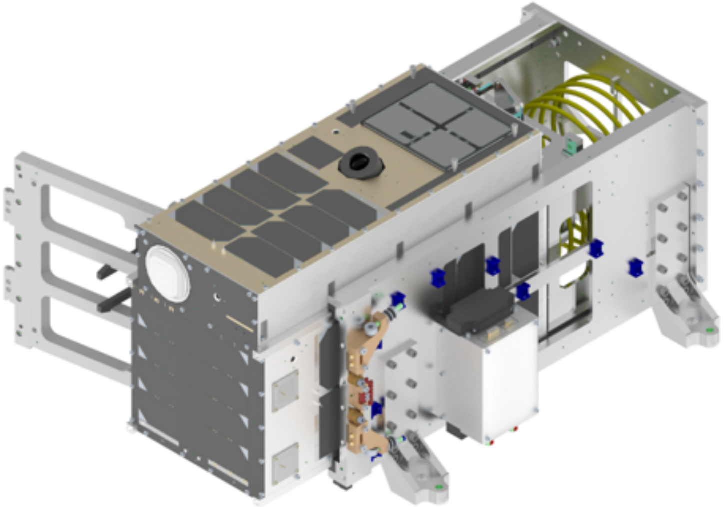
XALT Adapter with mounted Spacecraft

Spacecraft and Dispenser

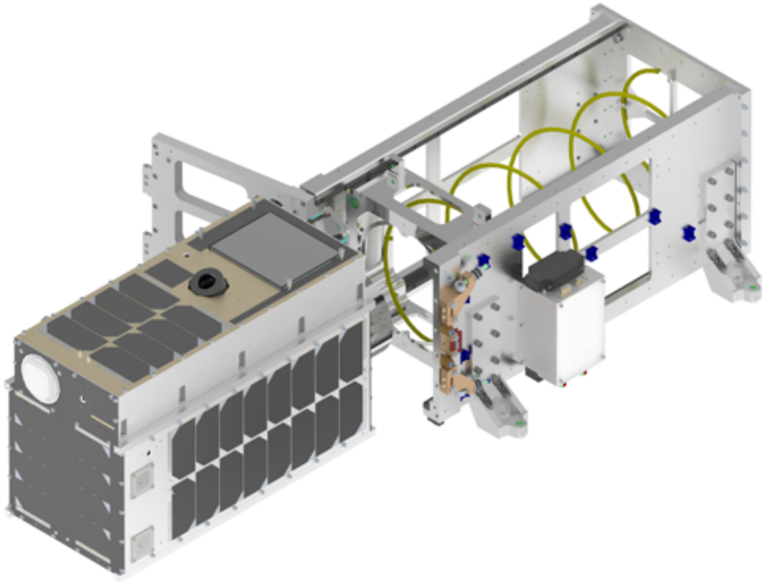
XPOD – SFL's dispenser for NEMO spacecraft



1) Spacecraft is stowed



2) Door opens and spacecraft ejection begins

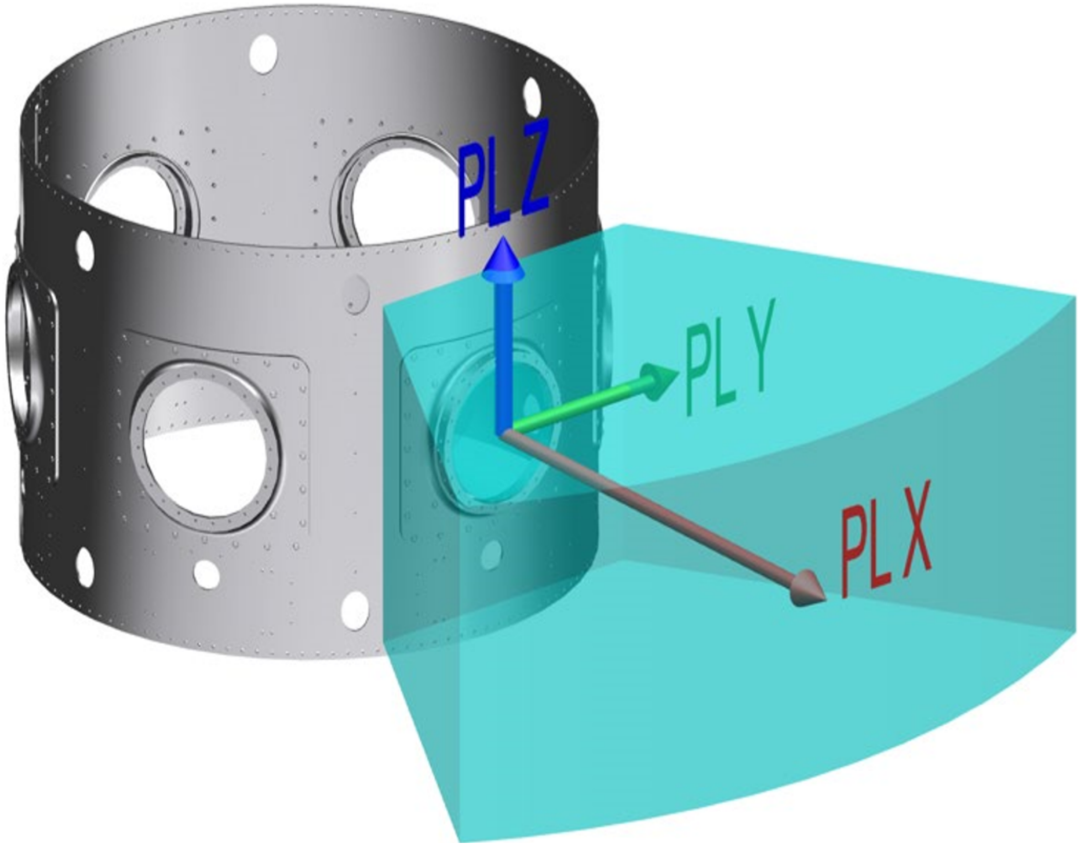


3) Spacecraft is fully ejected

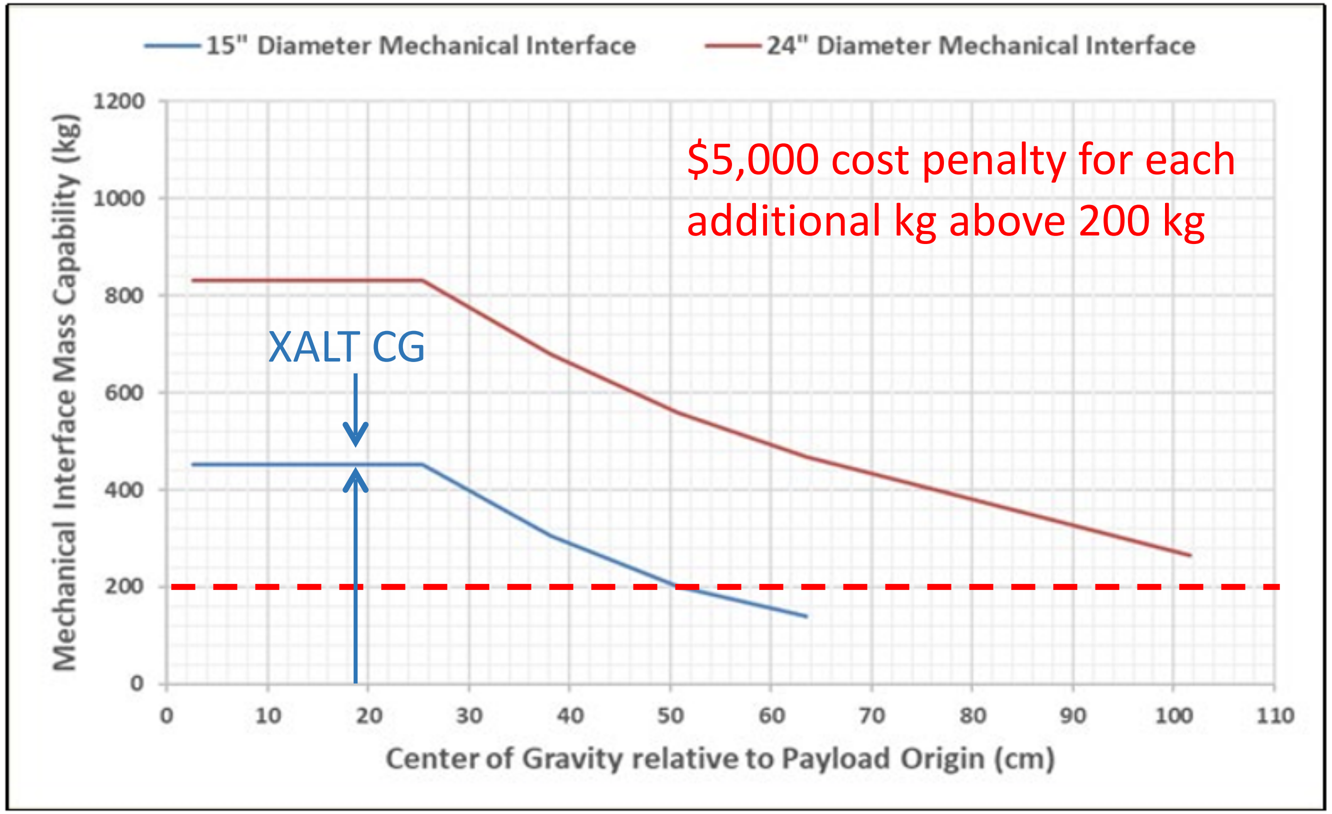
Illustration of XPOD Delta Deployment Sequence

Volume Requirements

REQ-004: XALT's mass and volume shall remain within the maximum mass profile and volume envelope specified by SpaceX



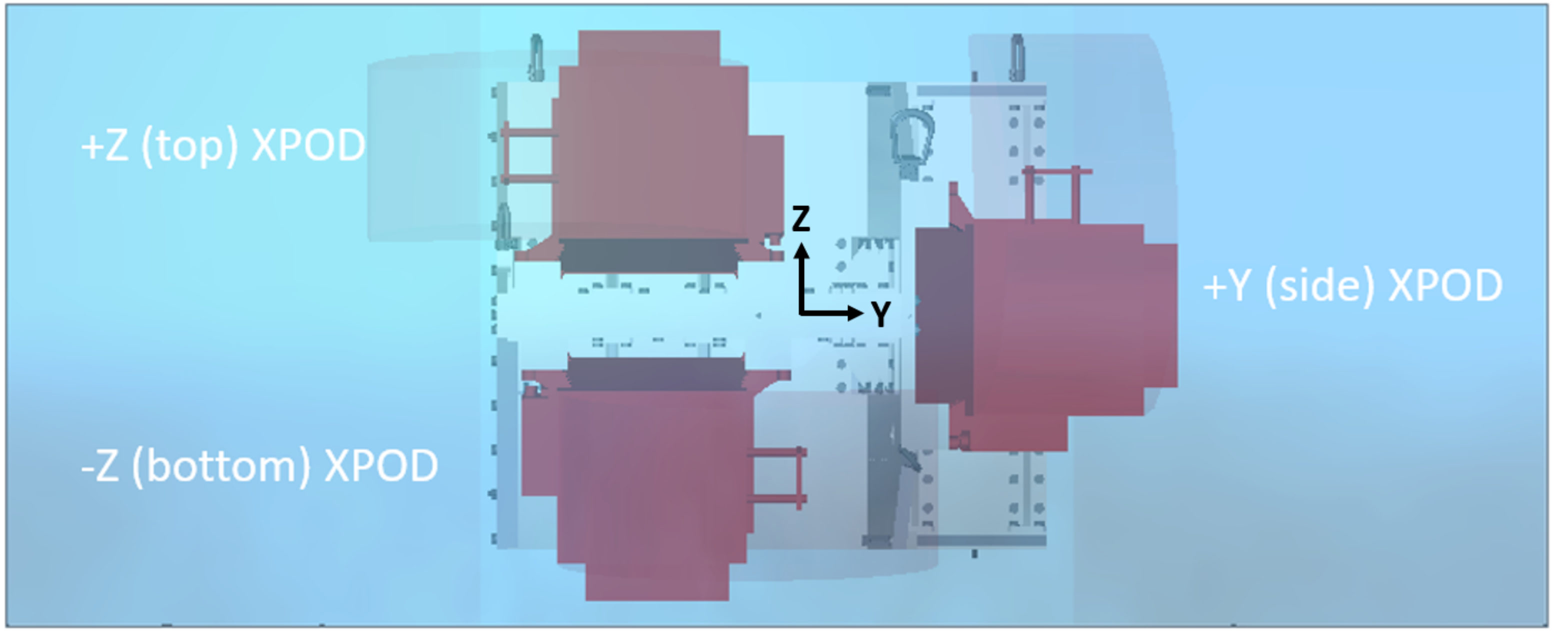
Allowed Payload Volume on 15" Diameter Port [Source: SpaceX]

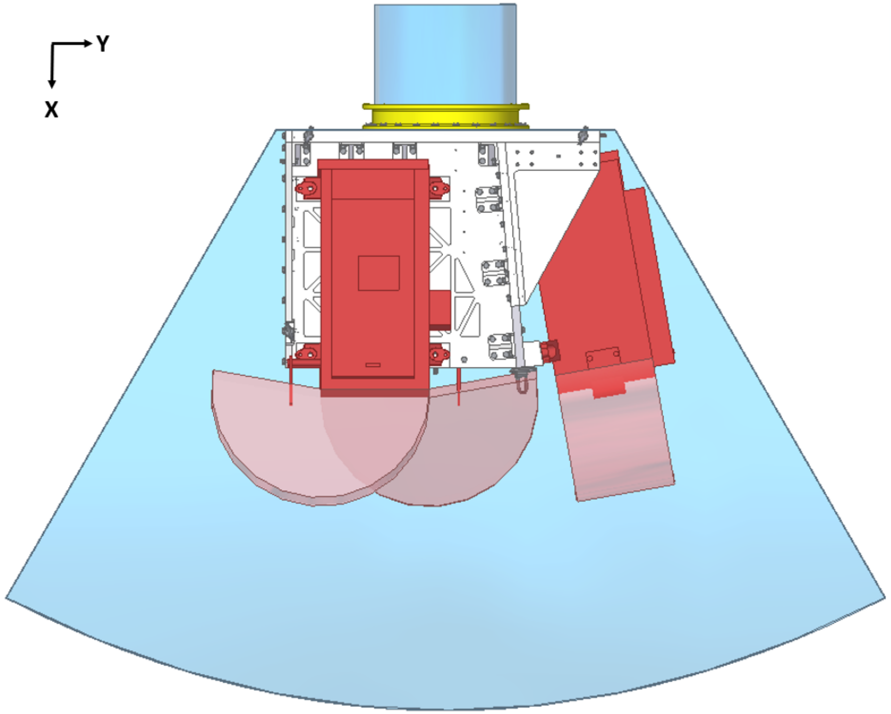


Allowed Payload Mass on Rideshare Launch [Source: SpaceX]

GHGSat-C3/C4/C5 Volume

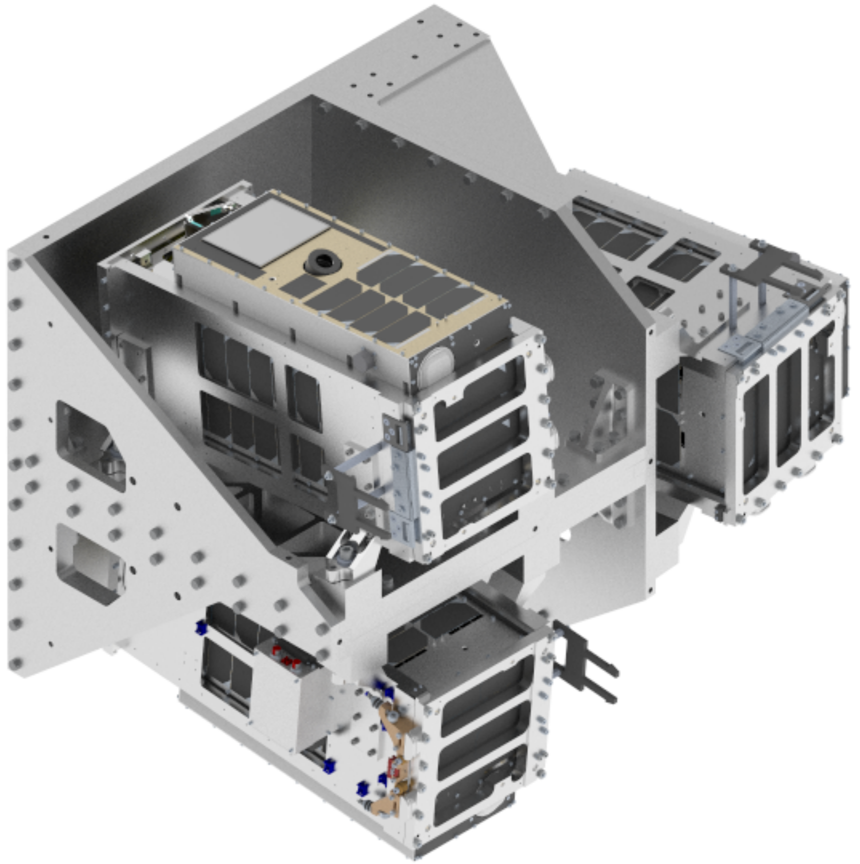
- Entire launch payload fits within the allowed payload volume.
- Volume swept by door opening is accounted for.



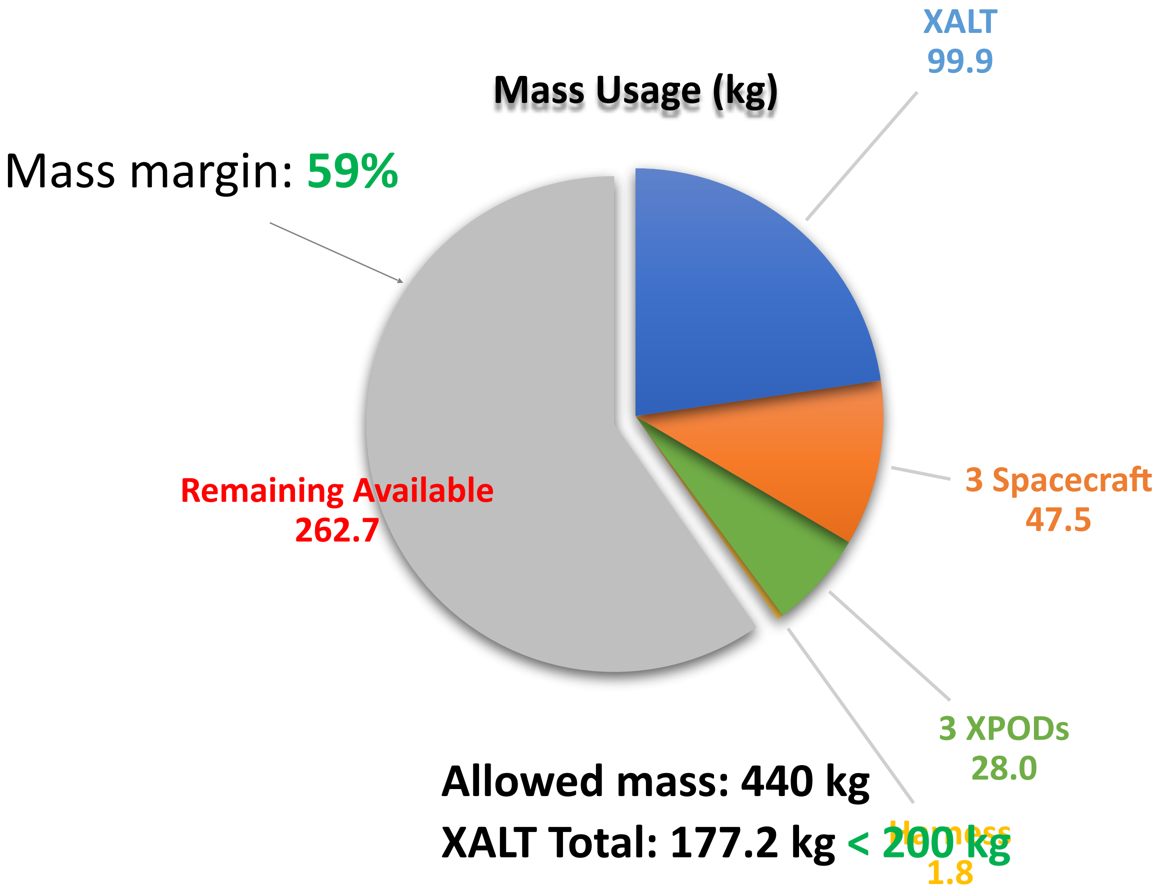


Front and Top View of GHGSat-C3/C4/C5 Launch Payload inside Allowed Volume

Mass of XALT with GHGSat-C3/C4/C5



GHGSat-C3/C4/C5 Launch Payload in Flight Configuration

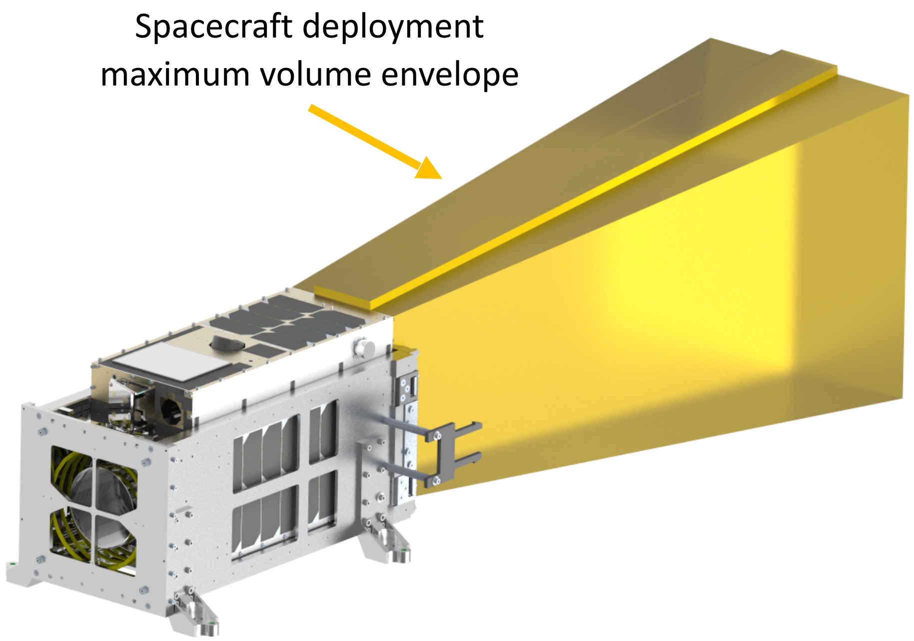


GHGSat-C3/C4/C5 Launch Payload Mass Allocation Breakdown

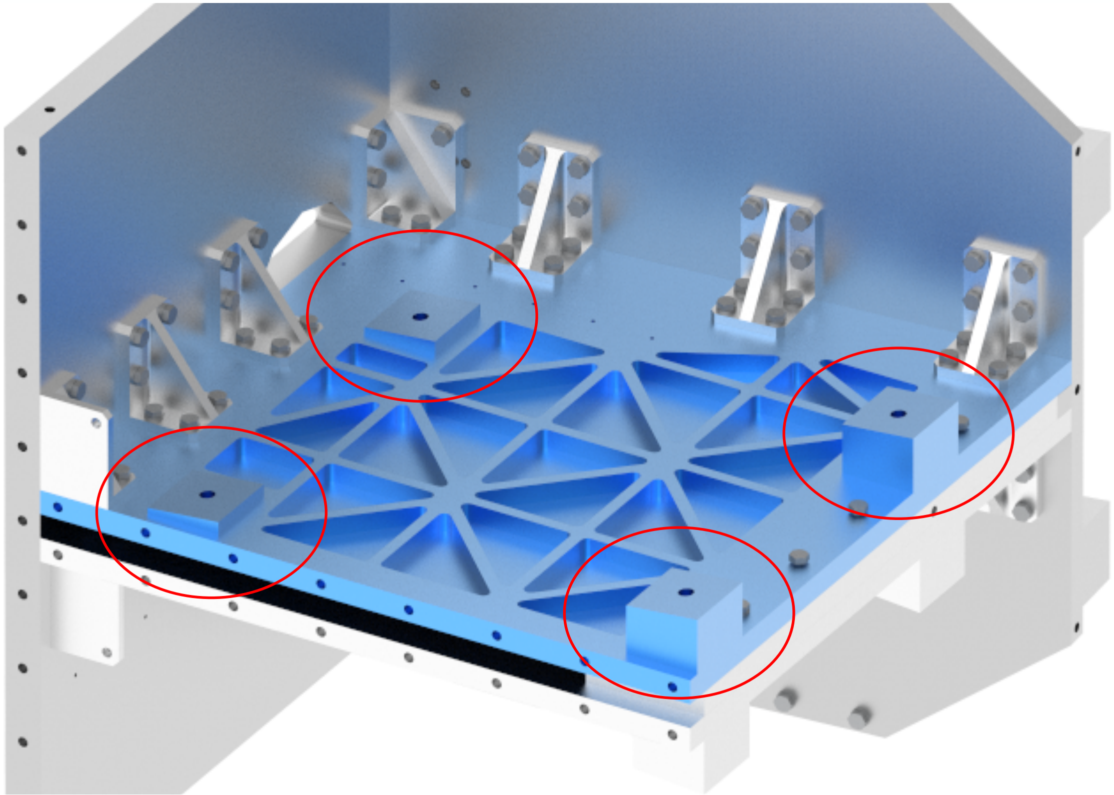
How are XPOD Dispensers Mounted?

REQ-003: XPODs should be mounted such that there is at least 10° angle separation between their deployment axis.

- Worst-case deployment error: 5°
- Each XPOD dispenser inclined 5° by mounting bosses



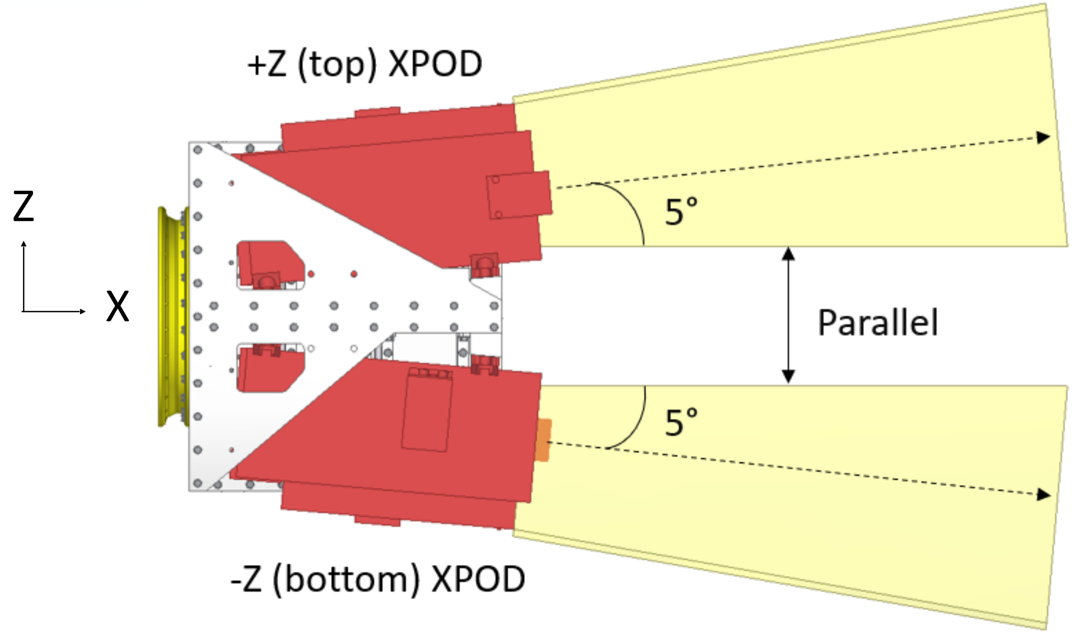
XPOD Delta Showing Worst-Case Deployment Path of Spacecraft



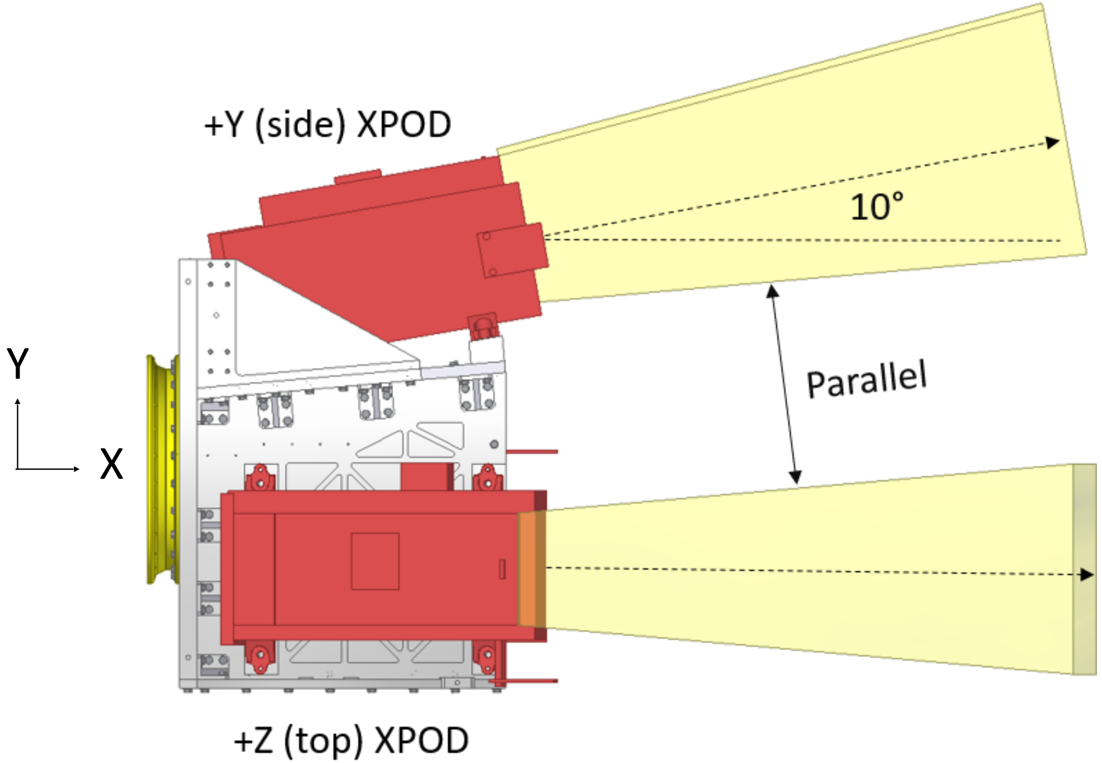
View of Top XPOD Platform and its four Mounting Bosses

Spacecraft Ejection Ensures no Collisions

The XPODs are positioned such that in the worst case, the spacecraft ejection path will be parallel.



Side View of Worst-Case Spacecraft Ejection Path

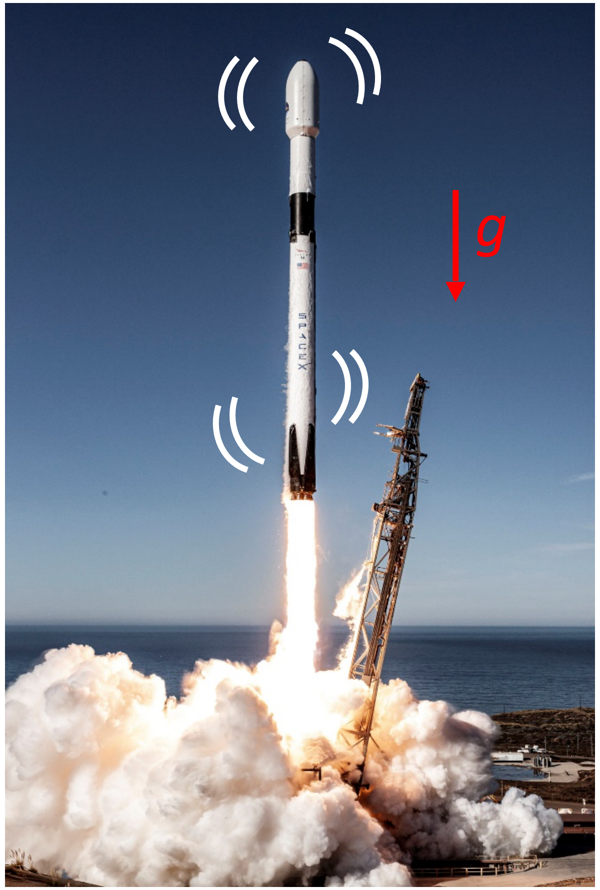


Top View of Worst-Case Spacecraft Ejection Path

XALT Design Validation & Testing

Maximum Predicted Launch Environment

- Each payload mounted on the rocket must withstand the maximum predicted launch environment.
  - Static loading (launch vehicle acceleration)
  - Dynamic loading (vibrations)
  - Shocks



Falcon 9 Rocket Launch in November 2020 [Credits: ESA]

UTIAS SFL 1998 20 YEARS 2018

Quasi-Static Load

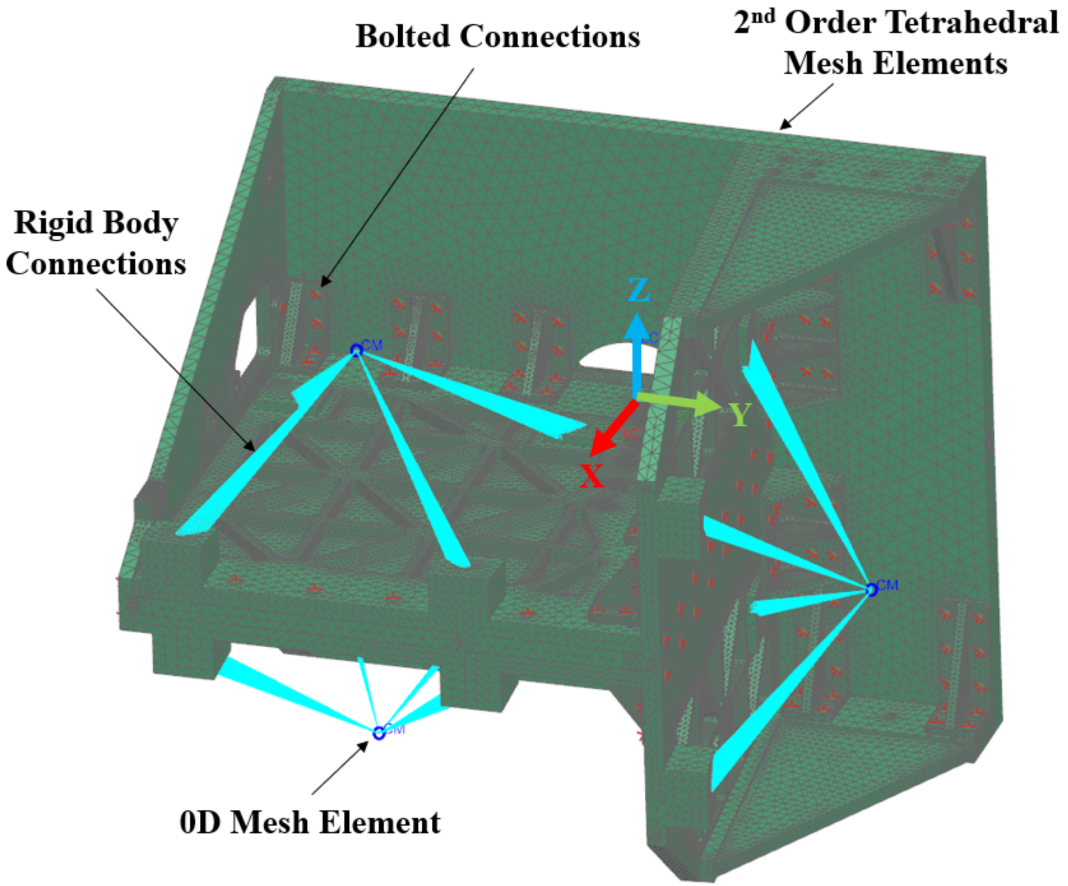
REQ-006: XALT shall withstand the maximum load factor with positive stress margins including a safety factor of 2.

- For a mass of 177 kg:
  - Axial Load Factor: 5.84*g*
  - Lateral Load Factor: 11.5*g*
- Load Factor rounded up to 12*g*.
- Design Safety Factor of 2 is applied.
- **Quasi-static load analysis performed using 24*g* in each direction.**

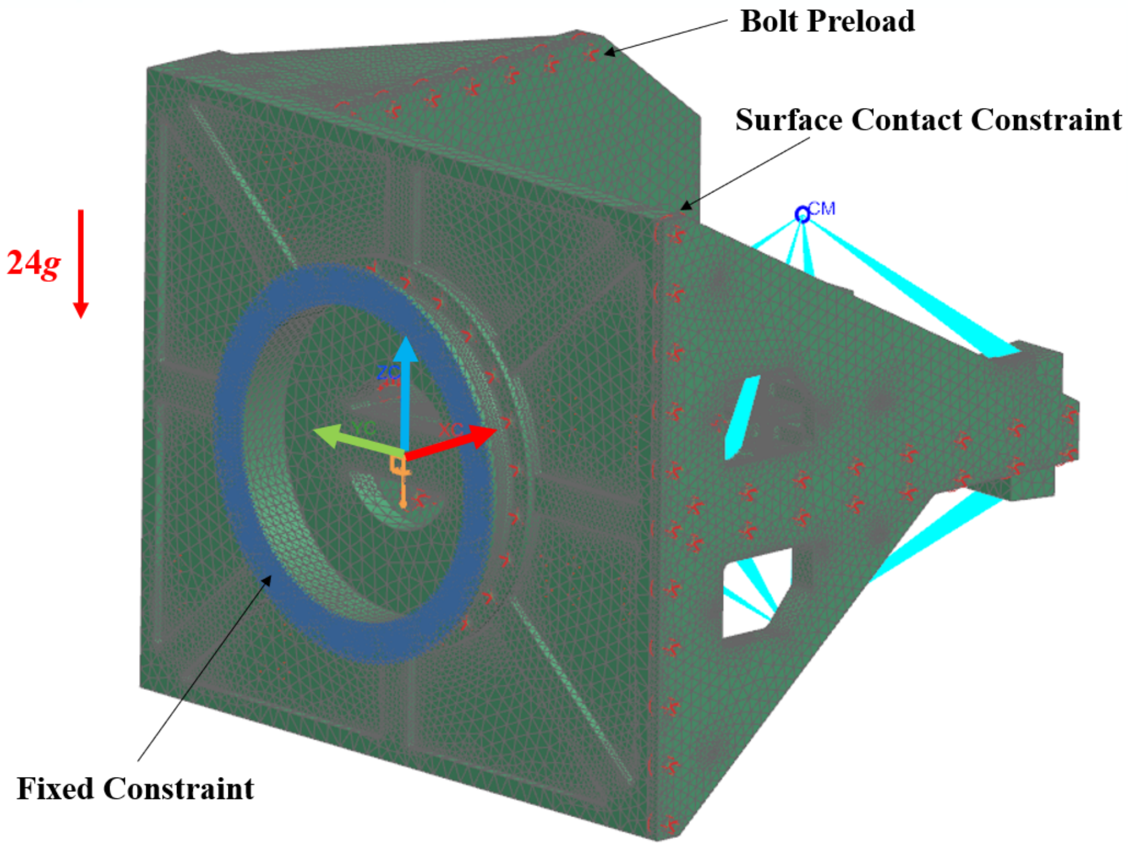
Rideshare Payload Design Load Factors [Source: SpaceX]

Payload Mass (kg)	Dispenser Ring Load Factor (g)	
	Axial X_{PL}	Lateral RSS Y_{PL}, Z_{PL}
1	7.4	12.9
30	7.4	12.9
100	6.4	12.0
225	5.5	11.1
400	5.1	10.3
600	5.1	9.4
900	5.1	8.1

Quasi-Static Load: FEM

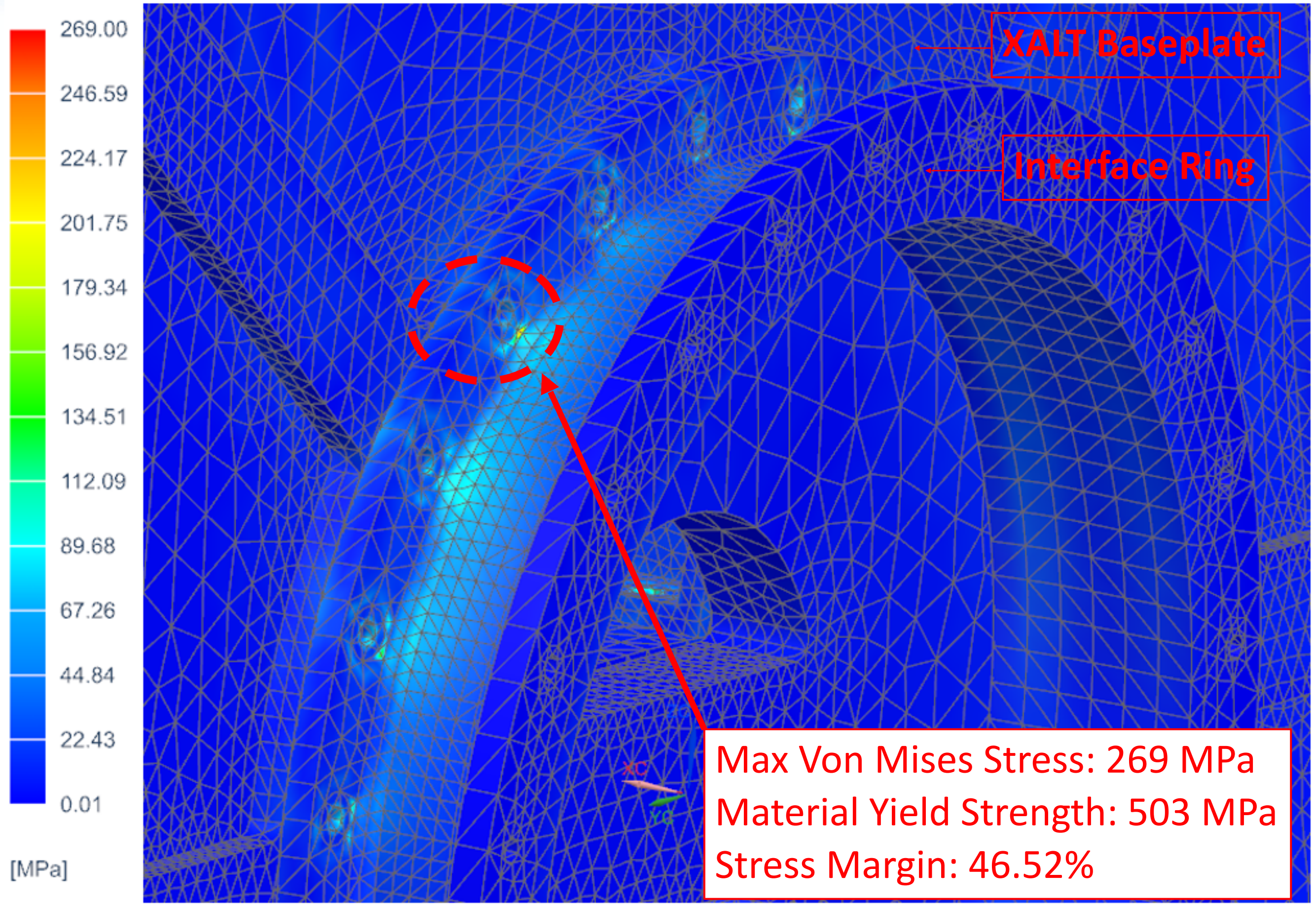


FEM of Launch Payload



Constraints Applied in the FEM

Quasi-Static Load: Maximum Von Mises Stress



Von Mises Stress Contours for Loading in -Z Direction

Max Von Mises Stress in Each XALT Part for Loading in -Z

Part	Material Yield Strength [MPa]	Max Simulated Stress [MPa]	Safety Margin [%]
15” Interface Ring	503	269	46.52
Base Plate	503	109.15	78.30
-Y Panel	503	117.43	76.65
+Z XPOD Platform	503	98.02	80.51
-Z XPOD Platform	503	86.82	82.74
+Y XPOD Platform	503	107.27	78.67
Middle Support	503	71.67	85.75
+Y Platform Support	503	81.29	83.84
L-Bracket A	503	174.87	65.23
L-Bracket B	503	192.10	61.81
L-Bracket C	503	167.41	66.72
L-Bracket D	503	178.59	64.50

FEA Results: Bolt Load and Stress

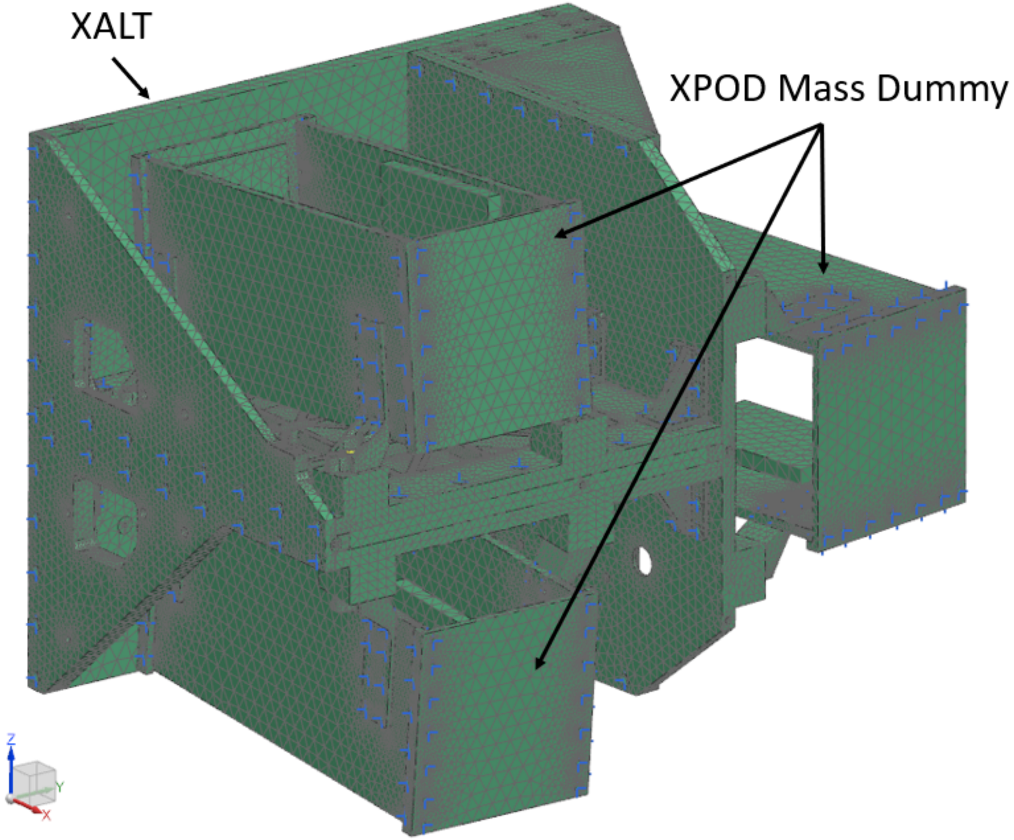
- A bolt load analysis was performed to ensure bolt failure and joint separation does not occur during worst-case quasi-static loading.

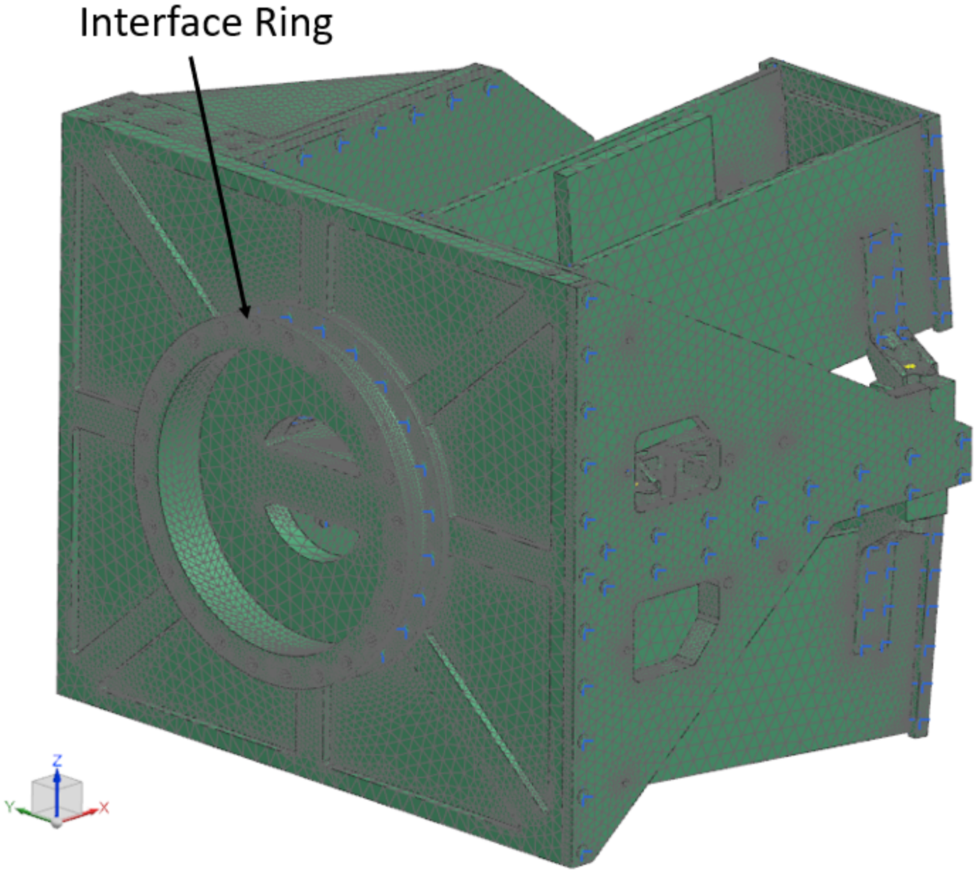
XALT M8 Bolt Stress Margin and Joint Separation Safety Margin

Loading Direction	Max Axial Force [N]	Max Axial Stress [MPa]	Tensile Strength [MPa]	Stress Margin [%]	Joint Separation Safety Margin [%]
+X	7889.01	156.95	689	77.22	98.34
-X	7852.23	156.22	689	77.33	99.15
+Y	8893.93	176.94	689	74.32	76.44
-Y	8815.86	175.39	689	74.54	78.14
+Z	9614.79	191.28	689	72.24	60.73
-Z	9514.45	189.28	689	72.53	62.92

Modal Analysis: FEM

REQ-007: The entire payload structure's first natural frequency (FNF) shall be above 40 Hz to avoid resonance with the launch vehicle.





Isometric Views of the GHGSat-C3/C4/C5 Finite element Model used for Modal Analysis

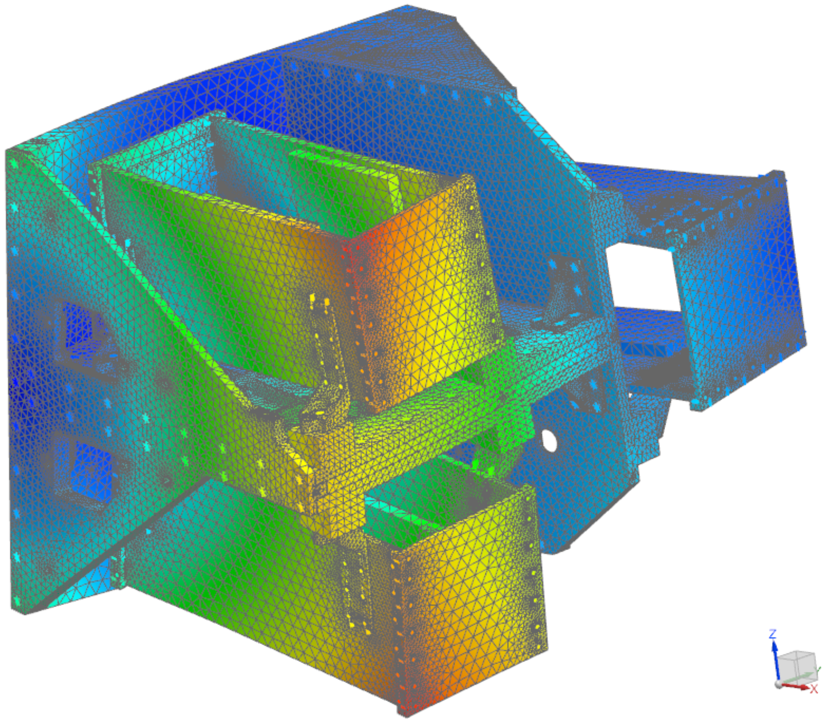
UTIAS SFL 1998 20 YEARS 2018

Normal Modes

- Modes with highest mass fractions in X, Y and Z will dictate the expected FNF when the payload is excited in the X, Y and Z direction respectively.

List of Normal Modes

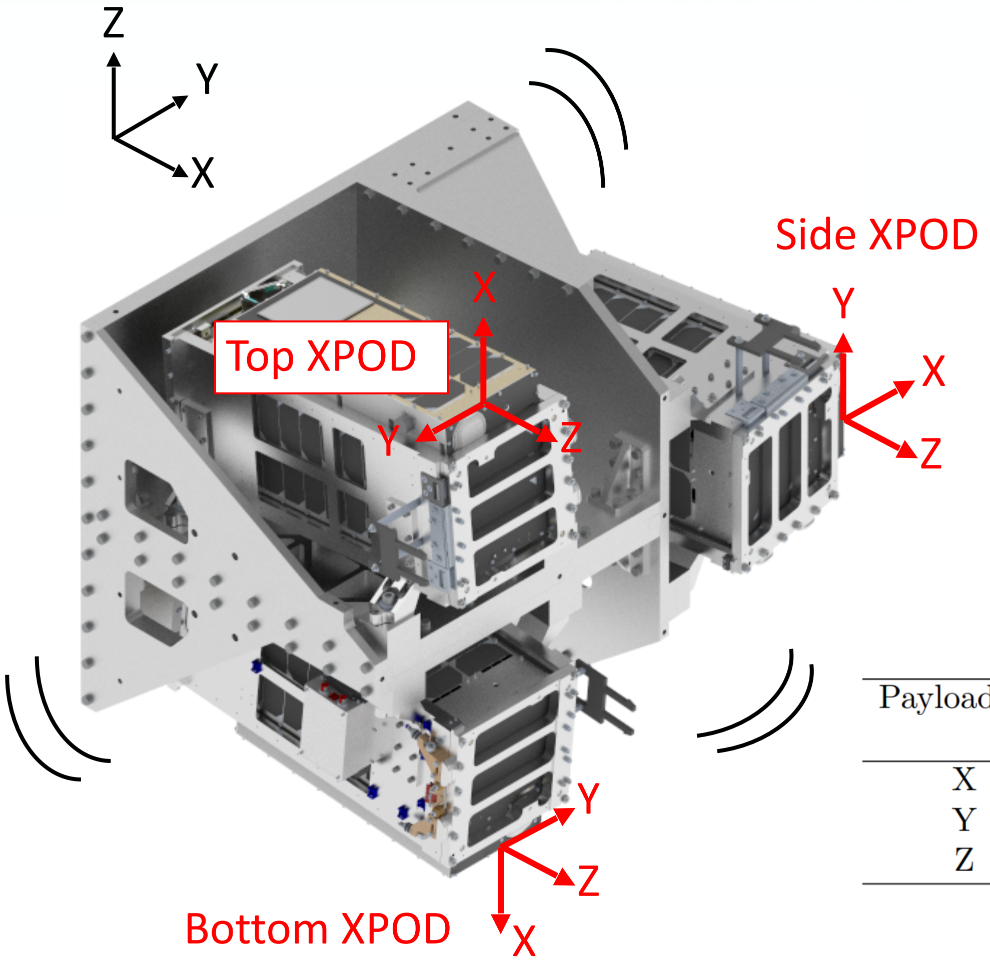
Mode	Frequency [Hz]	
1	57.18	[33% Mass Fraction along Z]
2	69.82	
3	76.43	[46% Mass Fraction along Y]
4	101.80	
5	142.07	
6	142.62	
7	143.80	
8	151/98	
9	183.22	
10	185.66	[48% Mass Fraction along X]
11	195.45	
12	223.52	

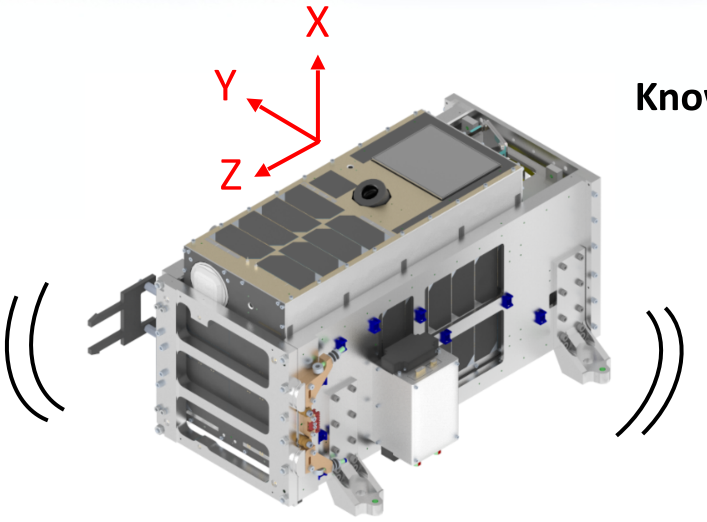


Mode Shape at Mode 1 (57.18 Hz)

Frequency Decoupling

REQ-008: The FNF of the entire assembly shall be decoupled from each XPOD's on-axis FNF by at least 15% to avoid amplifying resonance.





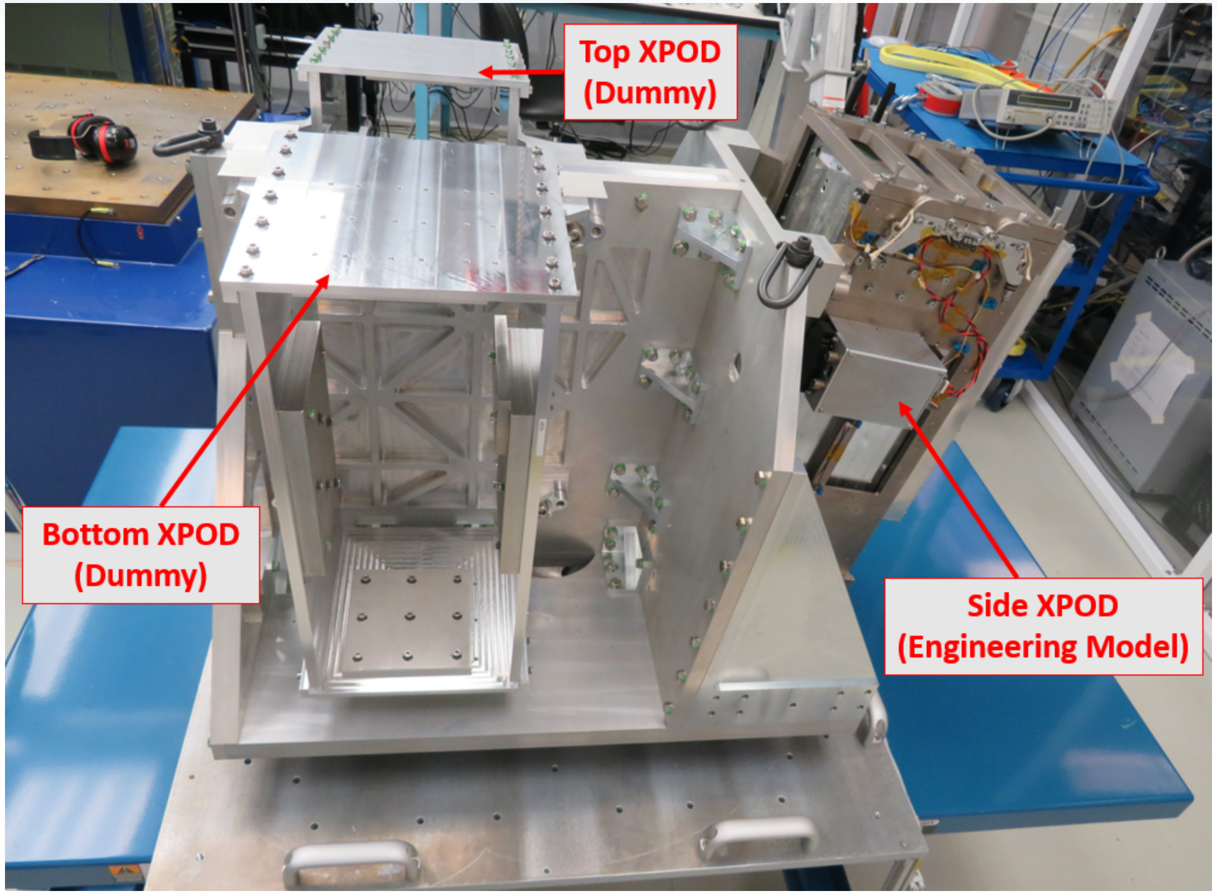
Known XPOD FNF from Past Testing

Axis	FNF [Hz]
X-axis	132
Y-axis	88
Z-axis	144

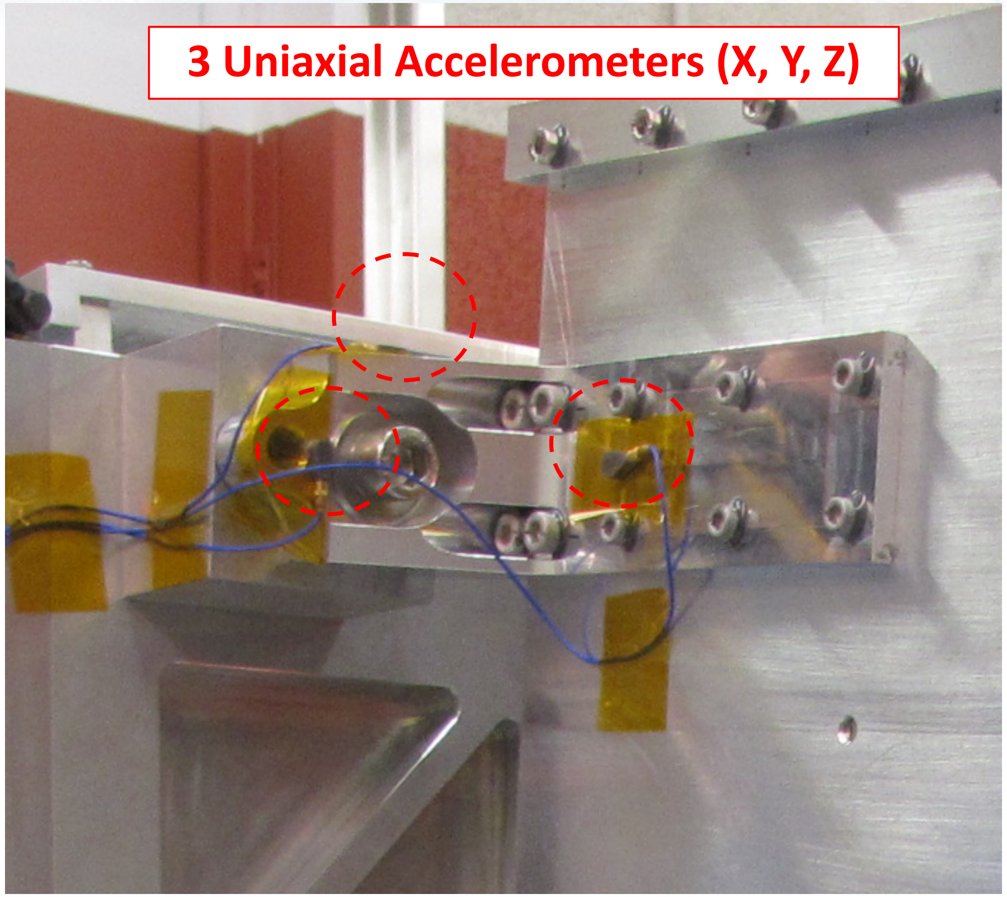
Comparison of Payload FNF and each XPOD's on-axis FNF

Payload CS	Payload FNF	On-Axis Top XPOD FNF	On-Axis Bottom XPOD FNF	On-Axis Side XPOD FNF	Min Frequency Decoupling
X	185.66 Hz	144 Hz	144 Hz	144 Hz	41.7 Hz
Y	76.43 Hz	88 Hz	88 Hz	132 Hz	11.6 Hz
Z	57.18 Hz	132 Hz	132 Hz	88 Hz	30.8 Hz

Vibration Testing Setup



XALT Testing Setup

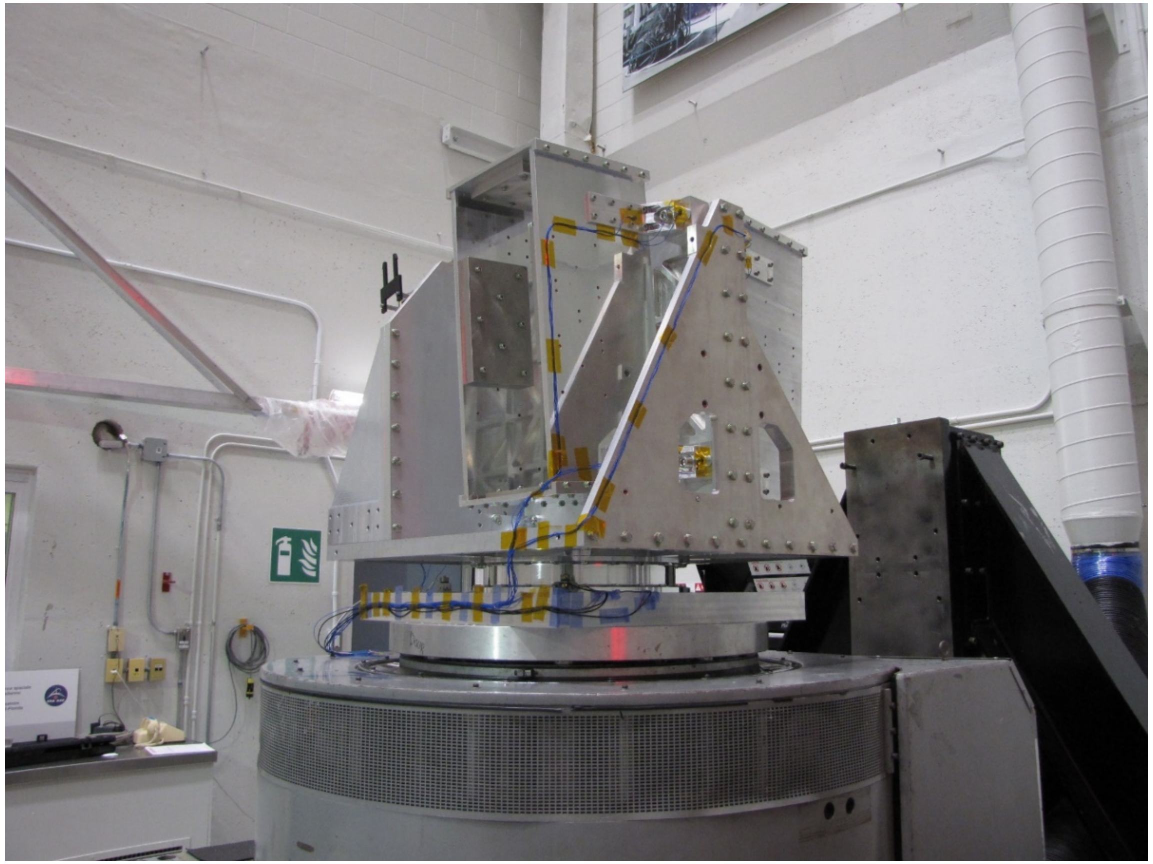


Accelerometer Installed on a Mounting Leg

Vibration Testing Levels

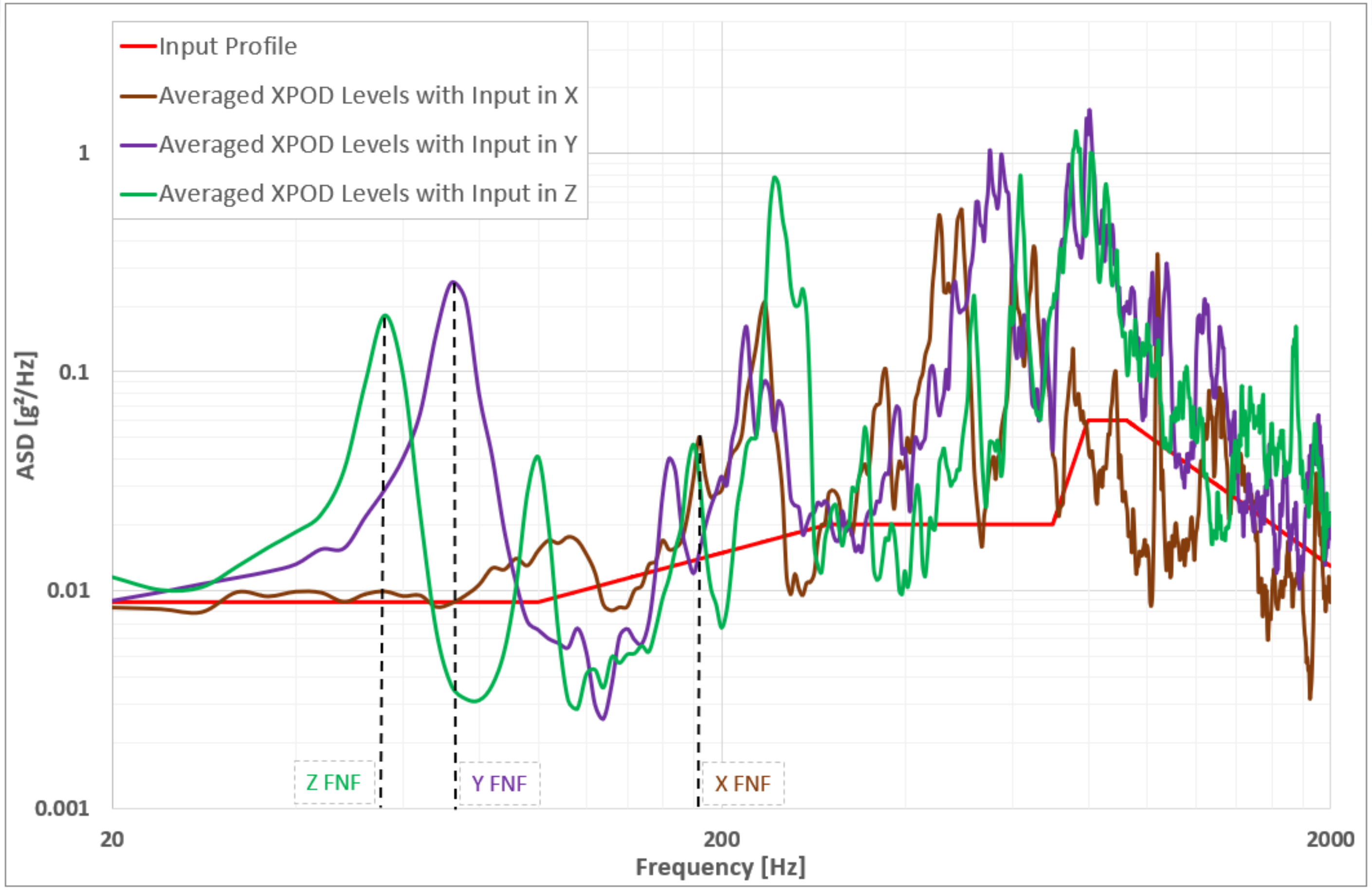
- Single Unit Approach: Apply protoqualification test levels on flight unit(s)
  - Quasi-static (sine-burst) test
  - Sine vibration test
  - Random vibration test
  - Shock test

- All protoqualifcation test profiles were provided by SpaceX and are applied at the ring interface.



XALT Testing Setup on Shaker Table

Random Vibration Test Results



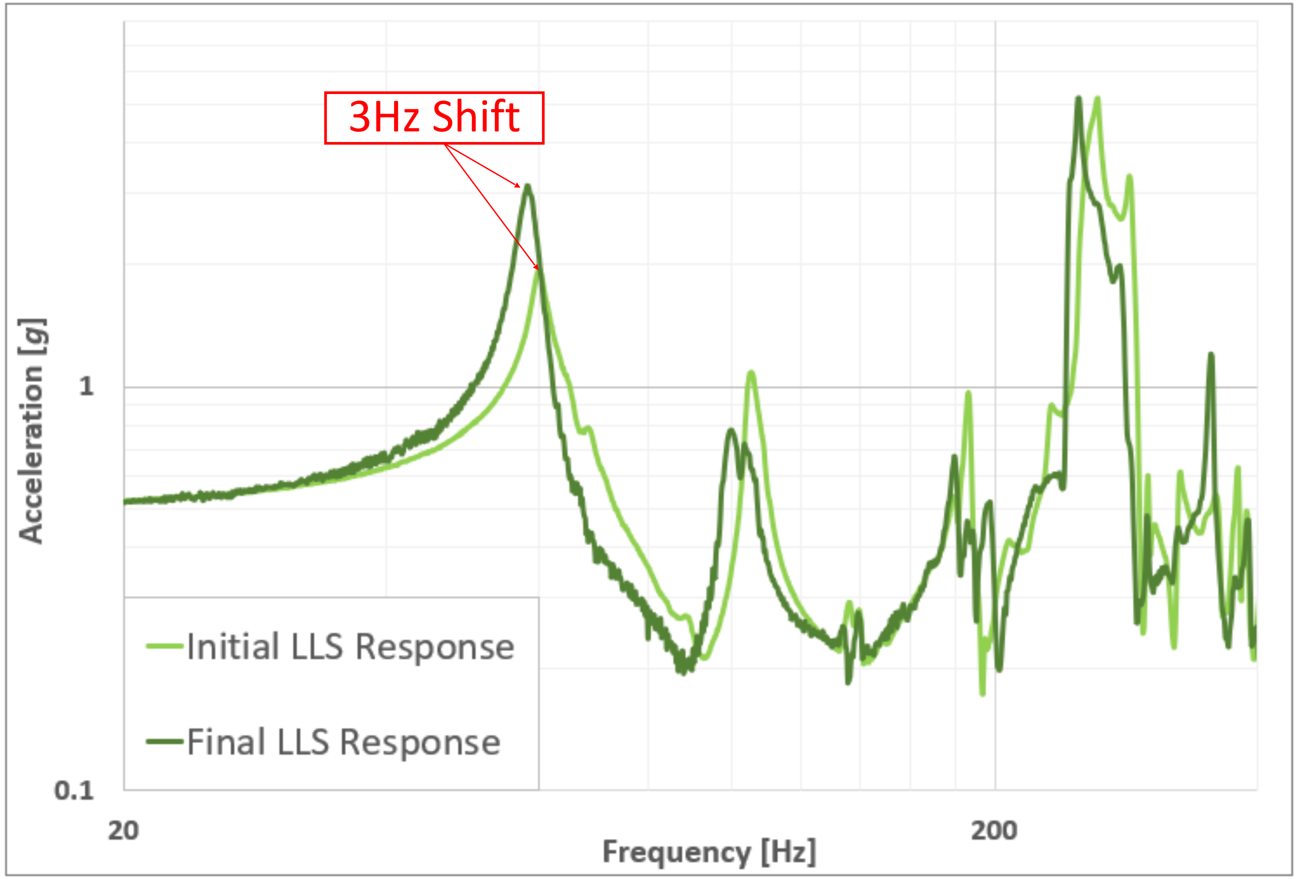
Compilation of Random Response for each axis measured for EM XPOD

FNF obtained from Simulation VS Experiment

Axis of Excitation	Simulated FNF [Hz]	Experimental FNF [Hz]	Difference [%]
X	185.66	180	3
Y	76.43	76	0.6
Z	57.18	56	2

Low Level Sine Test Results

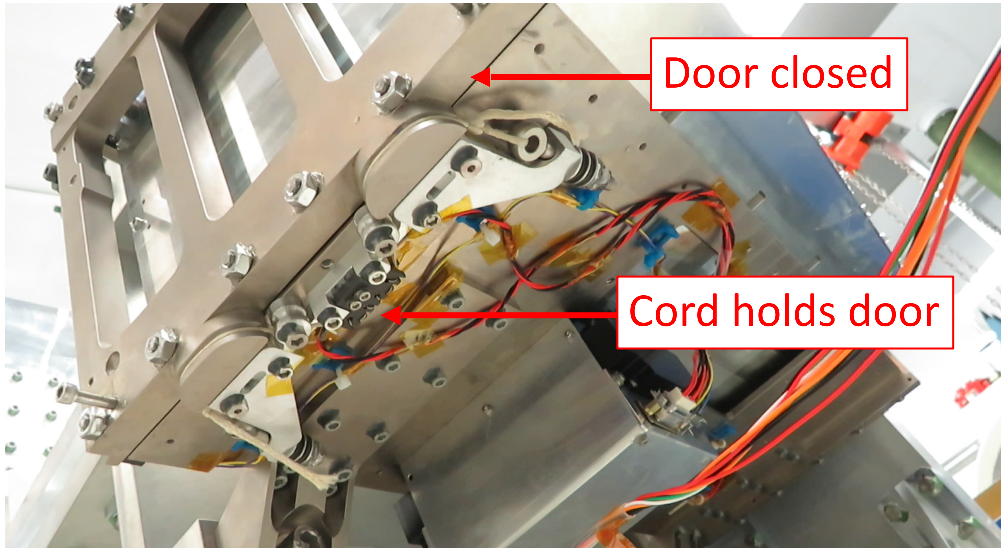
- Low level sine sweep test is performed at the very beginning and at the very end of the testing.
- Used to track changes in the natural frequencies.
- Maximum FNF shift of 3 Hz (5% difference) was observed for data recorded in the Z axis.



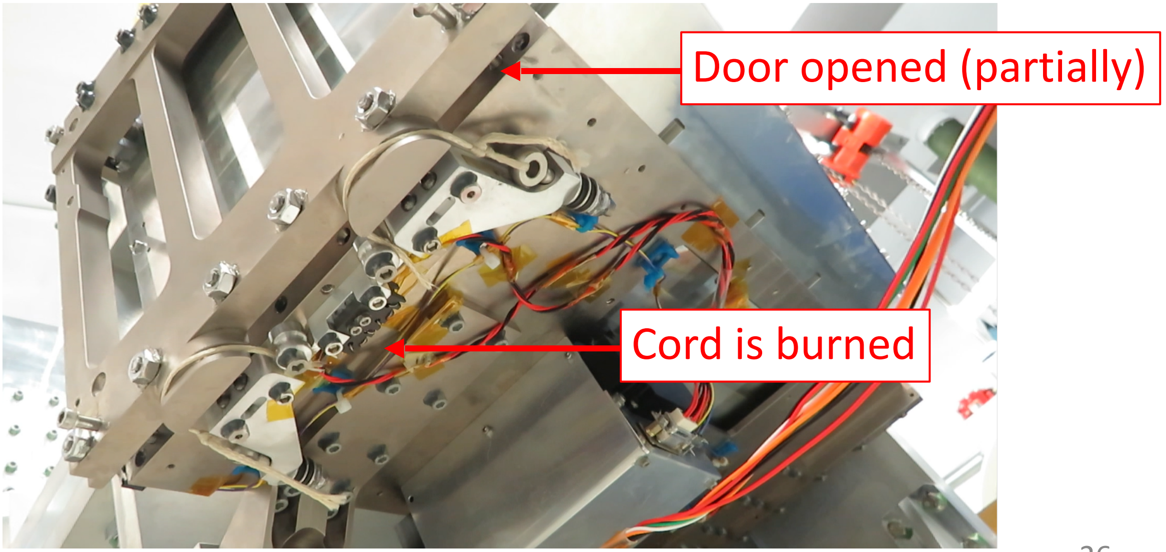
Low Level Sine Response Data along Z-axis

Post Vibration Test Verification

- Once all vibration tests were complete, the following verifications were performed:
  - Visual inspection for damage or signs of wear and tear.
  - Torque verification on each bolt to verify for any loosening.
  - XPOD deployment test to verify that the deployment mechanism was still functional.



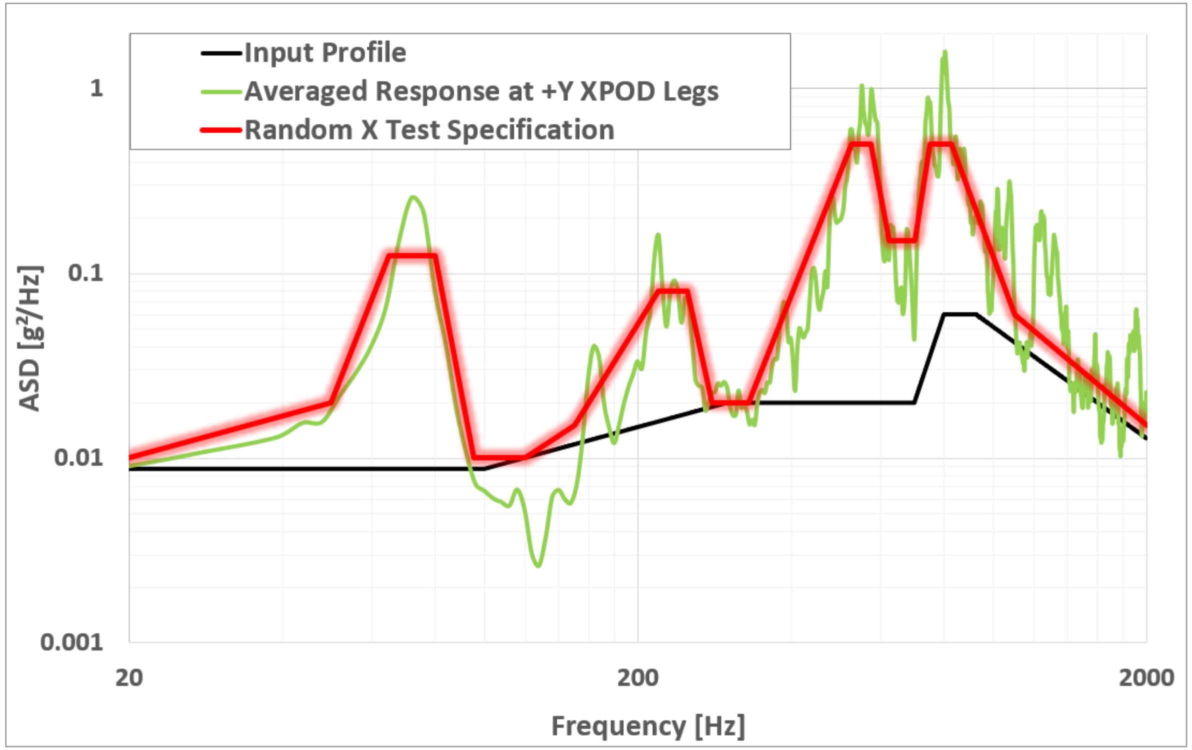
XPOD Deployment Test (before)



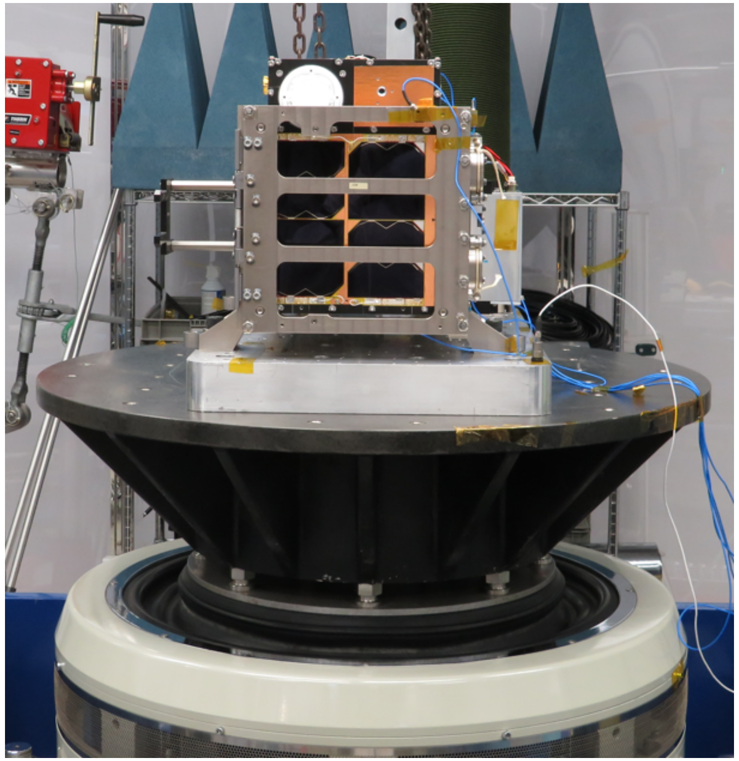
XPOD Deployment Test (after)

XPOD & Spacecraft Testing Profile

- Loaded XPOD testing profiles were generated using the test data recorded at the mounting legs.
- Profiles were enveloped using NASA guidelines for spacecraft vibration testing **[source: FEMCI guidelines].**



Random X Test Specification for Loaded XPOD



GHGSat-C3 Setup for Testing in X Direction

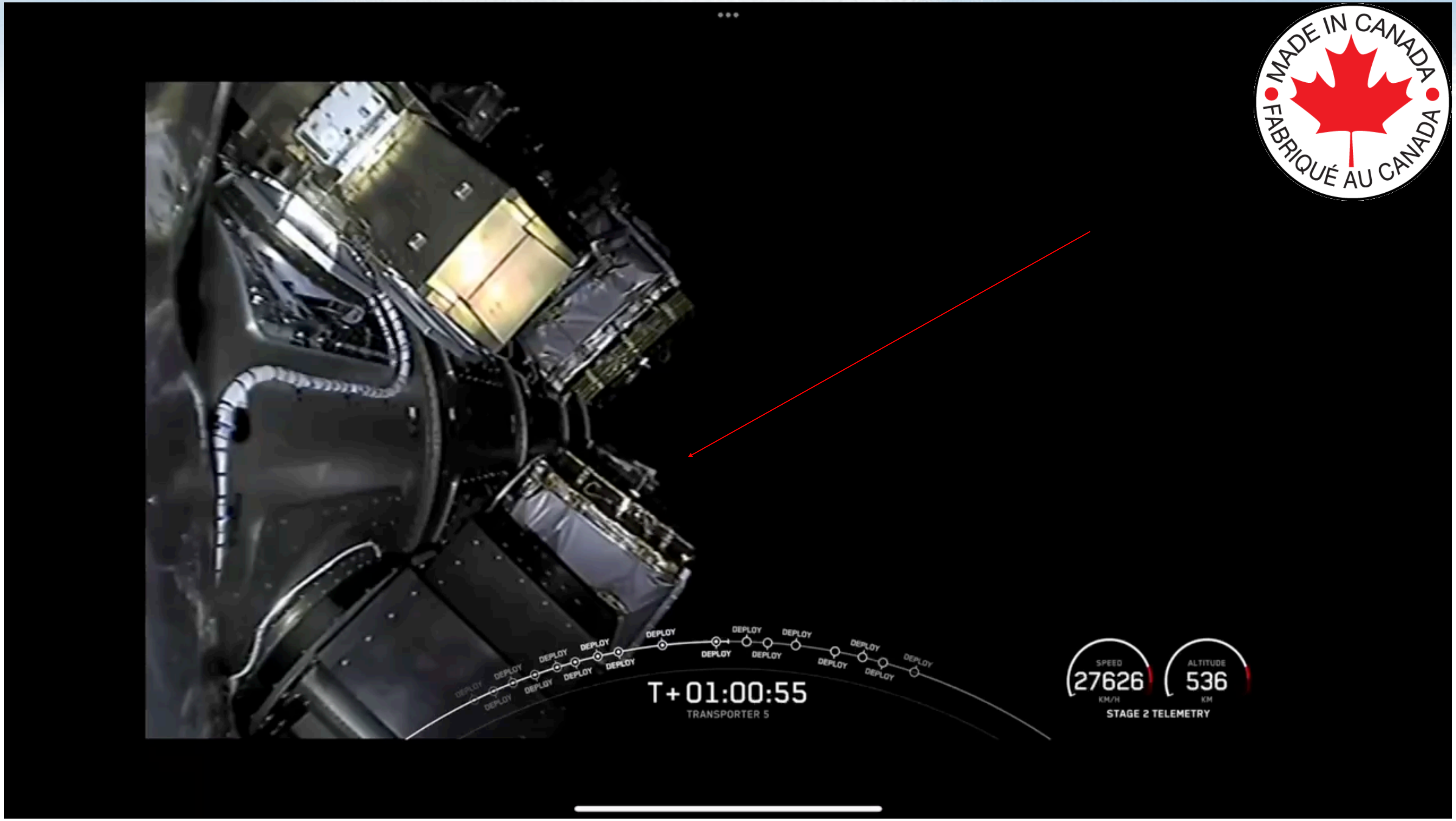
Launch of GHGSat-C3/C4/C5

- GHGSat-C3/C4/C5 was launched onboard a Falcon 9 as part of the SpaceX Transporter-5 Rideshare mission.
- Transporter-5 Launch:
  - Launched May 25th 2022, 2:35pm ET
  - Carried 59 Payloads to low Earth orbit

Transporter-5 Launch [Credits: SpaceX]

UTIAS SFL 1998 20 YEARS 2018

GHGSat-C3/C4/C5 Deployment in Space



Payload Deployment [Source: SpaceX]

Smaller Satellites, Bigger Return

Thank you! Questions?

UTIAS SFL 1998 20 YEARS 2018

www.utias-sfl.net

@SFL_SmallerSats

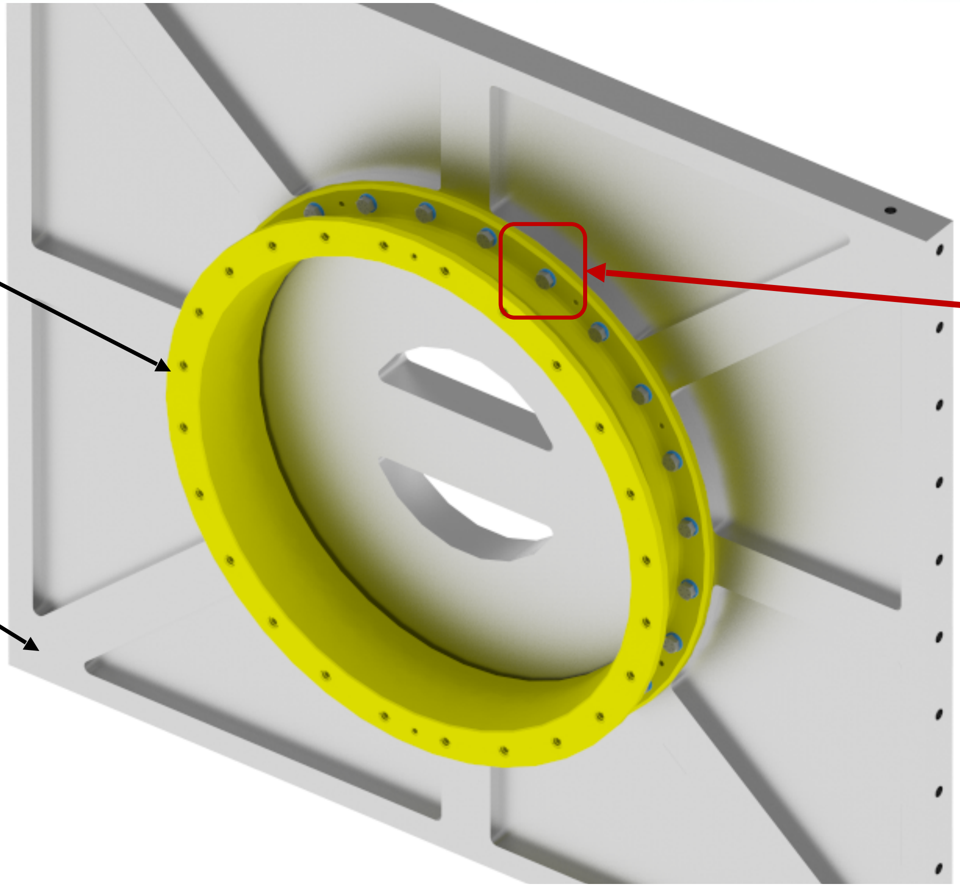
UTIAS SFL 1998 20 YEARS 2018

XALT Mounting

REQ-001: XALT shall mount on the 15” diameter Interface Ring with thru-holes.

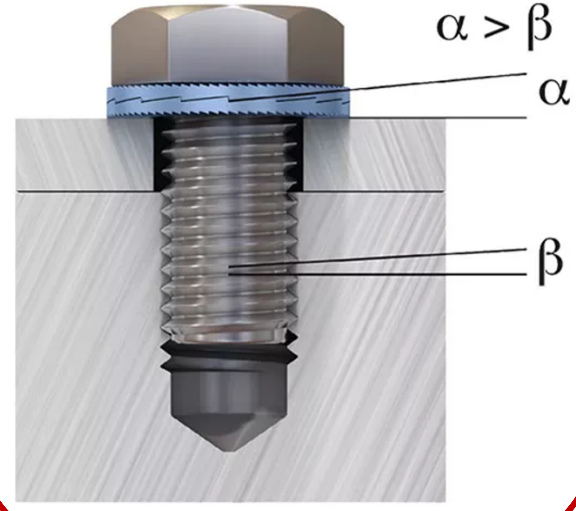
15” Mechanical Interface Ring

XALT Base Plate



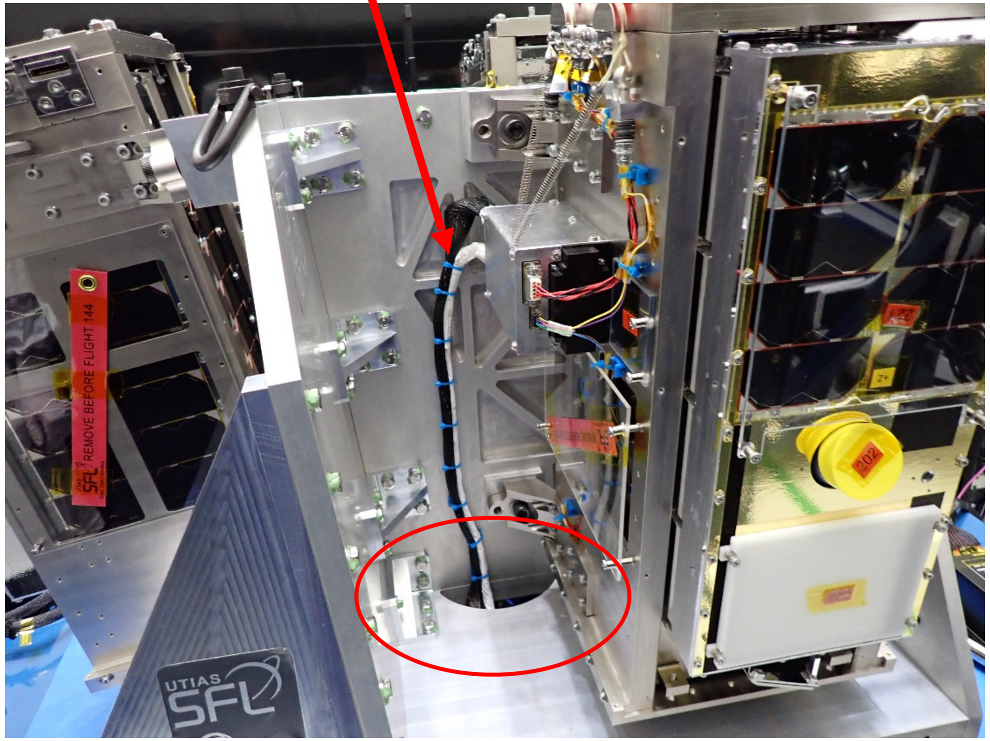
View of 15” Interface Ring attached on XALT Baseplate

Hex Head Screw with Nord-Lock Washer

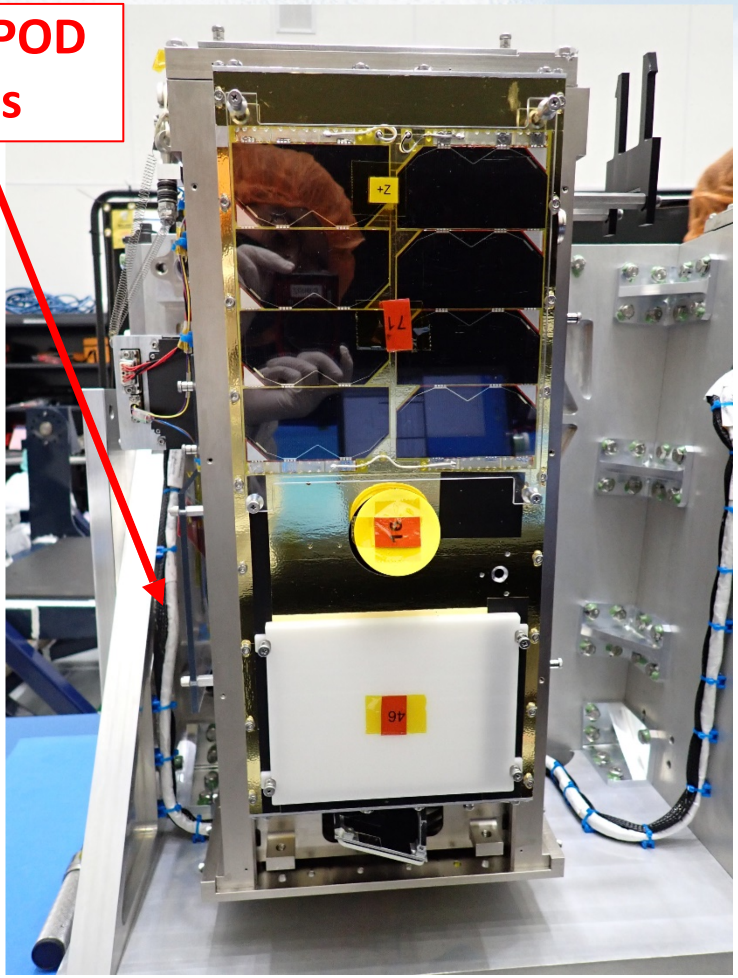


Wire Harness Considerations

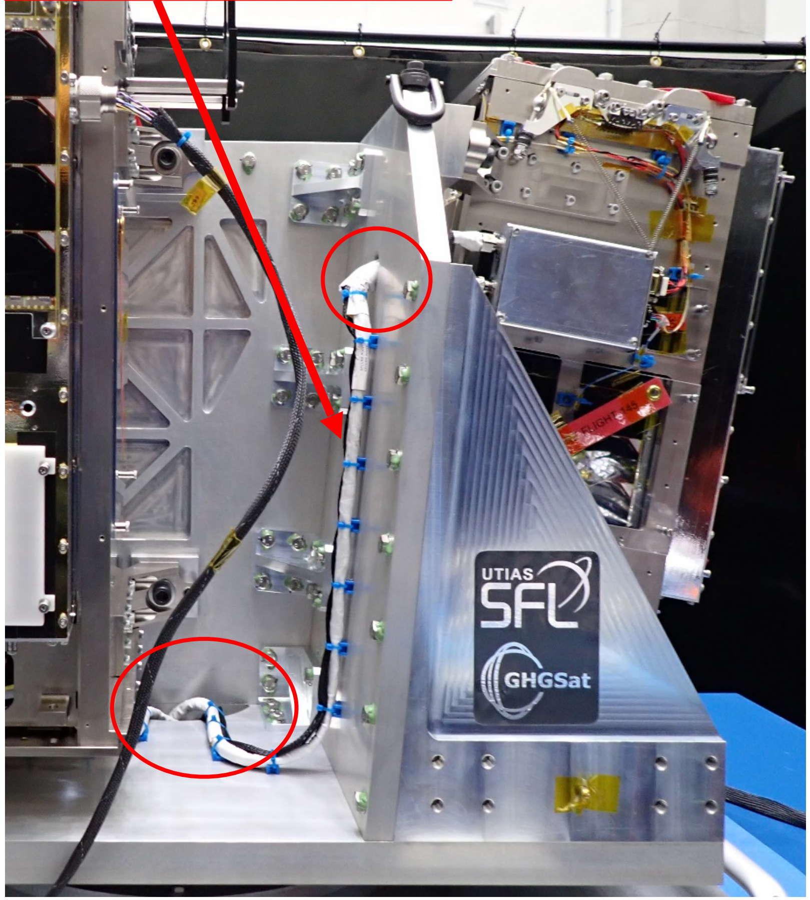
Top XPOD Harness



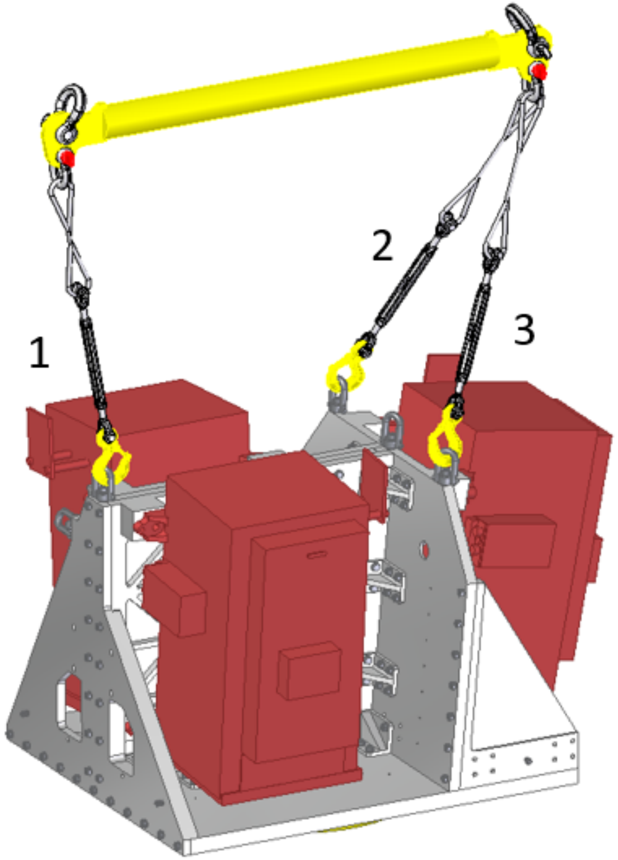
Bottom XPOD Harness

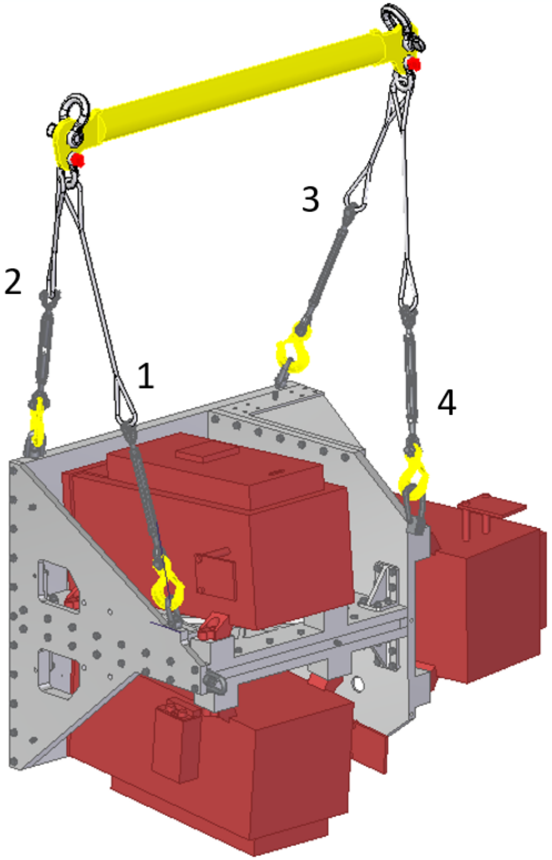


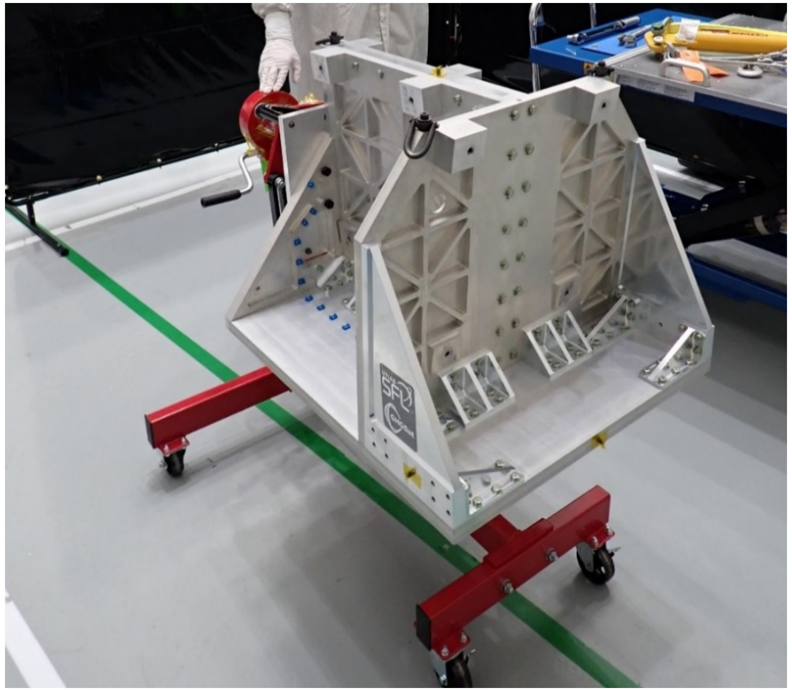
Side XPOD Harness



Ground Handling Considerations

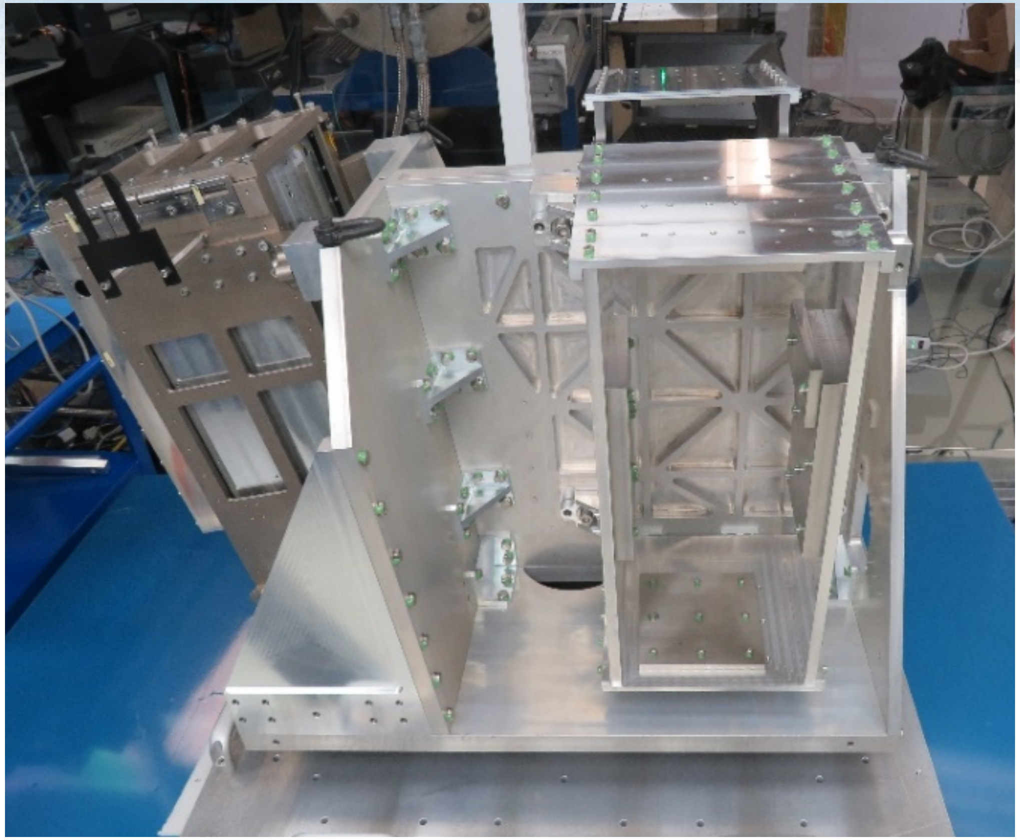






EM XPOD Placement - XALT Testing

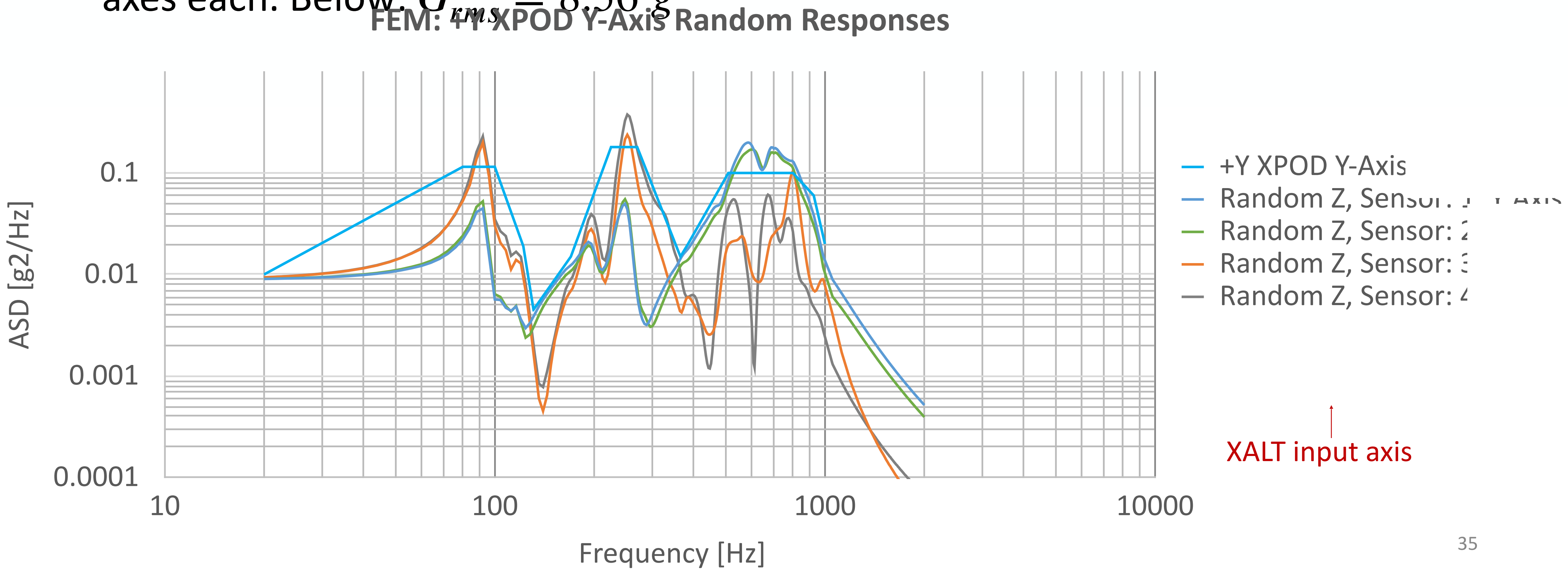
- Two objectives for XALT vibration testing:
  - 1. Measure most severe response of the payload using a mass model
  - 2. Measure the response at interfaces where XPODs mount to XALT
- Only one EM XPOD and spacecraft mass model available, and only seven three-axis accelerometers available
- Preparation required: select locations for accelerometers and EM XPOD with spacecraft mass model



XALT with XPOD/mass model and mass dummies for testing

Analysis Prior to XALT Test

- Original FEM used to predict random vibration response
- Responses plotted and enveloped to compute G_{rms}. 3 XPODS with 3 response axes each. Below: $G_{rms} = 8.56\ g$



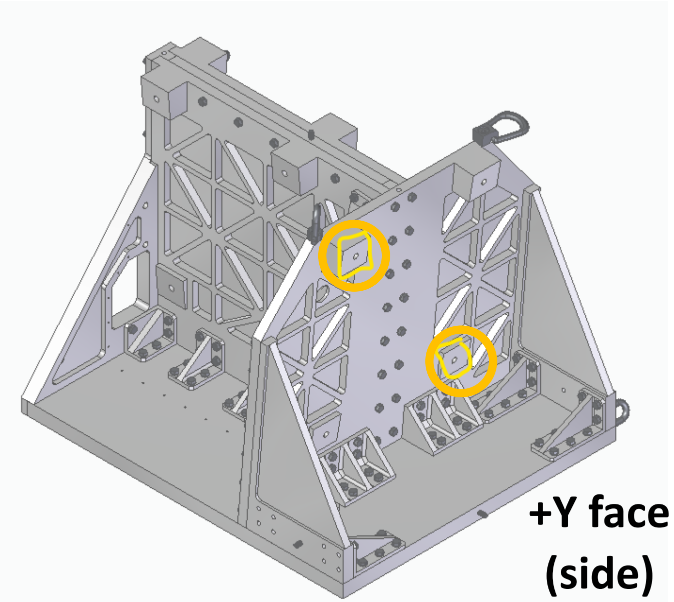
Setup Used for Testing

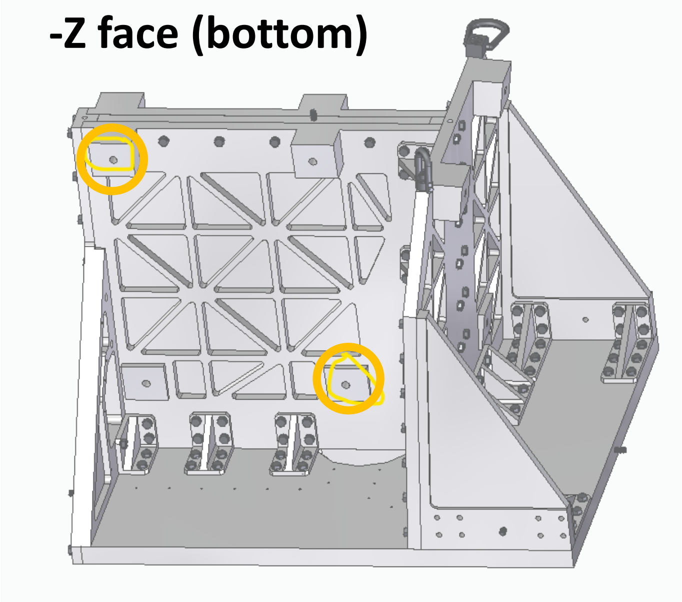
XPOD Summary (g)

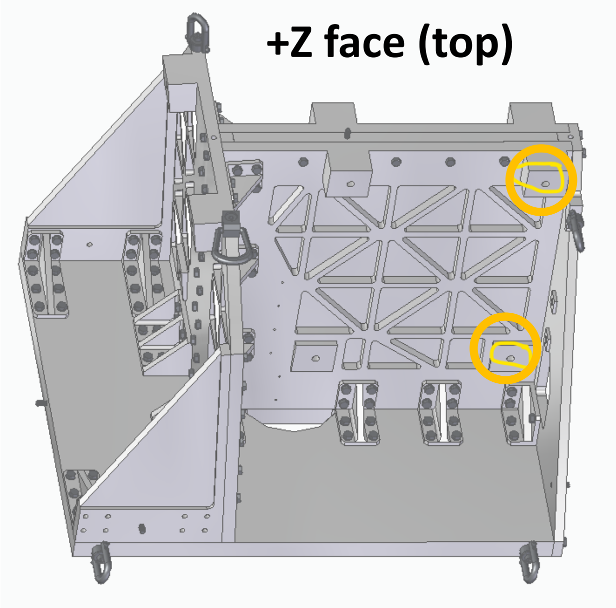
XPOD Position	+Y (side)	+Z (top)	-Z (bottom)
X Axis Response	8.45	7.85	8.49
Y Axis Response	8.56	8.03	7.68
Z Axis Response	7.89	6.64	7.03
Average	8.30	7.51	7.73

Local XPOD response (X, Y, Z Axis Response rows)

Accelerometer placement







FEA Results: Bolt Load and Stress

- A bolt load analysis was performed to ensure bolt failure and joint separation does not occur during worst-case quasi-static loading.

$$F_{preload} = \frac{T}{K \cdot d}$$

$$C = \frac{K_{bolt}}{K_{bolt} + K_{grip}}$$

$$F_{sep} = \frac{F_{preload}}{1 - C}$$

$$F_{axial} = F_{preload} + F_{t,eff} = F_{preload} + C \cdot F_{t,appl}$$

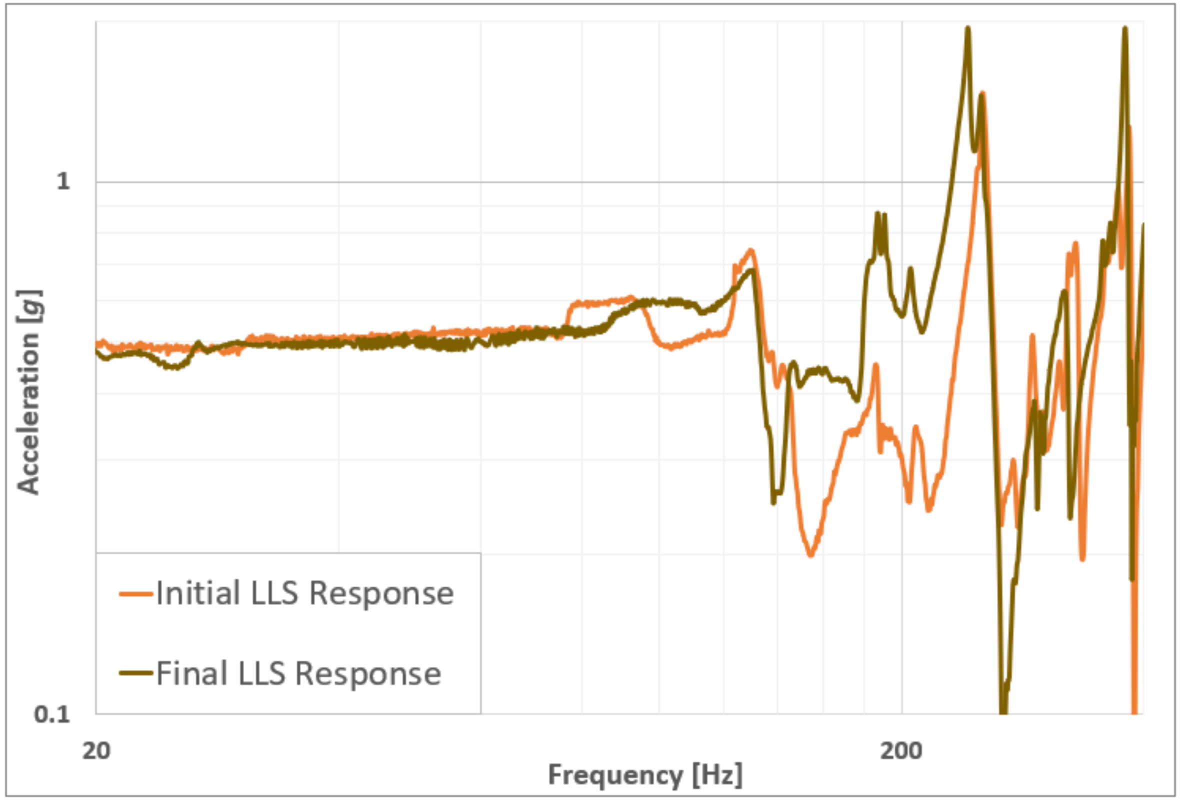
$$S_{sep} = \frac{F_{sep}}{F_{t,appl}} > 0$$

XALT M8 Bolt Stress Margin and Joint Separation Safety Margin

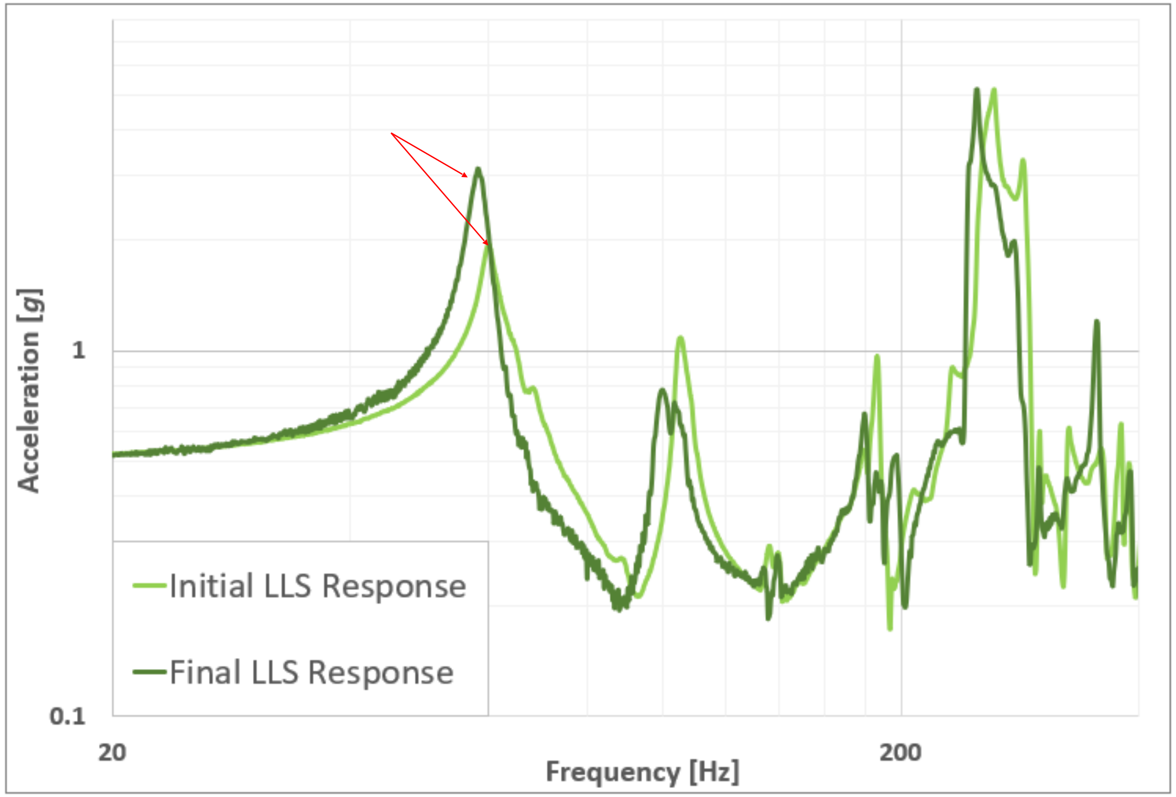
Loading Direction	Max Axial Force [N]	Max Axial Stress [MPa]	Tensile Strength [MPa]	Stress Margin	Joint Separation Safety Margin
+X	7889.01	156.95	689	1.55	60.37
-X	7852.23	156.22	689	1.56	116.97
+Y	8893.93	176.94	689	1.26	4.25
-Y	8815.86	175.39	689	1.28	4.58
+Z	9614.79	191.28	689	1.09	2.55
-Z	9514.45	189.28	689	1.11	2.70

Low Level Sine Test Results

Low level sine sweep test is performed between each test to track changes in the first natural frequency
FNF shifted by a maximum of 3 Hz (0.5% difference)

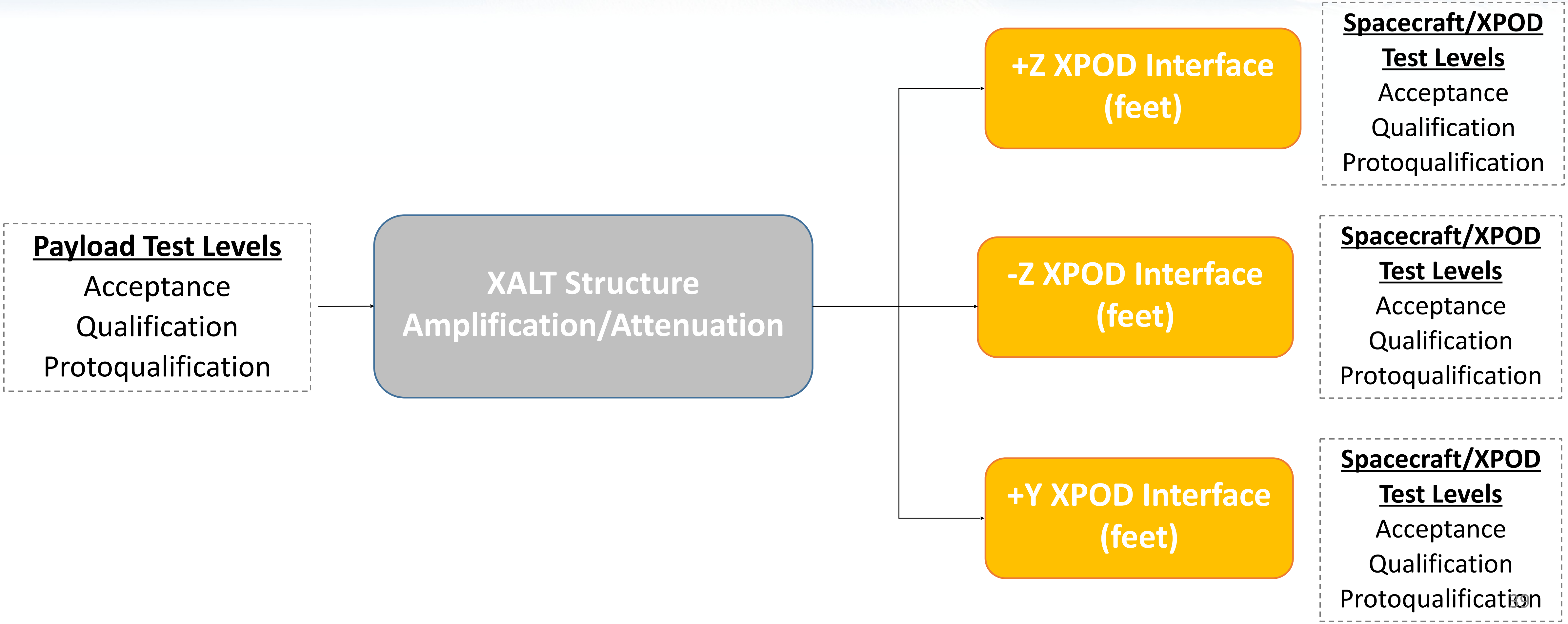


Low Level Sine Response Data along X-axis



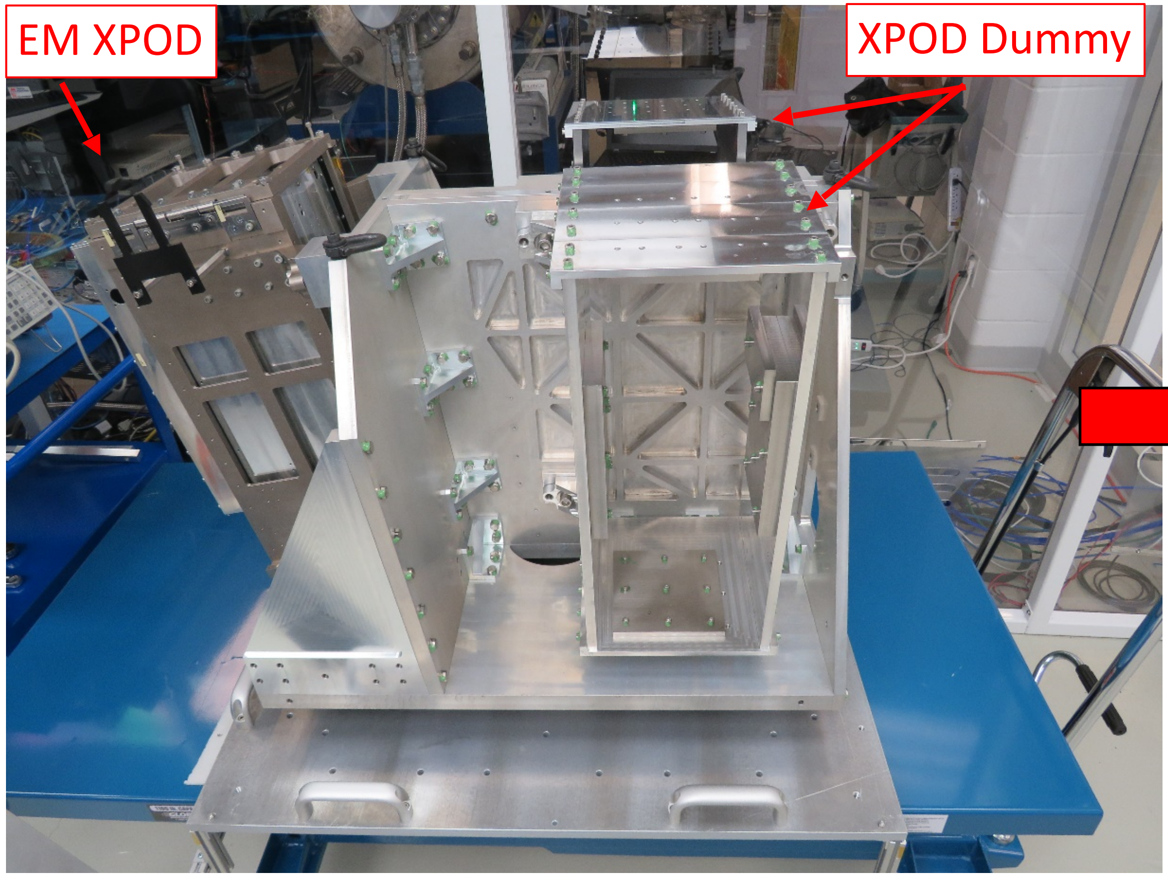
Low Level Sine Response Data along Z-axis

Model Correlation

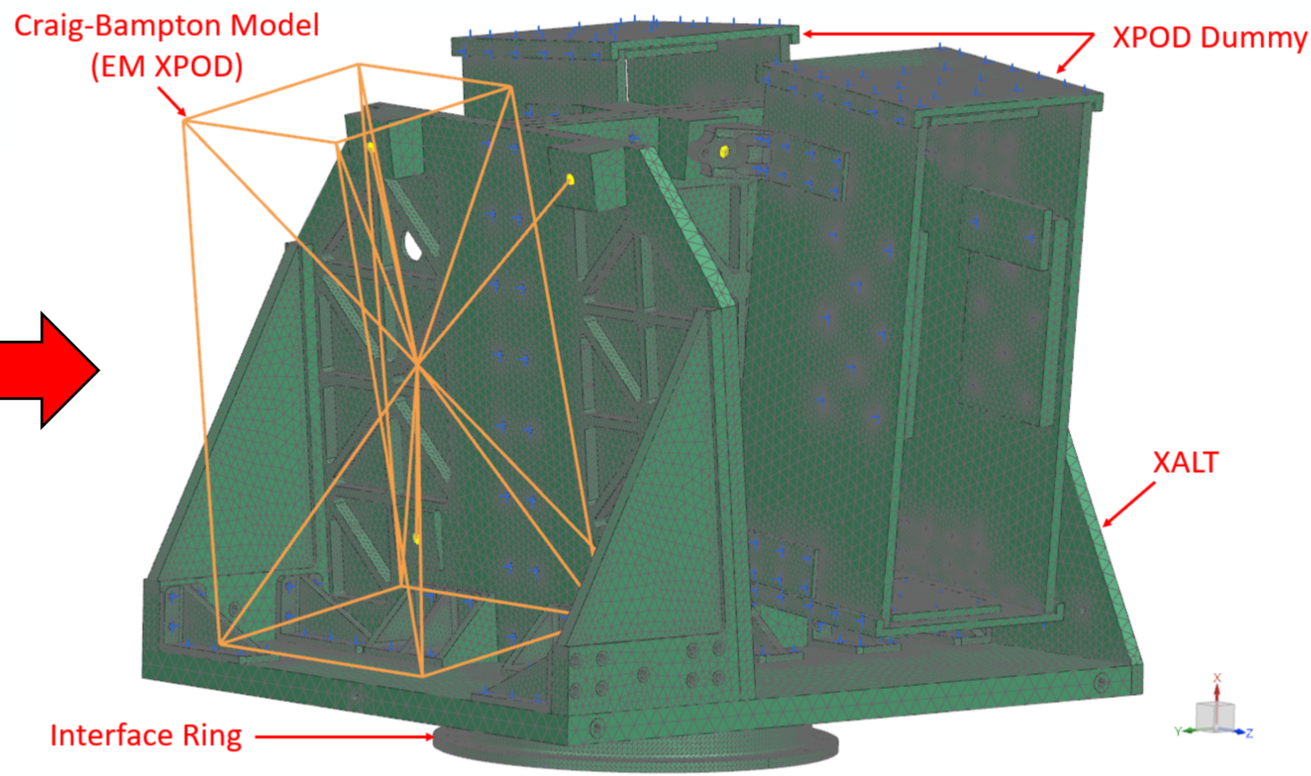


Model Correlation FEM Setup

- Generate a finite element model representative of the test setup.



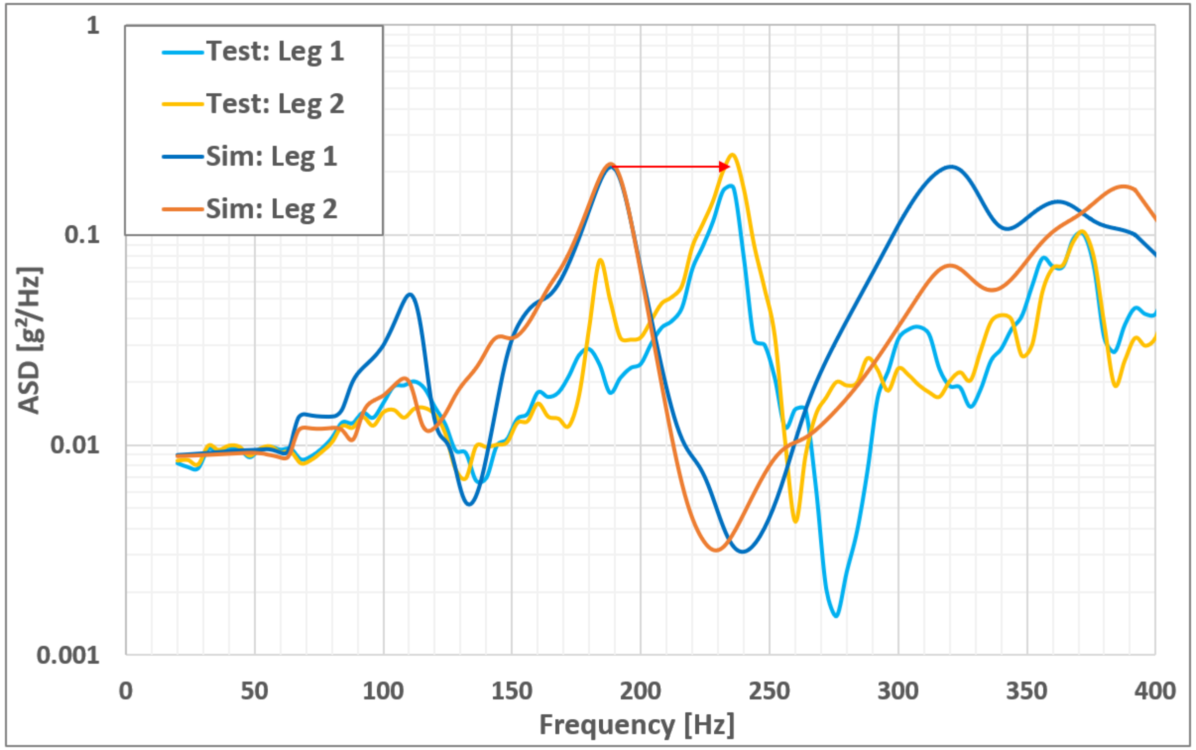
XALT Testing Setup



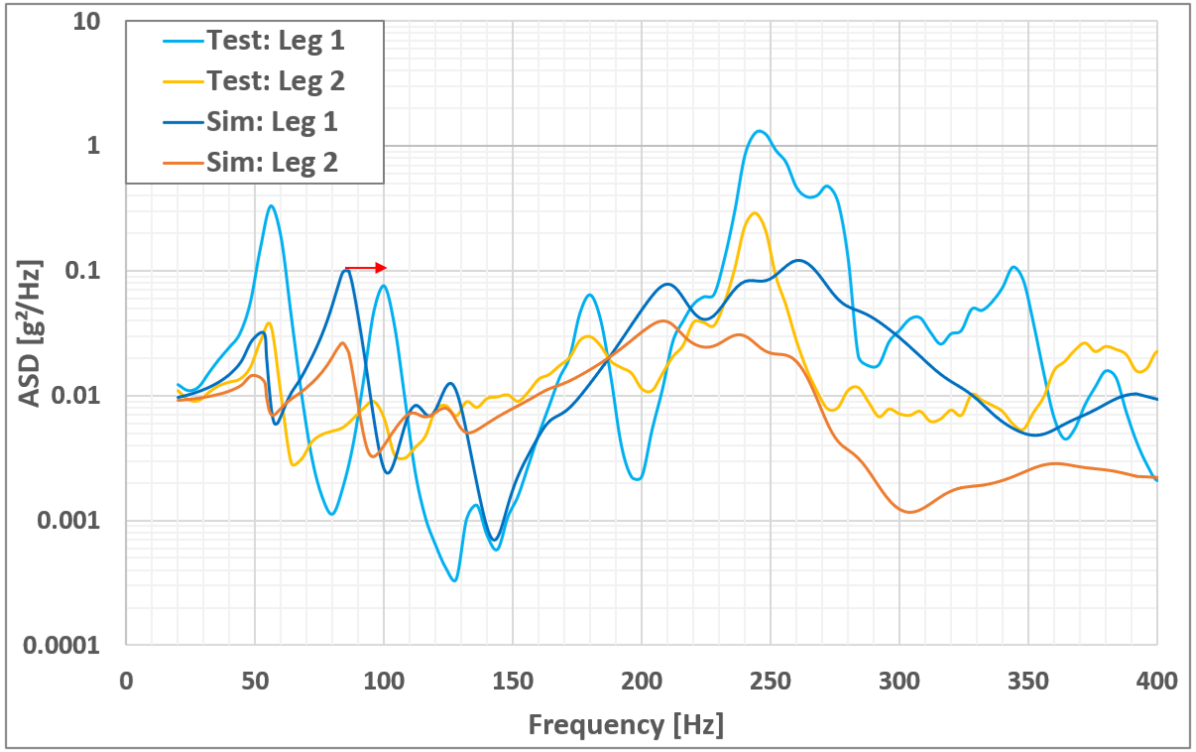
Model Correlation FEM Setup

Random Response Data – Iteration 1

Results only shown for side XPOD for X and Z axis only.
Frequency range limited to [20 Hz to 400 Hz] since it contains all relevant XPOD FNF.



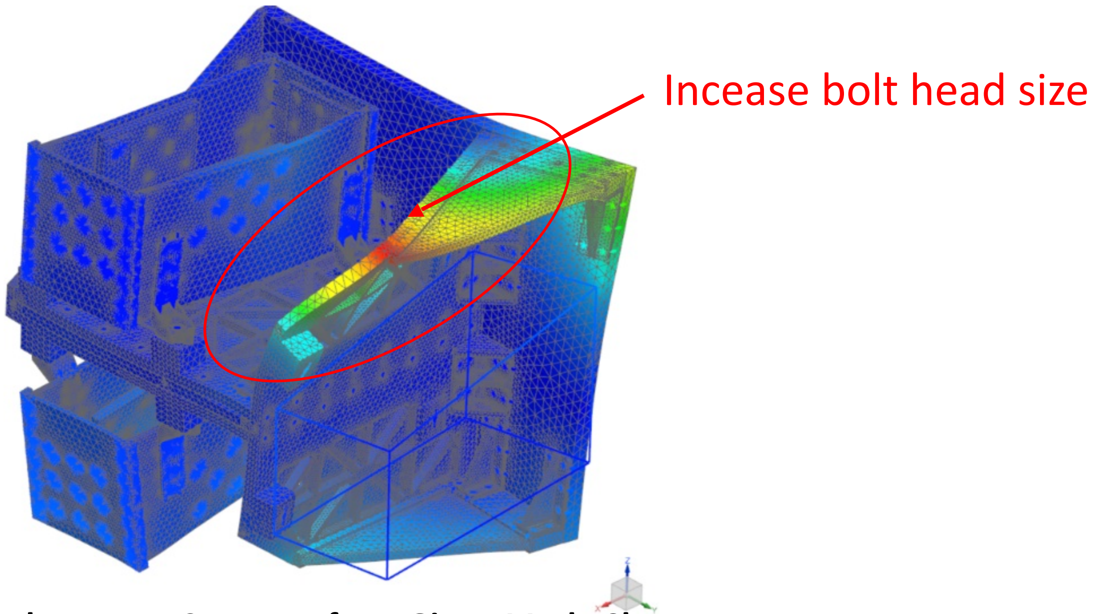
X-axis Random Test ASD Response for Side XPOD – Initial



Z-axis Random Test ASD Response for Side XPOD – Initial

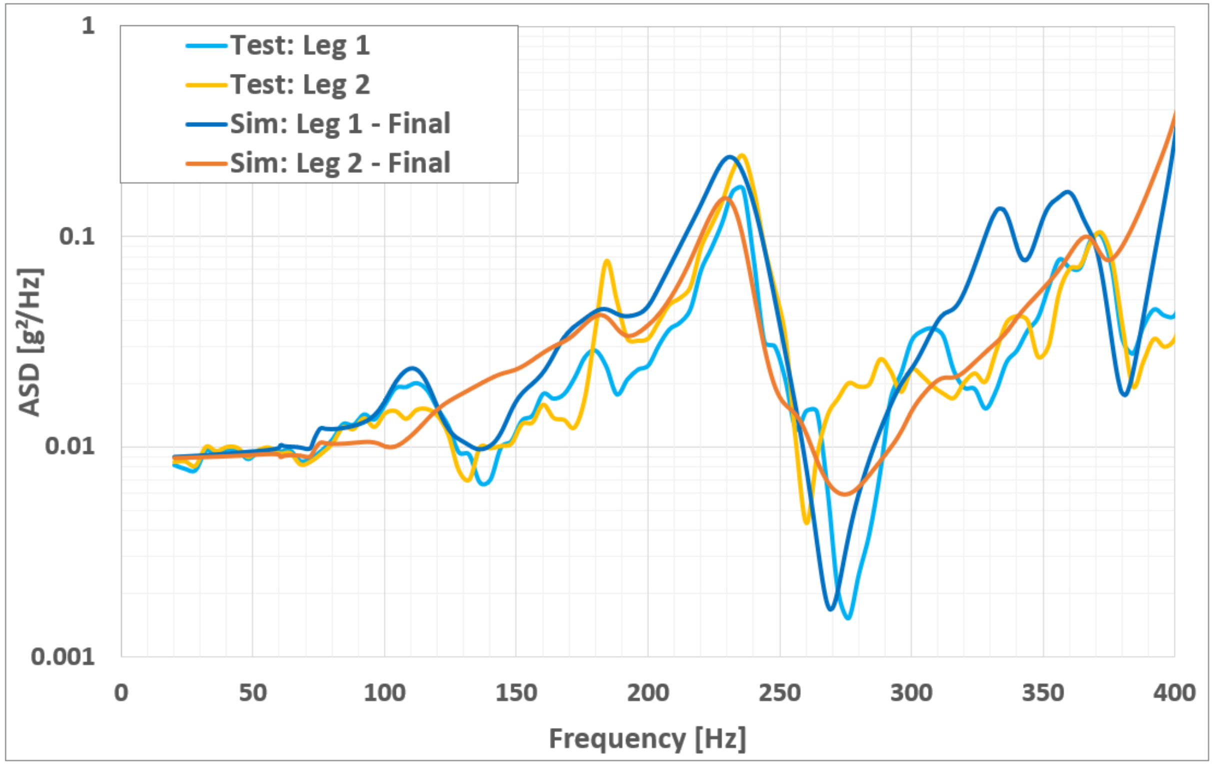
FEM Tuning

- Increase the head size of bolts
- Tune the CBUSH stiffness values
- In the ASD plot, a peak can be shifted left/right by decreasing/increasing the stiffness of the bolted connection in the region of highest deformation in the mode shape.

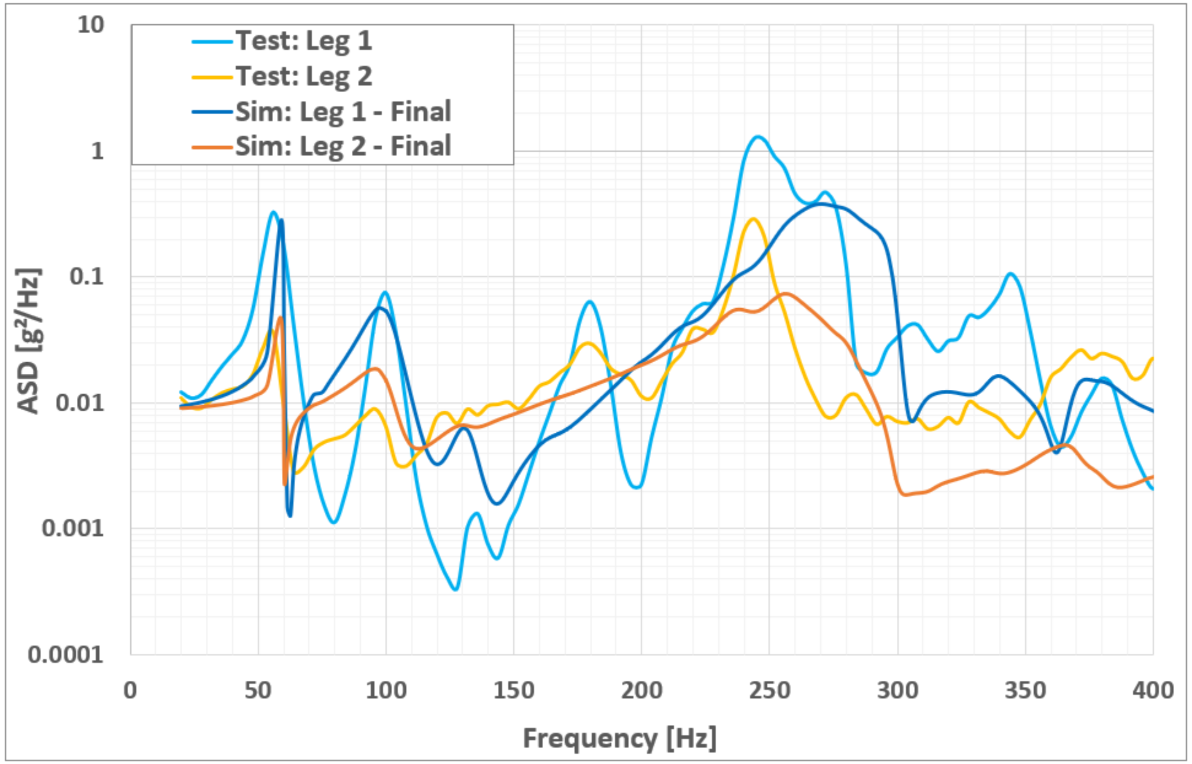


Displacement Contours for a Given Mode Shape

Random Response Plot - Final



X-axis Random Test ASD Response for Side XPOD – Final



Z-axis Random Test ASD Response for Side XPOD – Final

Viscous Damping Tuning

Viscous Damping Factor for each Mode up to 400 Hz

Mode	Frequency [Hz]	Viscous Damping [%]	X Mass Participation [%]	Y Mass Participation [%]	Z Mass Participation [%]
1	59.23	1	0.00571	0.00187	25.9160
2	73.22	3	0.11266	28.8149	0.15940
3	100.3	8	0.26675	0.77419	17.0694
4	104.2	10	0.35822	16.0438	0.09703
5	115.9	10	16.6910	5.05474	0.00104
6	131.9	5	1.62503	0.05880	2.62671
-	-	-	-	-	-
13	197.6	5	0.9396	0.20588	0.00037
14	201.1	4	0.73128	0.36090	0.07088
15	218.2	4	0.09947	0.02831	0.24102
16	232.4	4.5	20.9724	2.62065	0.17001
17	238.4	4	2.70539	0.33031	6.31499
18	257.3	4	0.37783	0.01092	3.00762
19	268.8	6	0.18131	0.06451	8.32037
20	279.2	2	0.00114	0.00265	2.61329
-	-	-	-	-	-
29	397.9	2	1.31181	0.10170	0.02181

Suggested Viscous Damping Factor

Mass Participation	Suggested Viscous Damping
0% - 5%	3.5%
5% - 10%	5%
> 10%	6.75%

UTIAS SFL 1998 20 YEARS 2018

Grms Comparison

- G_{rms} represents the overall energy or acceleration level of a random vibration profile.

Comparison of G_{rms} obtained for Simulated and Test Data

Axis of Excitation	XPOD	Avg Simulated G_{rms} [g]	Avg Test G_{rms} [g]	Difference [%]
X	+Y	4.14	3.44	20.16
	+Z	3.27	4.71	30.64
	-Z	3.46	4.93	29.92
Y	+Y	3.43	3.61	4.90
	+Z	2.69	3.14	14.46
	-Z	2.73	3.65	25.12
Z	+Y	3.59	4.60	21.97
	+Z	5.88	4.68	25.70
	-Z	5.81	4.91	18.48
Total Difference [%]				21.26