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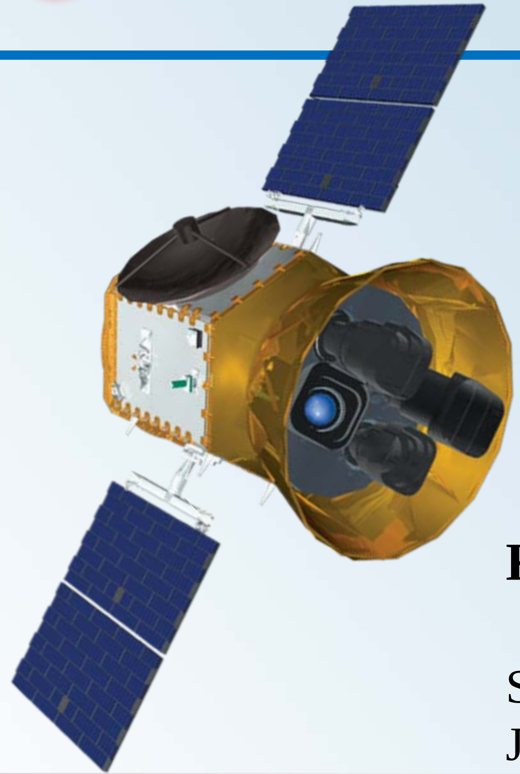
Transiting Exoplanet Survey Satellite

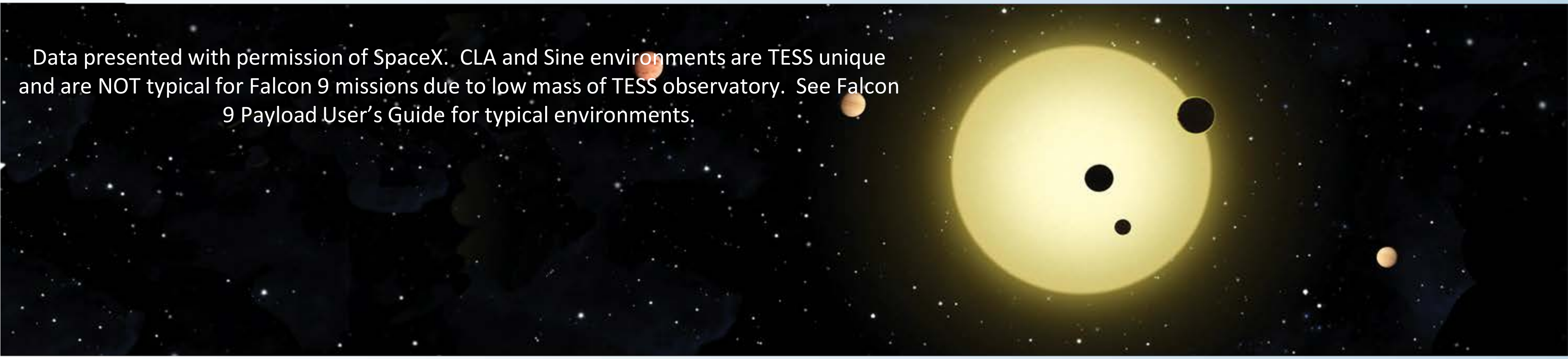


Design Limit Loads and Verification Approach for the TESS Observatory

Kyle Driscoll (Orbital ATK), Scott Gordon (NASA GSFC)

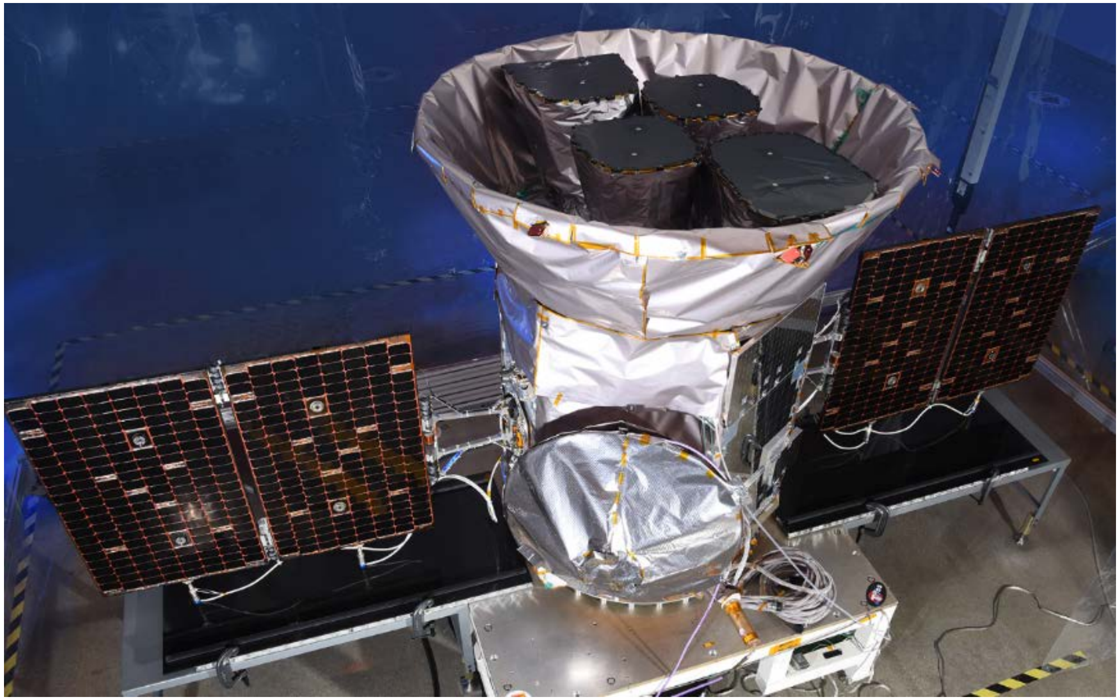
Spacecraft and Launch Vehicle Dynamic Environments Workshop
June 26-28, 2018

Data presented with permission of SpaceX. CLA and Sine environments are TESS unique and are NOT typical for Falcon 9 missions due to low mass of TESS observatory. See Falcon 9 Payload User's Guide for typical environments.



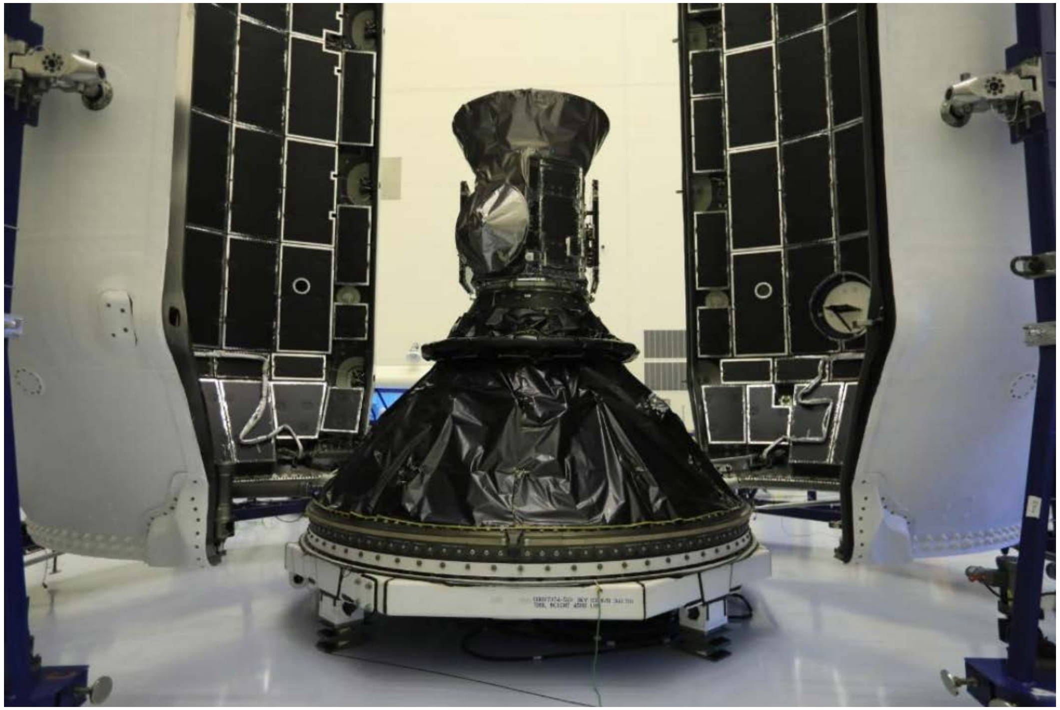
Outline

- TESS Overview
- Early CLA Results and Design Limit Loads Development
- Improvements with SoftRide
- Instrument-level Testing
- Observatory-level Testing
- Summary & Lessons Learned

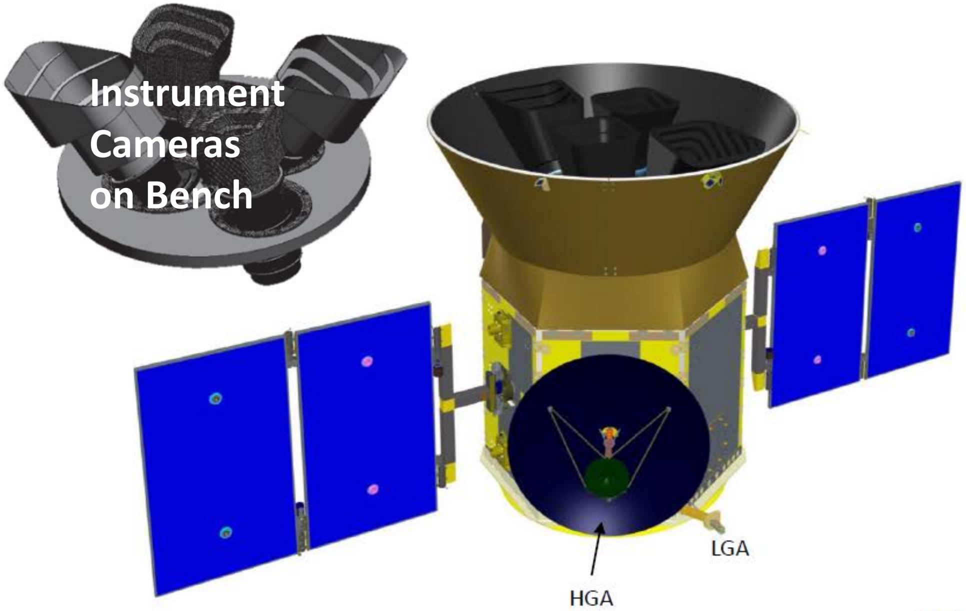


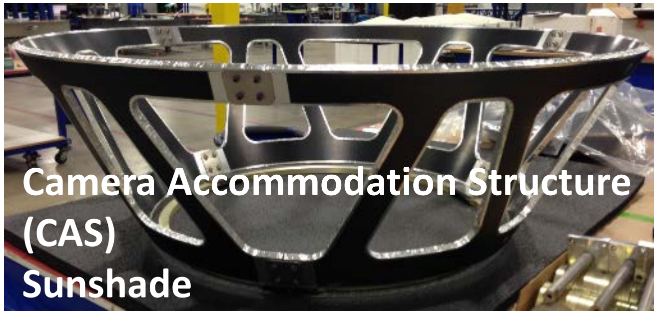
TESS Overview

- The Transiting Exoplanet Survey Satellite (TESS) is a NASA Explorer mission launched on Falcon 9 in April 2018
- Orbital ATK is the spacecraft provider, NASA GSFC provides project management and technical oversight, the instrument is managed by MIT Kavli Institute, and the instrument cameras were built and tested by MIT Lincoln Laboratory
- Orbital ATK, NASA GSFC, MIT Lincoln Laboratory, and NASA LSP/SpaceX were involved in launch loads development and verification

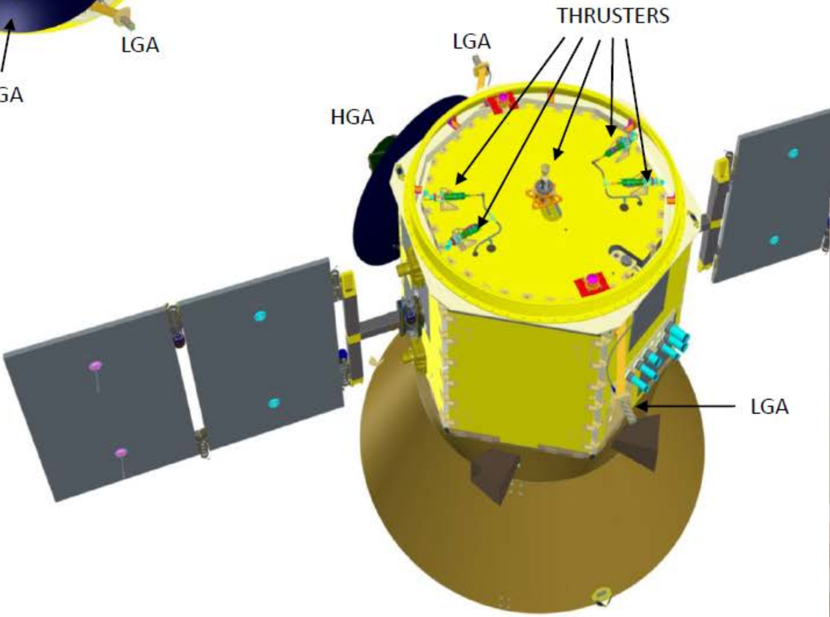


TESS Design


Instrument Cameras on Bench


Camera Accommodation Structure (CAS)
Sunshade

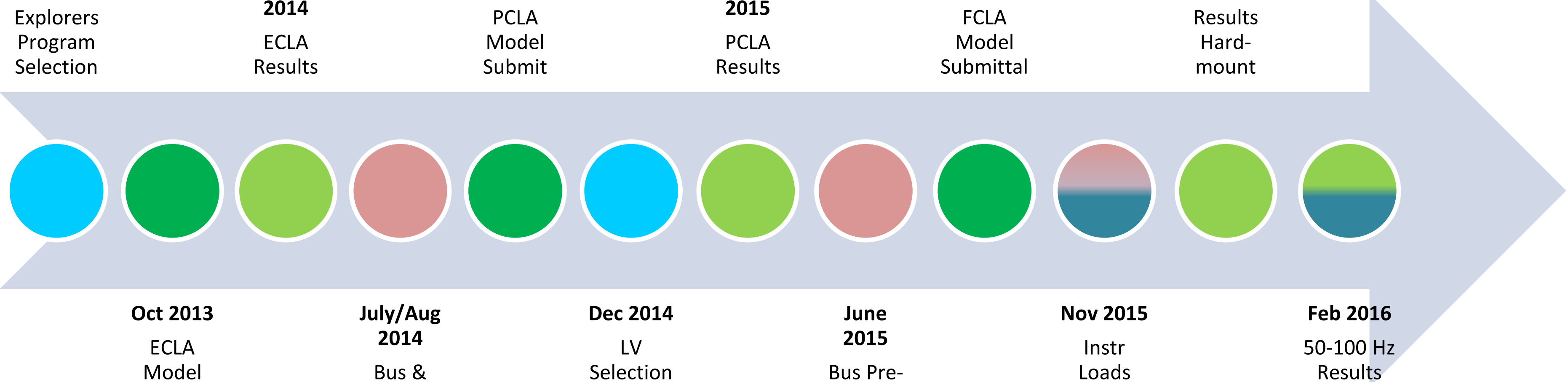

Partially Assembled Structure




Fuel Tank

Project Early Milestones

- Loads uncertainty risk was carried by the program through CDR because the LV was not selected until after PDR and the decision to use SoftRide was not made until well after CDR and Bus SLT



June 2013
Explorers Program Selection

Oct 2013
ECLA Model Submit

May 2014
ECLA Results

July/Aug 2014
Bus & Instr Pre-PDR Peer Review

Nov 2014
PCLA Model Submit

Dec 2014
LV Selection

Mar 2015
PCLA Results

June 2015
Bus Pre-CDR Peer Review

Oct 2015
FCLA Model Submittal

Nov 2015
Instr Loads Relief

Instr CDR

Bus SLT

Dec 2015
FCLA & 50-100 Hz Results Hard-mount

Feb 2016
50-100 Hz Results SoftRide Study

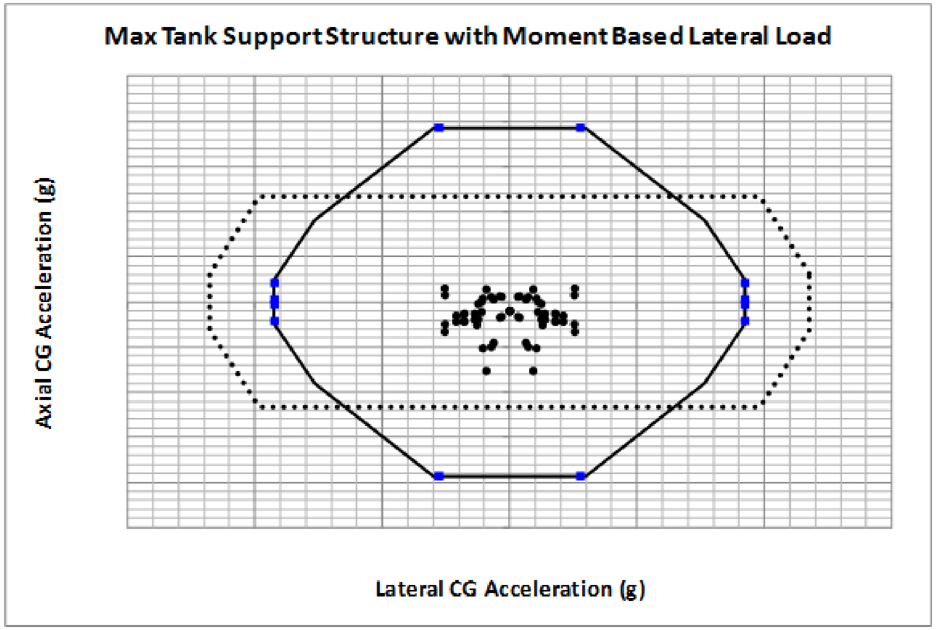
Bus CAS Sine Test & Model Corr

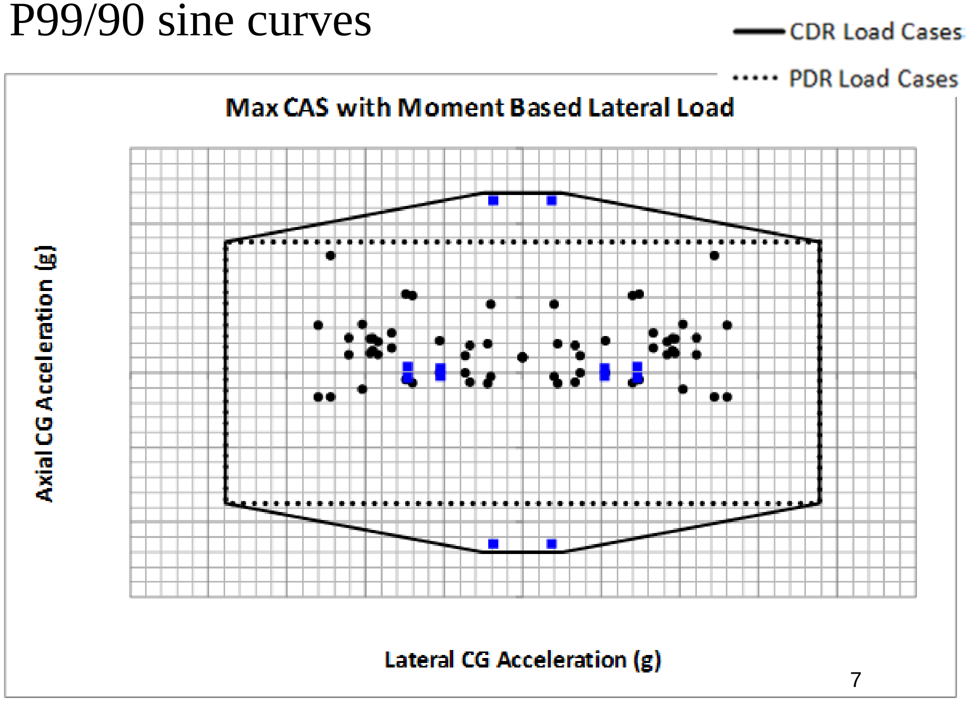
Early Coupled Loads Analysis (ECLA) Results

- Performed for both SpaceX Falcon 9 & Orbital ATK Antares
- CLA cases cover full sine environment spectrum (5-100 Hz)
- CLA results available shortly before PDR
- LV IRD defined Observatory Net CG Design Limit Loads
  - Max Lateral: 3.2g Lateral, 3.5g Axial
  - Max Axial: 2.5g Lateral, 9.2g Axial
- For PDR, envelope of CLA results analyzed and negative margins identified for tank support structure and instrument optical bench associated with Falcon 9 loads

Preliminary Coupled Loads Analysis (PCLA) Results

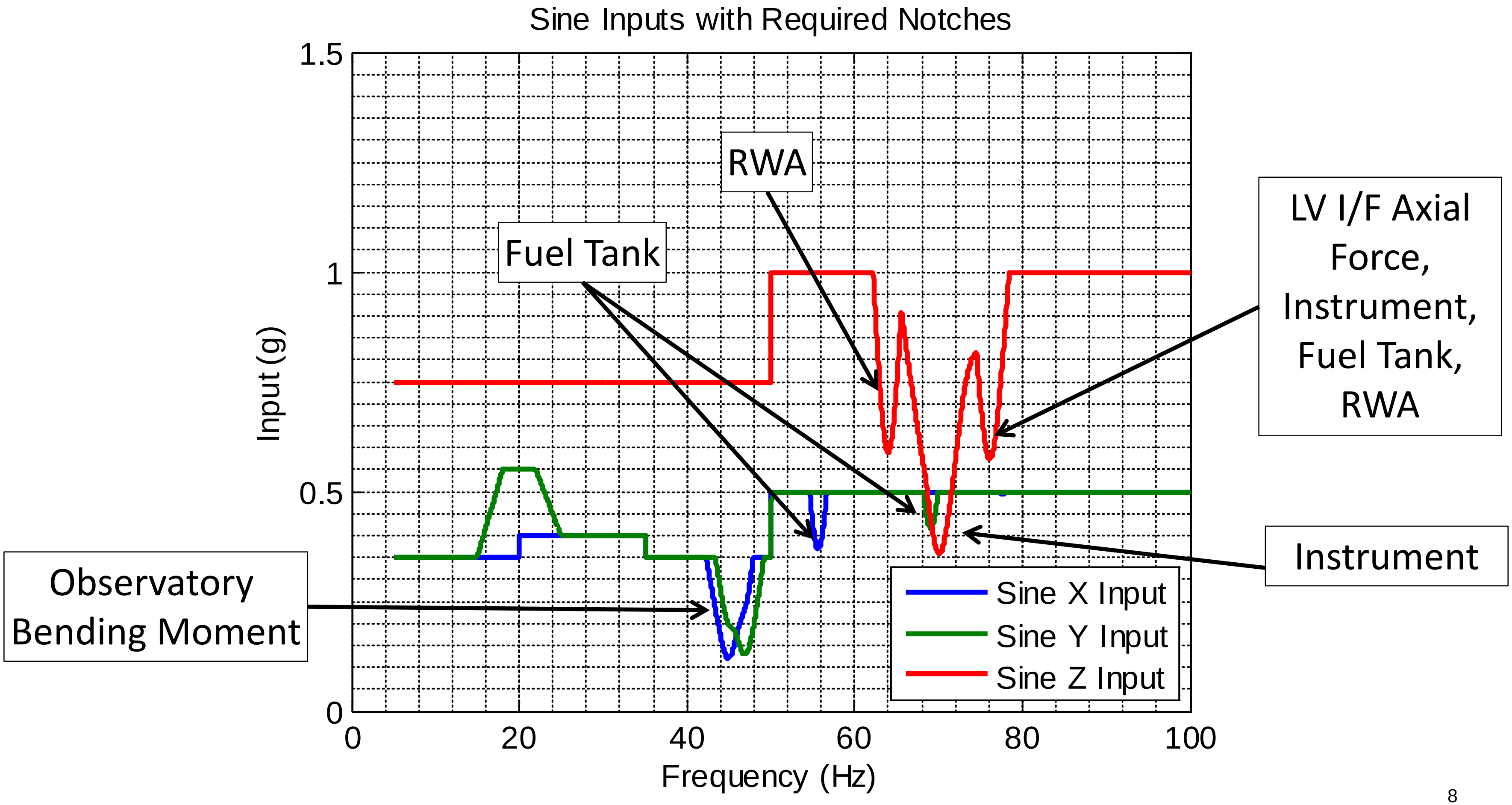
- PCLA performed for Falcon 9 prior to CDR
- CLA methodology changed since ECLA
- CLA covers environment through 50 Hz, and updated 50-100 Hz sine environment defined to be analyzed as a base shake
- Key Design Limit Loads defined based on ECLA were exceeded due to 50-100 Hz base shake sine predictions (Orbital ATK analysis)
- Where practical, more severe Design Limit Loads were defined, but 50-100 Hz sine spec still needed to be notched below LV P99/90 sine curves





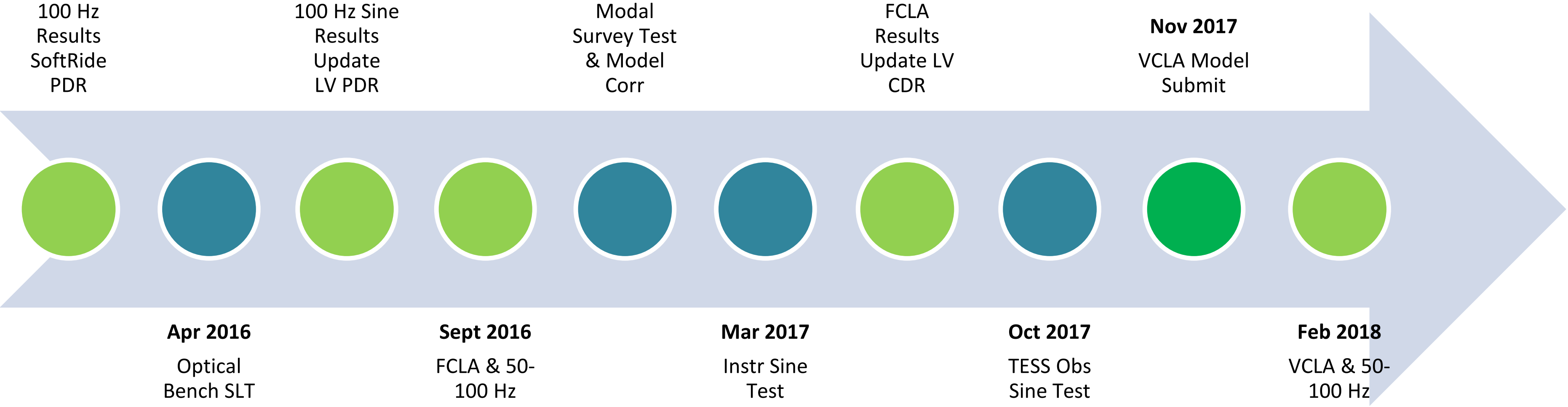
CDR 50-100 Hz Sine Vibration Analysis

- Instrument, LV I/F Axial Force, and S/C fuel tank responses drive the maximum notching of the LV sine vibration specification
- Notch depth violates LV P99/90 Flight Levels



Project Later Milestones

- Many iterations of FCLA Results were provided, but, with SoftRide, all Design Limit Loads requirements were met with significant margin except Observatory Lateral Net CG Limit Load (3.2g)
    - ➢ Loads mitigation methods applied in Dec 2016 to meet the 3.2g requirement
- Observatory Sine Test confirmed VCLA model was adequately test-correlated



Mar 2016
FCLA & 50-100 Hz Results SoftRide PDR

Apr 2016
Optical Bench SLT

June 2016
FCLA & 50-100 Hz Sine Results Update LV PDR

Sept 2016
FCLA & 50-100 Hz Results Update SoftRide CDR

Dec 2016
Solar Array Modal Survey Test & Model Corr

Mar 2017
Instr Sine Test

May 2017
FCLA Results Update LV CDR

Oct 2017
TESS Obs Sine Test

Nov 2017
VCLA Model Submit

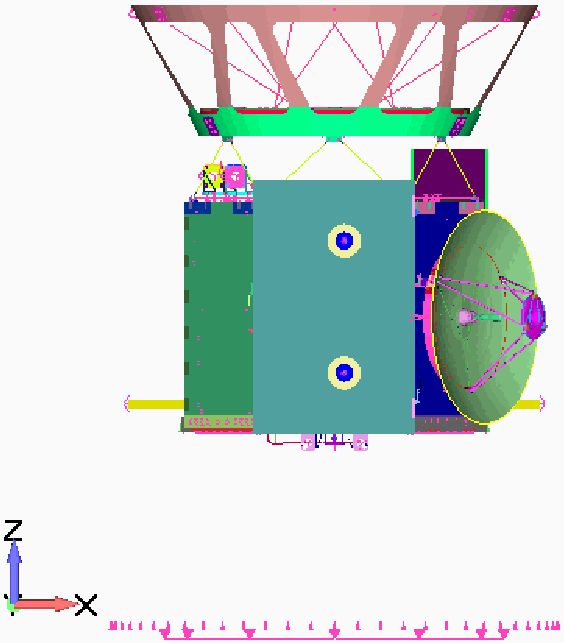
Feb 2018
VCLA & 50-100 Hz Results

SoftRide Development

- Shortly after CDR, Observatory Model was submitted to SpaceX for FCLA
- MUF remained at 1.4 since standard Falcon 9 MUF is 1.25 (defined for VCLA)
- Design Limit Loads were included in the Model Submittal Report
- Initial set of Hard-mount results provided December 2015 which exceed some Design Limit Loads including slight exceedance of Observatory Lateral Net CG Load
- SpaceX then started work with Moog CSA to develop a SoftRide system
- Initial results of SoftRide study provided February 2016 which show Design Limit Loads requirements are met
- CLA results updated between March 2016 and May 2017, but Design Limit Loads requirements continue to be met
- Loads mitigation implemented in analysis to meet the Observatory Lateral Net CG Limit
- Final Sine Vibration environment defined based on results

Structural Modes on SoftRide

- SoftRide Shear Modes at 45 Hz were at risk to amplify responses at Solar Array Bending Mode frequencies and Sunshade Mode frequencies, but components designed to provide adequate separation and tested early to confirm separation

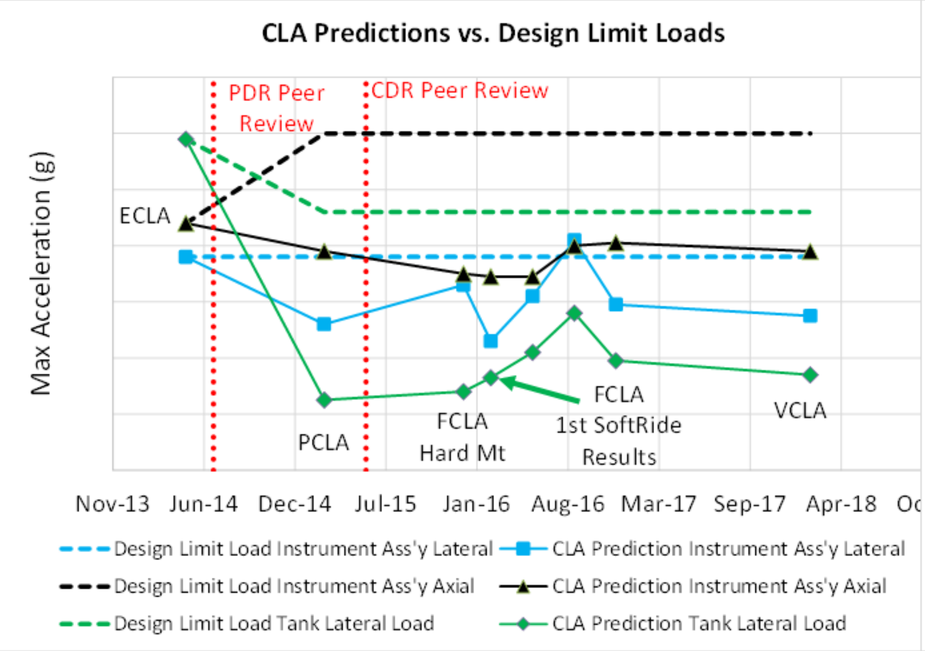

SoftRide Bounce Mode

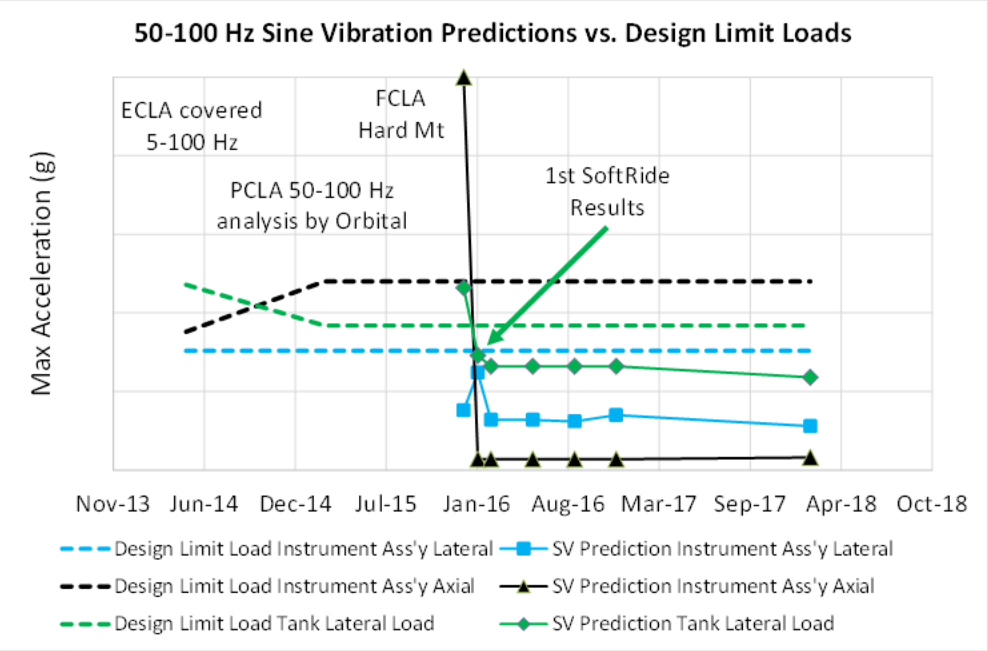
Launch Configuration Modes 1-15

Mode No.	Freq (Hz)	Effective Mass (%)						Description
		TX	TY	TZ	RX	RY	RZ	
1	7.8	34%	25%	0%	23%	31%	0%	SoftRide Rocking X
2	7.8	25%	34%	0%	31%	23%	0%	SoftRide Rocking Y
3	16.2	0%	0%	0%	0%	1%	0%	Propellant Slosh
4	16.4	0%	0%	0%	1%	0%	0%	Propellant Slosh
5	17.6	0%	0%	73%	0%	0%	0%	SoftRide Bounce
6	31.7	0%	0%	0%	0%	0%	9%	SA HDRM Bending
7	32.4	0%	0%	0%	0%	0%	0%	SA HDRM Bending
8	35.1	0%	0%	0%	0%	0%	0%	Sunshade Flex
9	35.4	1%	0%	0%	0%	0%	0%	Sunshade Flex
10	38.1	0%	0%	0%	0%	0%	41%	SoftRide Torsion
11	45.0	10%	0%	0%	0%	9%	0%	SoftRide Shear about Y
12	45.9	0%	11%	0%	10%	0%	0%	SoftRide Shear about X
13	59.2	1%	0%	0%	0%	1%	0%	Aft Deck Bending X
14	64.6	0%	0%	0%	0%	0%	0%	Sunshade Trefoil
15	68.2	0%	0%	0%	0%	0%	0%	Panel 3 Bending

Development of Key Design Limit Loads

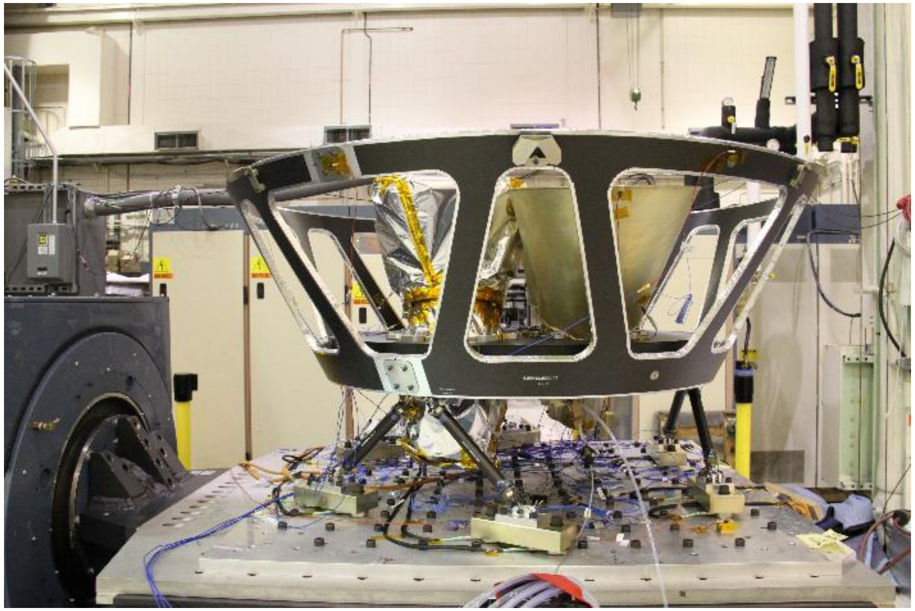
- Predictions decreased for PCLA, but since 50-100 Hz no long covered by coupled analysis, worst case loads increased
    - ➢ Based on Orbital ATK analysis, significant notching needed to limit to Design Limit Loads
- Starting with FCLA, SpaceX provided 50-100 Hz predictions based on model that includes the Ruag separation system
- SoftRide greatly reduced responses >50Hz

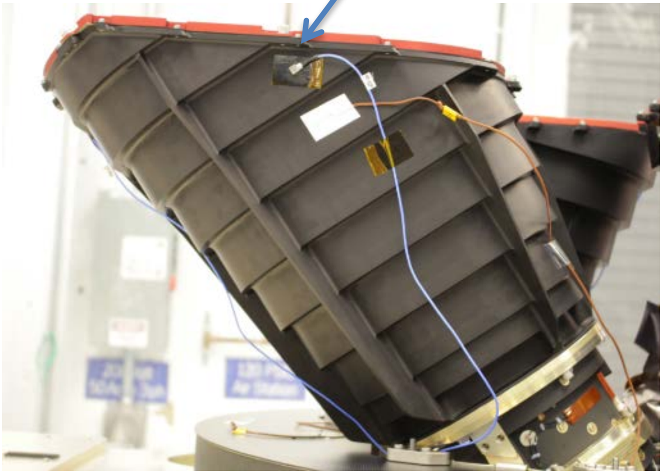

CLA Predictions vs. Design Limit Loads


50-100 Hz Sine Vibration Predictions vs. Design Limit Loads

Instrument Testing Summary

- Instrument test was performed including the optical bench and the Camera Support Assembly (bipod struts and sunshade)
    - ➢ Both Camera Support Assembly and individual Cameras were also tested separately
- Back-up Flight Camera Accommodation Structure was shipped to MIT LL from Orbital ATK Dulles for testing
- MIT LL contracted Orbital ATK Space Components Division San Diego to build the optical bench
- Key response limits were: Camera Tips and CGs and Top of Sunshade
- Response limits defined based on FCLA results
    - ➢ Additional margin added to FCLA results above MUF used for FCLA based on knowledge of changes made since FCLA model submission





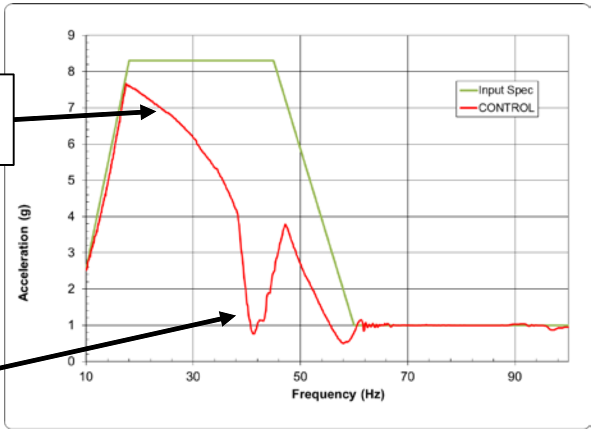
Accelerometers located at Camera Tip, CG, and Bottom allowed for both Rotational and Translational Accelerations to be measured

Instrument Test Measurements

- Sine test input levels derived from CLA and Observatory base-drive results
  - Input below 50 Hz increased to cover maximum quasi-static camera acceleration from CLA
- Limits set for Sunshade, Camera CG and Camera Hood
  - Limits include a 1.25 protoflight test factor and a 1.25 uncertainty factor
  - Goal was to achieve 500 rad/sec^2 at camera CG during lateral testing (Design value was 820 rad/sec^2)

Sine Vibration Test - Camera CG Response Limits						
	Sine X and Sine Y			Sine Z		
Frequency	Axial	Lateral	Rotation	Axial	Lateral	Rotation
10 - 50 Hz	13 G	8.3 G	310 rad/s^2	13 G	4 G	250 rad/s^2
50 - 100 Hz	4 G	5 G	500 rad/s^2	6 G	4 G	250 rad/s^2

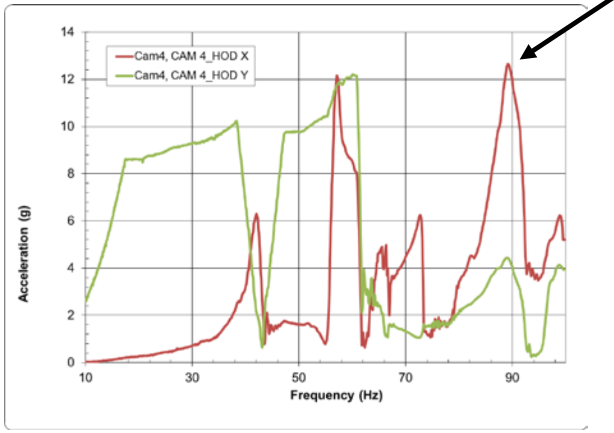
Input Spec (Y) vs Control w/ Notches



Camera Lateral CG Notch

Sunshade Notch

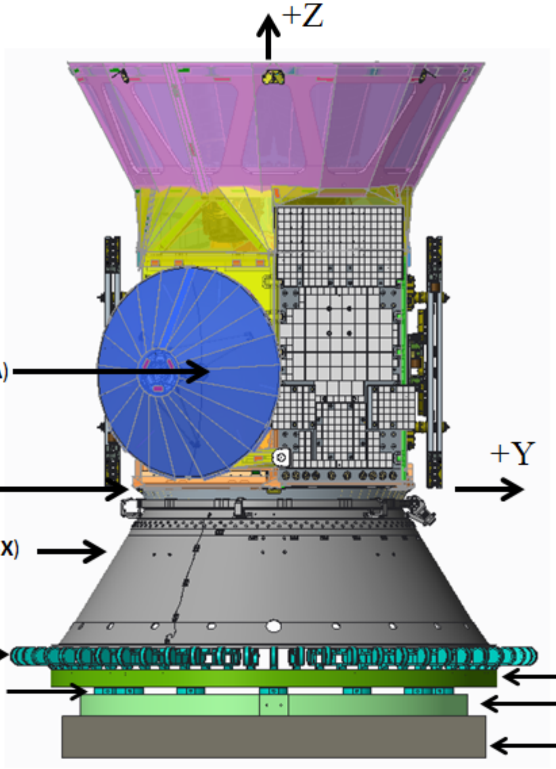
Camera Hood Response



Max Rotation = 530 rad/sec^2

Observatory Test Hardware

Side View



OA provides TESS to I/F Ring Hdwr (NAS1351N4-14 A286 Stainless)

TESS Observatory (**OA**)

Interface Ring (**GFE**)

RUAG Payload Adapter (**SpaceX**)

SoftRide (**SpaceX**)

Force Gauges (**OA**)

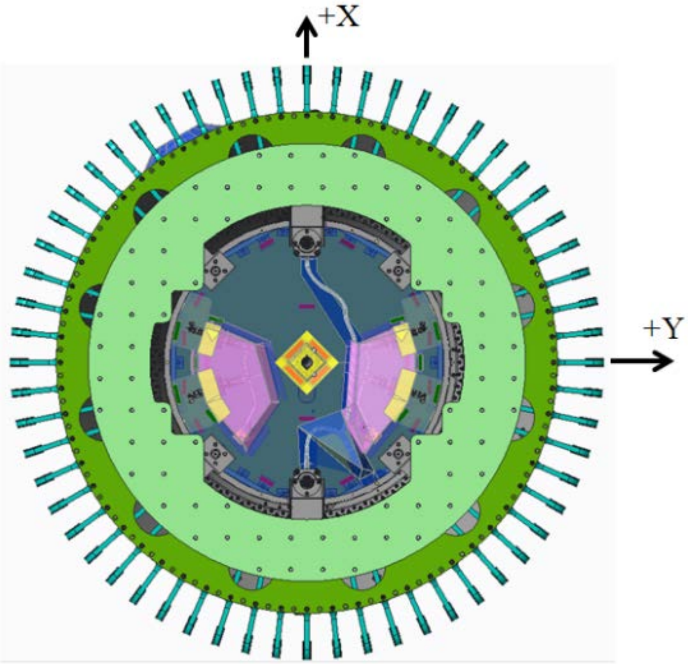
OA provides Vibe Adapter to LIS Hdwr (91251A442 Black Oxide)

Isolation System to Force Gauge Adapter (**OA**)

Vibe Table Adapter (**OA**)

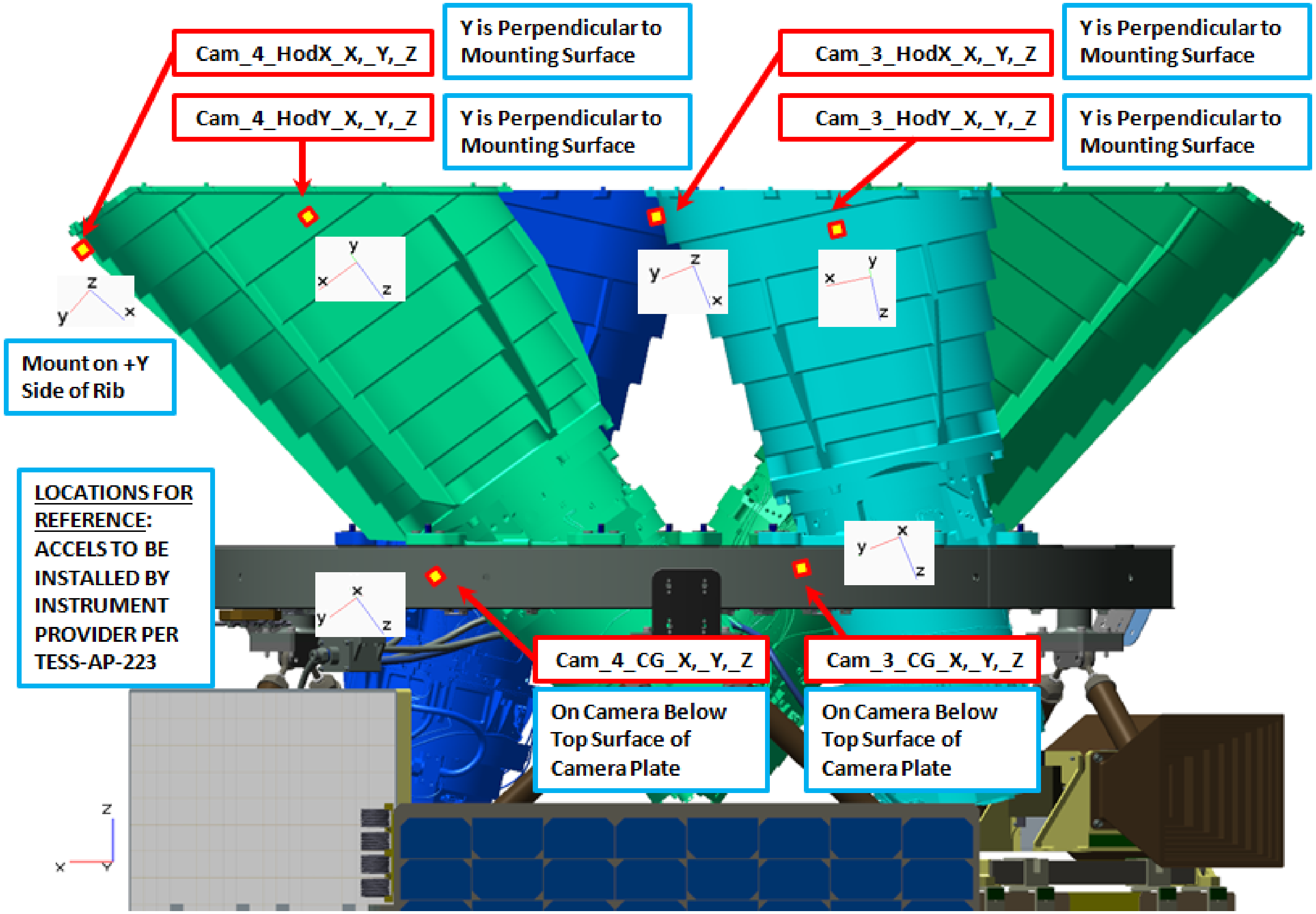
Vibe Table (**OA**)

Bottom View (Table not shown)



Observatory Instrument Accelerometers

- Subset of instrument test accelerometers chosen for observatory test



Cam_4_HodX_X,_Y,_Z

Y is Perpendicular to Mounting Surface

Cam_4_HodY_X,_Y,_Z

Y is Perpendicular to Mounting Surface

Cam_3_HodX_X,_Y,_Z

Y is Perpendicular to Mounting Surface

Cam_3_HodY_X,_Y,_Z

Y is Perpendicular to Mounting Surface

Mount on +Y Side of Rib

LOCATIONS FOR REFERENCE: ACCELS TO BE INSTALLED BY INSTRUMENT PROVIDER PER TESS-AP-223

Cam_4_CG_X,_Y,_Z

On Camera Below Top Surface of Camera Plate

Cam_3_CG_X,_Y,_Z

On Camera Below Top Surface of Camera Plate

Observatory Testing – Mass Sim Configuration

- Initial lateral and vertical sine vibration testing performed using Mass Simulator in place of the Observatory
- Testing was performed to 1) Check-out shaker controller, 2) Final calibration of I/F force transducers, 3) Characterize LV Hardware Dynamics

Observatory Mass Simulator

Ruag 937S Separation System

SoftRide Isolation System

I/F Force Transducer Ring

Observatory Testing – Test Configuration

Contamination Tent
(not yet closed out on bottom)

Shower Cap Contamination
Cover over Sunshade

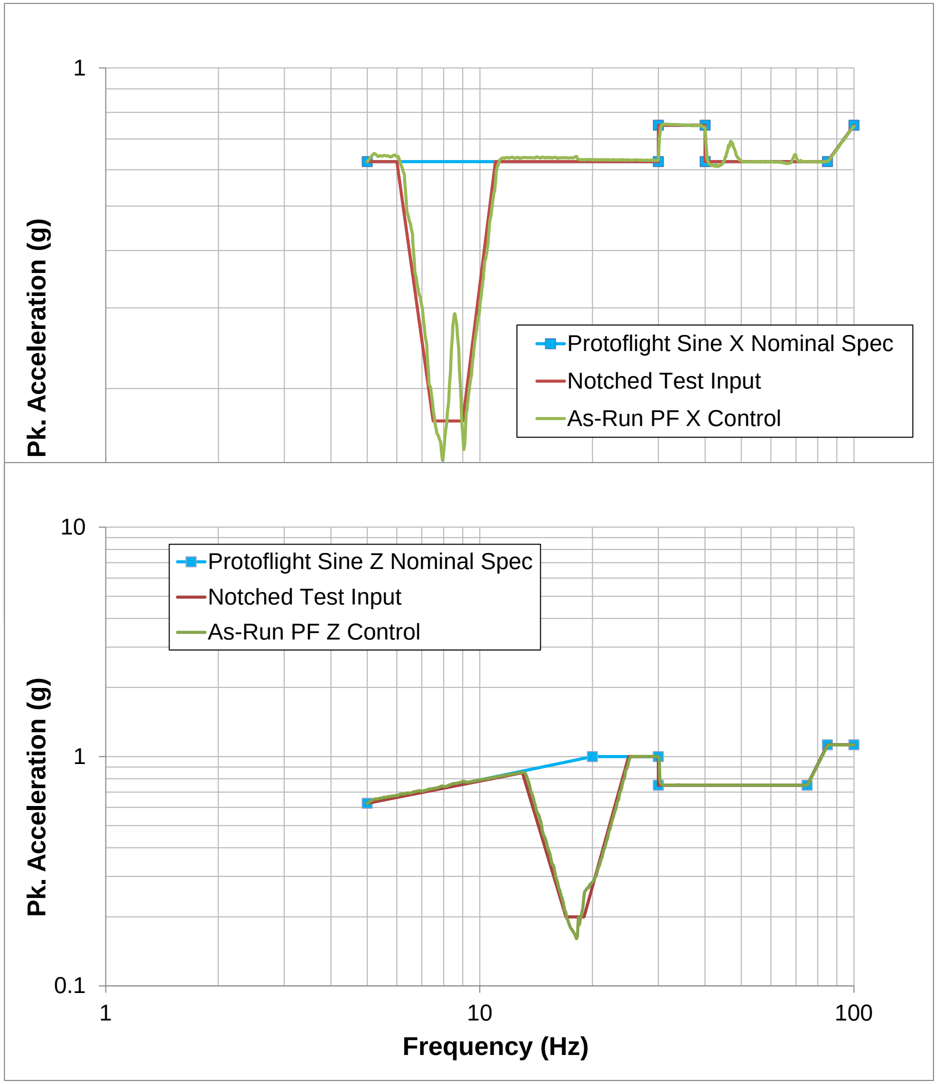
Ruag 937S Separation System

SoftRide Isolation System

I/F Force Transducer Ring

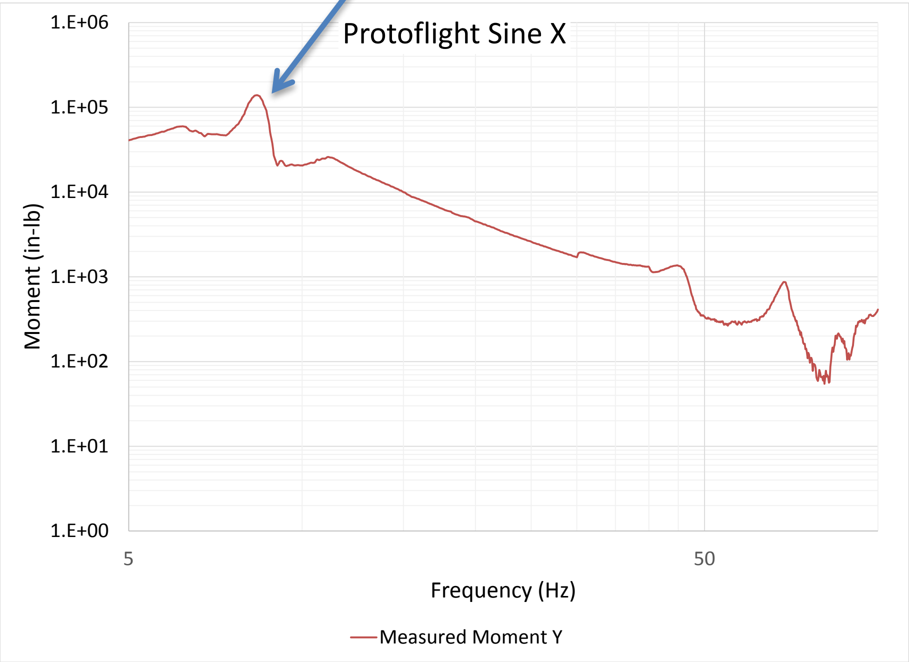
Observatory Testing – Measurements (1/2)

- Sine Specification changed during the program but acceptable since CLA results are enveloped by Design Limit Loads
- Notching only required at SoftRide Rocking and Bounce Modes

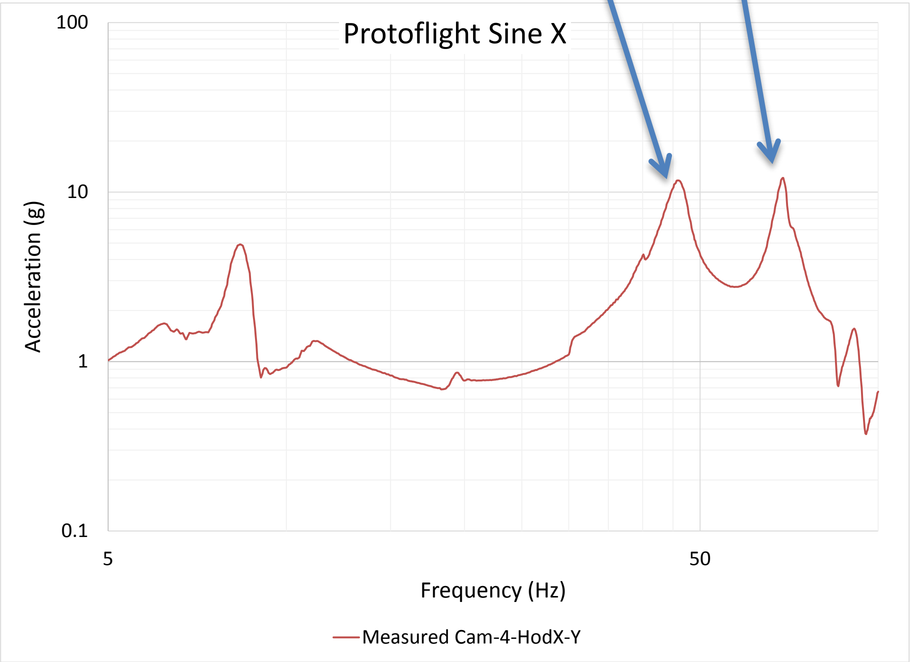


Observatory Testing – Measurements (2/2)

Protoflight X-axis Measurements



8 Hz SoftRide Rocking Mode
Goal was to achieve Bending Moment Limit. Overshoot acceptable based on SLT demonstrated capability



69 Hz Bench Bending Mode

45 Hz SoftRide Shear Mode

Summary and Lessons Learned

- To reduce the time required for a CLA cycle, 1) the LVP should be provided a set of critical response limits and 2) the LVP should analyze the higher frequency (50-100 Hz) portion of the launch transient environment in addition to the lower frequency coupled events
  - Critical modes for small S/C are often >50 Hz
  - Especially critical to support design of SoftRide system
  - LVP should perform 50-100 Hz bases shake sine analysis regardless of SoftRide if LV hardware (e.g., PLA) should be included in the stack analyzed (Including Ruag significantly affected results)
- Make decision on SoftRide as early as possible to avoid design churn associated with attempts to meet severe load requirements
- Care must be taken when installing a contamination tent around a shaker if the tent is stationary and connected to the spacecraft
- Mass model testing with SoftRide provides valuable model correlation data
  - Rigid mass simulator provides a simple configuration where the SoftRide performance can be isolated
- Plan accelerometer locations early in the design to allow CLA predictions for accelerometer locations to be recovered and used during testing at both the Instrument-level and Observatory-level
  - Allows for a direct comparison to launch predictions and ensures design allows for accelerometer installation
- Sine vibration testing on SoftRide is simple, fast, and low-risk
  - Since behavior is simple, test measurements match pre-test predictions closely
  - Since higher frequency responses are low, few critical responses to watch
  - Even with thorough data review after lower level runs by Orbital ATK, NASA GSFC, and MIT LL, 3-axis sine testing was completed in 3 days (not including mass sim runs)