Space Launch System Mobile Launcher Modal Pretest Analysis
IMAC XXXVII

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Background

- NASA is developing an expendable heavy lift launch vehicle capability, the Space Launch System (SLS), to support lunar and deep space exploration.
- The Mobile Launcher (ML) is a very large heavy beam/truss steel structure designed to support the Space Launch System during its buildup and integration in the Vehicle Assembly Building (VAB), transportation from the VAB out to the launch pad, and provides the launch platform at the launch pad.
- Programmatic decision was made to not refurbish Marshall Space Flight Center (MSFC) Test Stand (TS) 4550 and use it for the ground vibration test of the Artemis 1 integrated vehicle and referred to as the Integrated Modal Test (IMT).
- ML will serve as the IMT modal test fixture supporting the Artemis I integrated vehicle.

MSFC Test Stand 4450 & Apollo SA-500D Installed

ES072007001TPA 359063.01.02

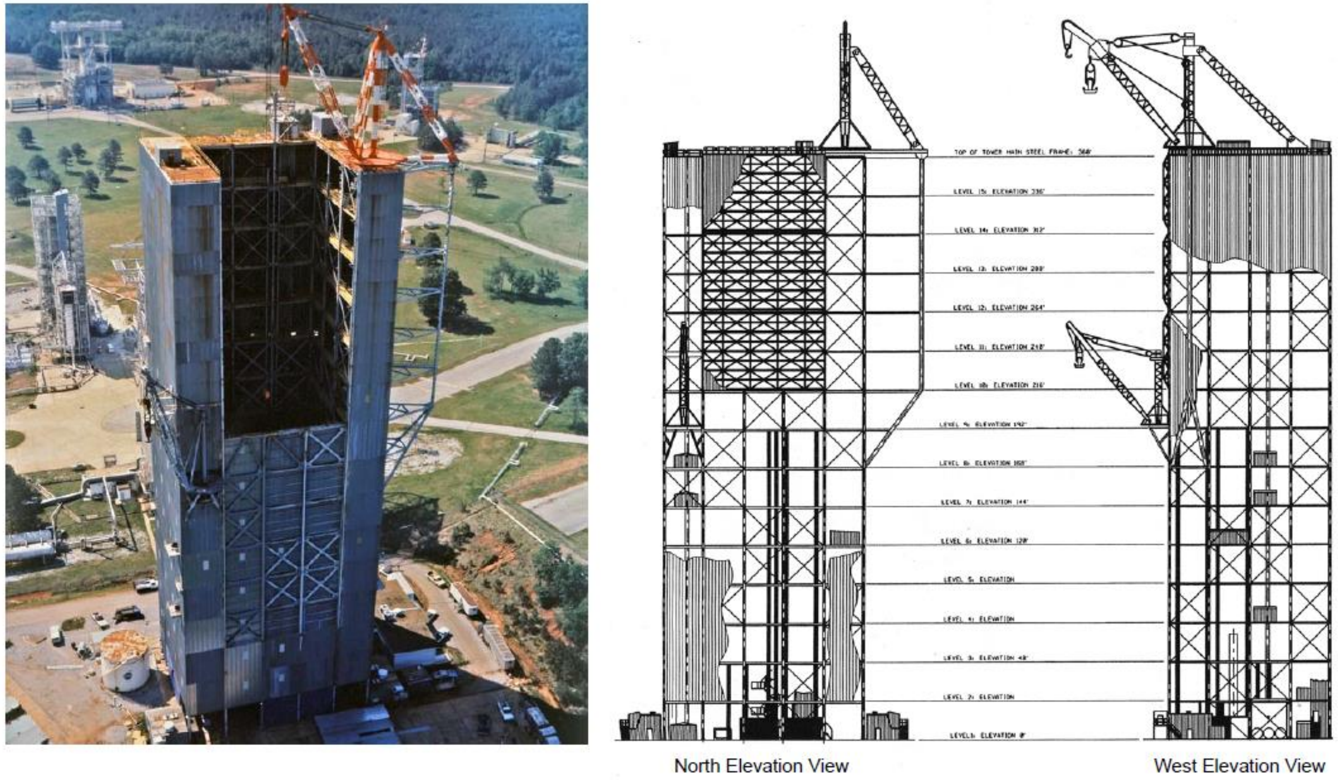
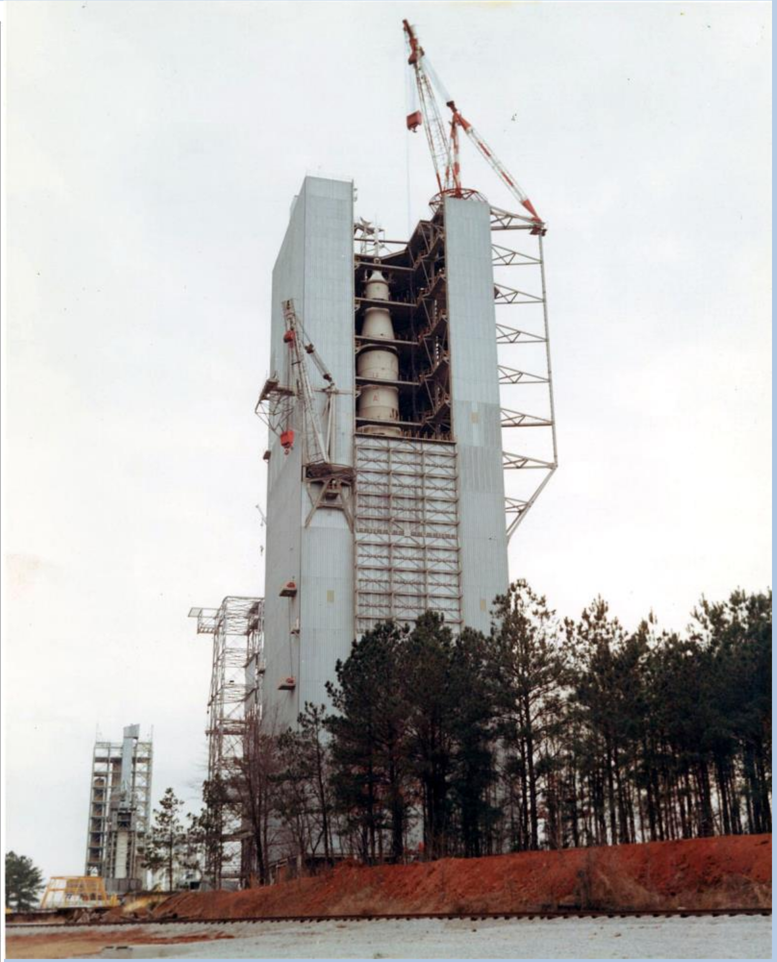
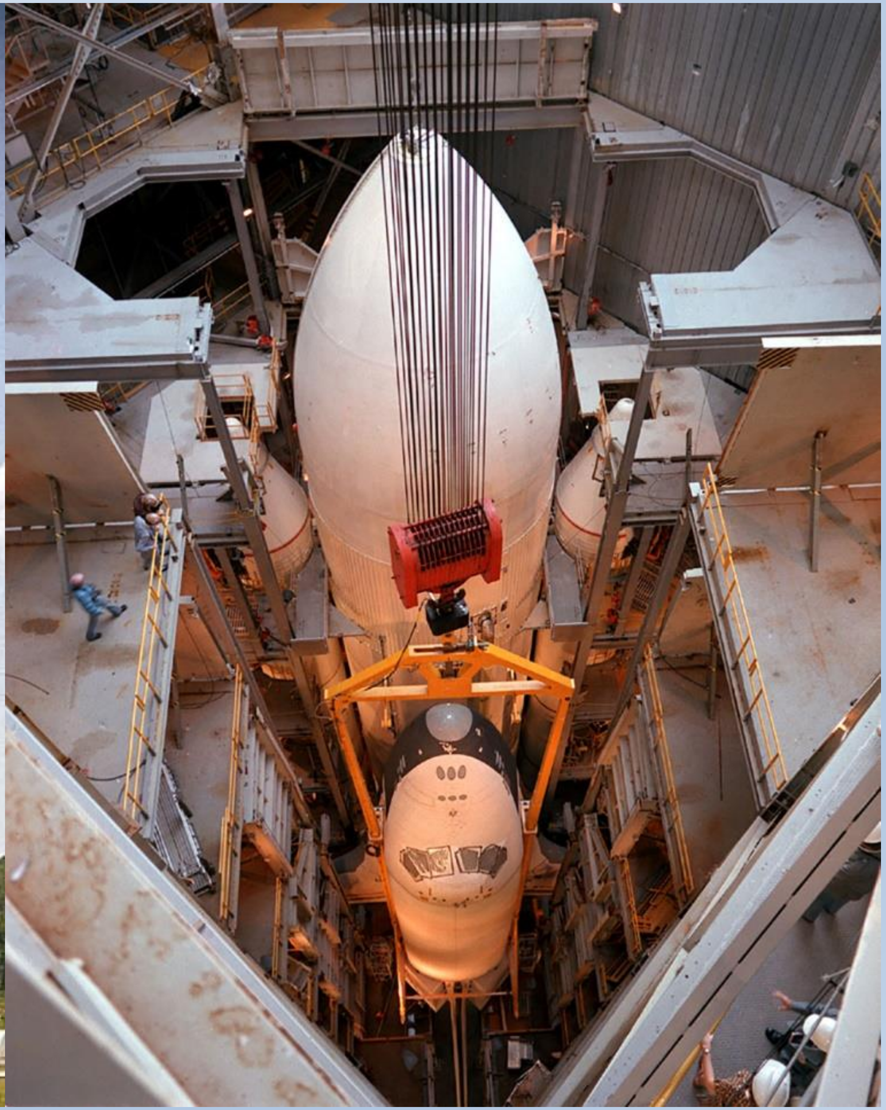


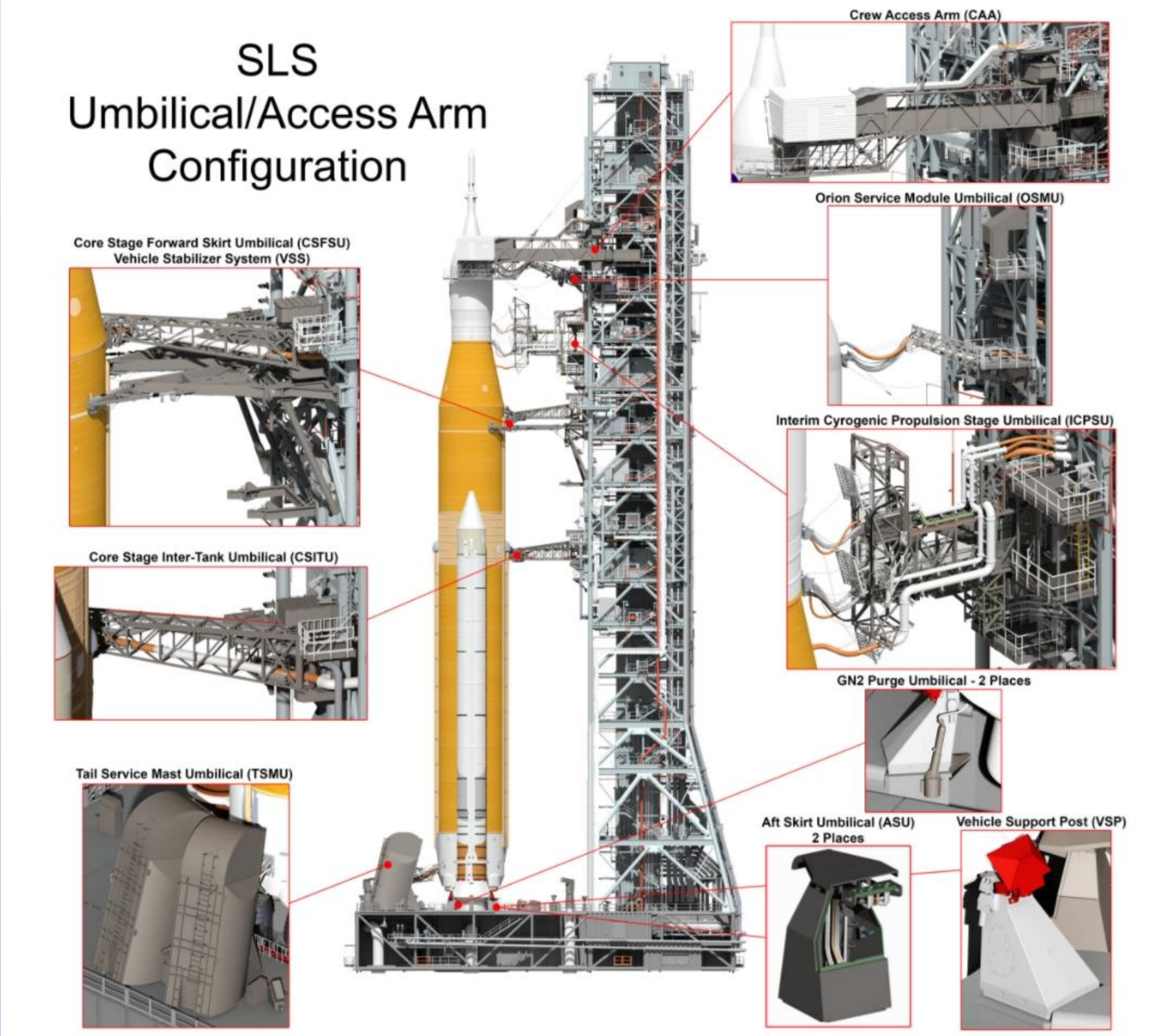
FIGURE 2-4
Test Stand 4550 Photograph
and Elevation Profiles



MSFC Test Stand 4450 & Shuttle Orbiter Enterprise



Mobile Launcher (ML)

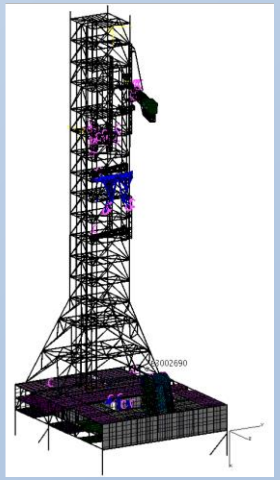


Crawler Transporter (CT-2)

Integrated Modal Test (IMT) Challenge

- The ML (and ML with CT) as the IMT modal test fixture presents unique technical challenges due to the ML (and ML with CT) providing a flexible boundary condition and its structural dynamics coupling with the Artemis I integrated vehicle.
  - CT modes couple with ML modes.
- In addition, the ML is significantly heavier than the Artemis I integrated vehicle and therefore motion in the ML will end up “driving” responses in the Artemis I integrated vehicle.
- This could very well make it very challenging to identify the modes pertaining to the Artemis 1 integrated vehicle.
- As a risk mitigation, a building block approach has been adopted, of which a modal test of the ML with and without the CT, referred to as the ML Only modal test, was performed.

ML Only Modal Test

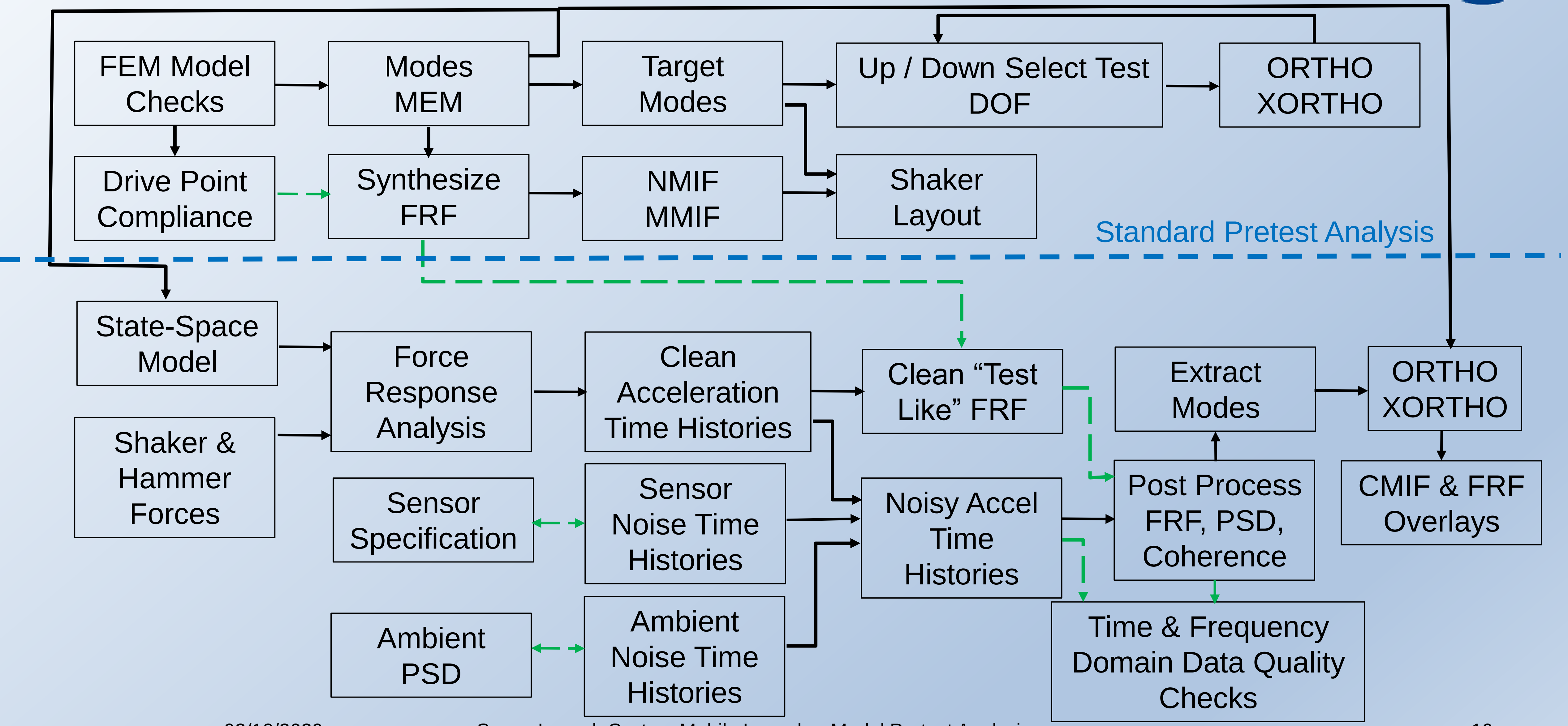


- Three test configurations:
  - ML on VAB Support Posts (i.e., 6 support points).
  - ML on CT (i.e., 4 support points).
  - ML on VAB Support Posts and CT (i.e. 10 support points).
- Almost 400 accelerometers distributed over the ML and CT.
- Inertial lateral shakers on the ML Tower and inertial lateral and inertial vertical shakers on the ML Deck.
- Anticipated target modes are very low in frequency and closely spaced.
- Very tight testing schedule.
  - Test performed June 2019.

ML Only Modal Test Pretest Analysis

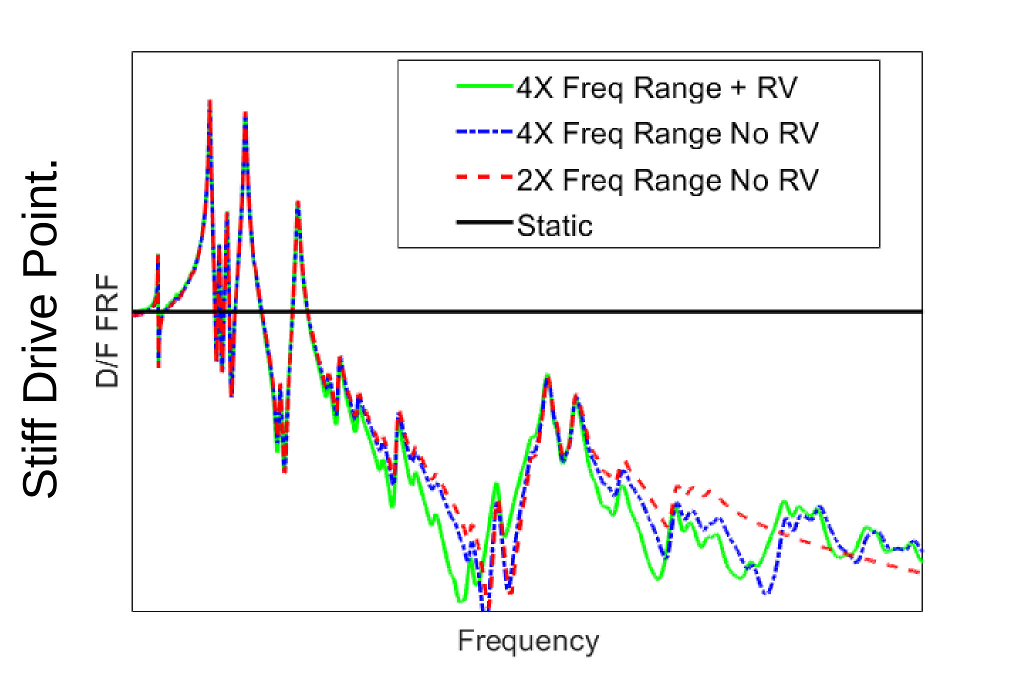
- Pretest analyses were performed to provide an as-run end-to end simulation for all test configurations to determine if the target modes could be captured.
  - Independently select primary and secondary target modes.
  - Verify adequacy of previously selected ~ 400 test DOF.
  - Verify adequacy of previously selected shaker/hammer locations and orientations.
  - Perform force response analysis to assess:
    - Shaker feasibility to adequately excite the ML with planned shaker random and sine excitations and modal hammer.
    - Effects of sensor and ambient noise.
    - Effects of anticipated modal damping levels.
  - The “test like” acceleration time histories were processed and modes extracted using the same data processing software available to the test team.
- This “as-run end-to-end” simulation aspect was done to ensure a high likelihood of successfully identifying the primary target modes.

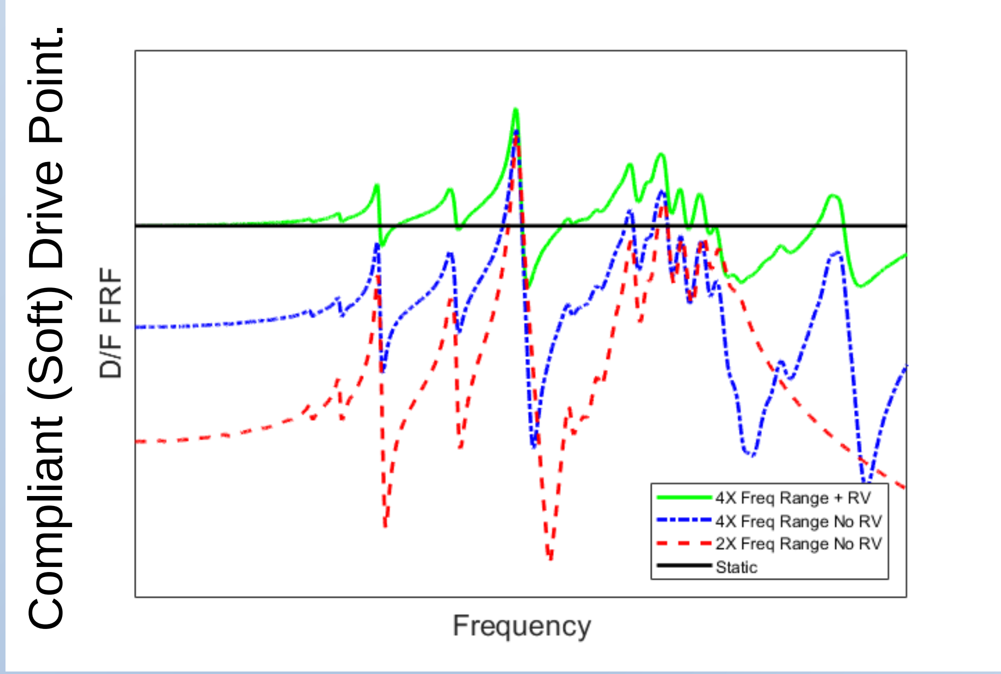
Pretest Analysis



Accounting For Out-of-Band Compliance

- Cannot assume a Mode Displacement approach (i.e., retaining only modes up to a certain frequency) will accurately capture all significant compliance at shaker drive points.
  – Mode acceleration method or residual vectors (used in this pretest analysis) may need to be used to capture the static elastic contribution.

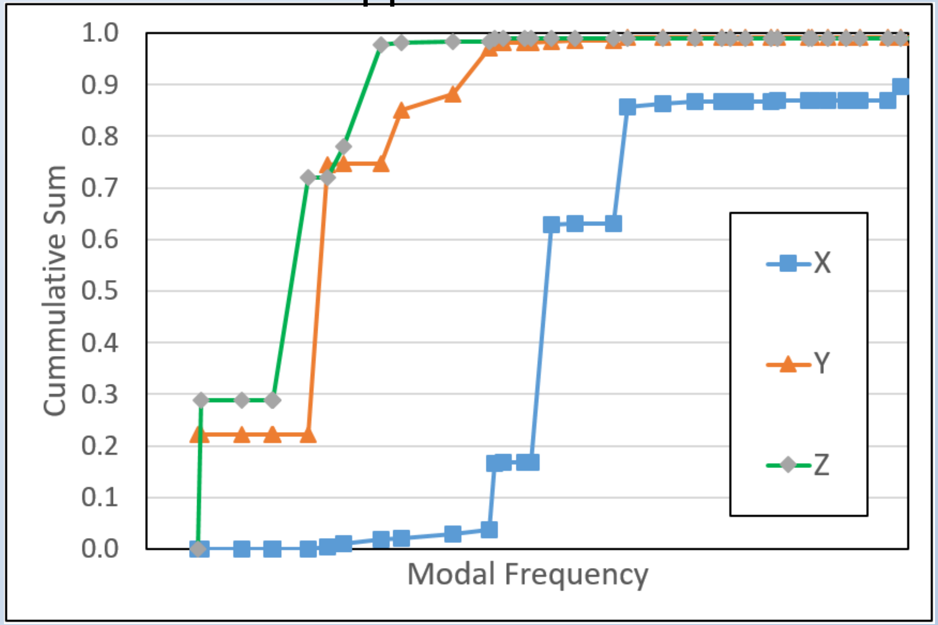




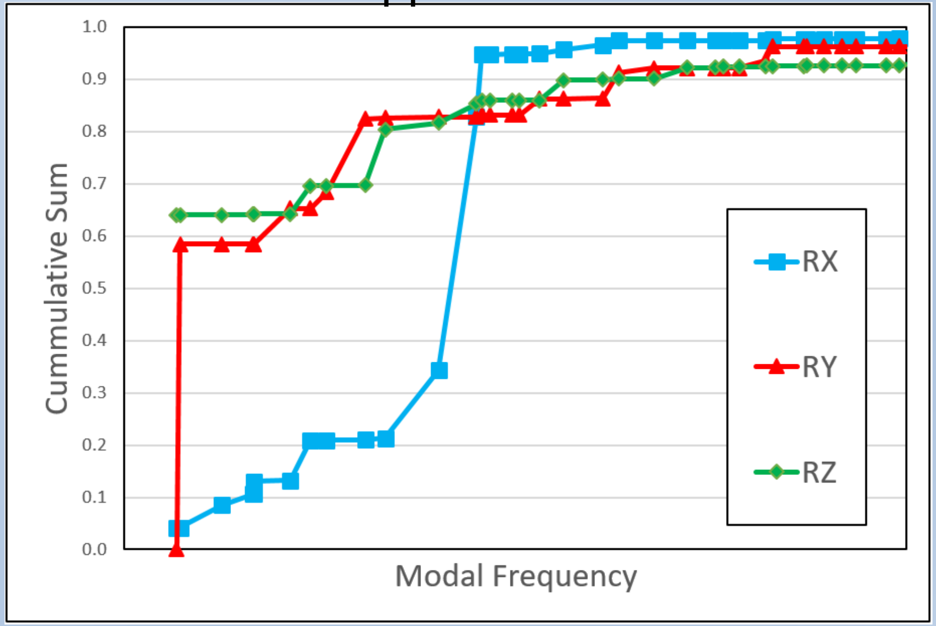
Target Mode Selection

- Primary and secondary target modes selected based upon modal effective mass and engineering judgement to capture fundamental characteristics of the ML and CT-2.
  - Because the CT-2 has a significant amount of grounded mass due to the way its four trucks are modeled and constrained to ground this was taken into account when determining a “small” modal effective mass fraction threshold.

ML on VAB Support Posts Translational



ML on VAB Support Posts Rotational



Test DOF Selection Verification

- Self and cross-orthogonalities metrics were the criteria used to verify the ML and CT-2 test DOF were adequate to identify all primary target modes.
  - Primary target modes self orthogonality off-diagonals magnitudes were 5% (10% is a more common threshold) or less and the magnitudes of the off-diagonals of the cross orthogonality of the primary target modes and all FEM modes within the frequency range of interest were 5% (10% is a more common threshold) or less.
  - The more rigorous criterion of 5% was considered in order to obtain a “well correlated” ML FEM.

ML on CT

All FEM Modes In Frequency Range Of Interest Shapes

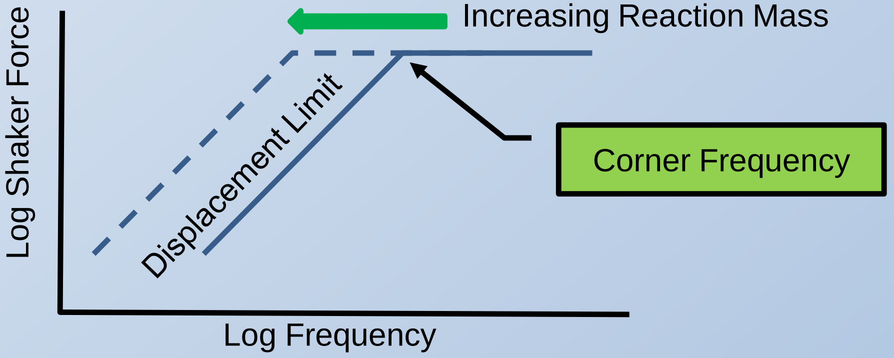
FEM Primary & Secondary Mode Shapes

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	S1	P12	S2	S3	P13	P14	P15	P16	P17	P18	24	25	26	P19	28	S4	34	35	36	37	42	43	44	P20	S5
P1	1.00																													-0.01			-0.01			0.01
P2		1.00																				0.01														
P3			1.00	-0.02											0.01																					
P4			-0.02	1.00																																
P5					1.00																						-0.01			0.01						0.02
P6						1.00																					-0.01									0.04
P7							1.00																													
P8								1.00											0.02		0.02				0.04		0.05	-0.04							-0.02	-0.11
P9									1.00							0.01			0.02		0.01				0.04		0.05	-0.03	0.01					-0.01	-0.01	-0.14
P10										1.00																	0.01			0.02						-0.05
P11											1.00																									0.04
S1												1.00		0.01																						
P12													1.00						0.01												0.01					0.01
S2												0.01		1.00																						
S3			0.01												1.00																					
P13									0.01							1.00		0.01	-0.01						-0.03		-0.02	0.02	-0.01			0.01		0.02		0.22
P14																	1.00		-0.05		-0.03	-0.01			-0.02	-0.01	-0.08	0.04	-0.02					-0.01	0.05	-0.02
P15																0.01		1.00	-0.02			0.01					-0.01								0.02	-0.06
P16								0.02	0.02				0.01			-0.01	-0.05	-0.02	1.00	0.01	-0.15			-0.01	-0.09		-0.30	0.16	-0.06			0.02		-0.04	0.17	
P17																			0.01	1.00				0.01		-0.02	0.02	-0.01	0.01			-0.02		-0.01	-0.01	-0.04
P18								0.02	0.01								-0.03		-0.15		1.00			-0.01	-0.05	-0.01	-0.25	0.10	-0.05	0.01		-0.03	0.02	-0.03	0.14	-0.07
P19								0.04	0.04							-0.03	-0.02		-0.09		-0.05		0.01	-0.03	1.00		-0.18	0.09	-0.04			0.01		0.02	0.06	0.31
S4					-0.01	-0.01		0.05	0.05	0.01						-0.02	-0.08	-0.01	-0.30	0.02	-0.25			-0.03	-0.18	-0.03	1.00	0.19	-0.08	0.02	-0.01	-0.02	0.03	-0.05	0.26	0.12
P20								-0.02	-0.01								0.05	0.02	0.17	-0.01	0.14				0.06		0.26	-0.12	0.05		0.02		-0.01	0.10	1.00	0.28
S5	0.01				0.02	0.04		-0.11	-0.14	-0.05	0.04		0.01			0.22	-0.02	-0.06		-0.04	-0.07	0.01	-0.04	0.07	0.31	-0.05	0.12	-0.05	-0.02	0.06	-0.14		0.05	-0.27	0.28	1.00

Off-diagonal entries having magnitudes less than 0.01 not shown.
Off-diagonal entries having magnitudes greater than or equal to 0.05 are highlighted in yellow.

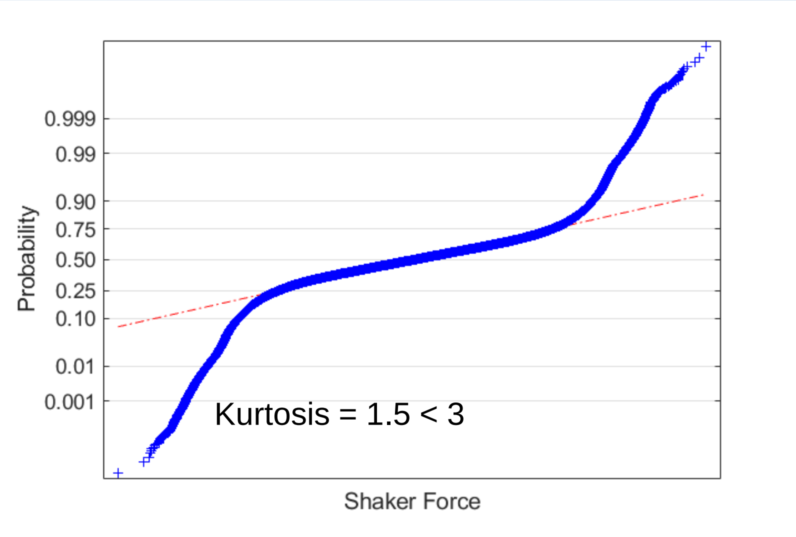
ML Shakers 1

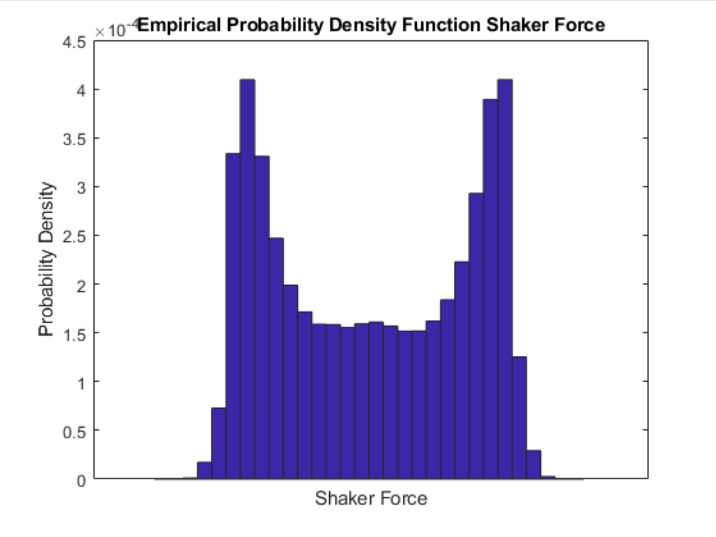
- The ML Only modal test shakers are inertial reaction mass shakers.
  - 3 lateral (horizontal) ML shakers with their inertial reaction mass riding on bearing rails.
  - 2 vertical ML shakers with their inertial reaction mass moving on vertical guide-posts.
  - NASA/Marshall Space Flight Center (MSFC) test personnel designed and fabricated the ML shakers and incorporated the hydraulic actuators from their modal shakers used during the Ares I-X Flight Test Vehicle (FTV) modal test in 2009.



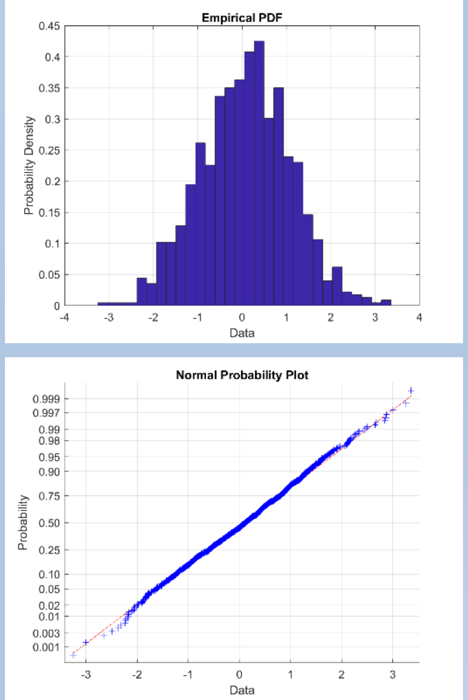
ML Shakers 2

- MSFC test engineers supplied shaker force time histories for different shaker inputs.
- ML Shaker forces displayed significant nonlinear behavior.
- Normal probability plots extremely handy for easily determining if signals are Gaussian, and if not why not.



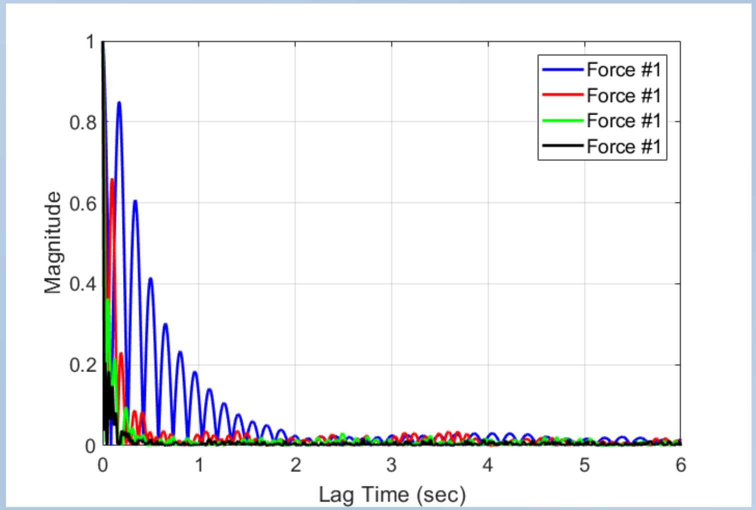


Gaussian zero mean unit standard deviation example.



Generating Uncorrelated ML Shaker Forces

- Shaker force time histories for the different shaker inputs were examined.
- Autocorrelation functions shows they were essentially uncorrelated for time lags > 5 sec.
- "Slinky" approach was used to generate the uncorrelated shaker force time histories used in the force response analysis.
  - Because the data processing frame length was significantly longer than five seconds, lopping off only first five seconds would have end up with the five ML random shaker force time histories being correlated and having very high coherences. This is due to each ML shaker force time history essentially being time delayed versions of themselves.
  - *Zero Correlation ≠ Zero Coherence.*



Force Response Analysis 1

- Utilized an open-loop MIMO modal state-space approach when using the five uncorrelated random ML shaker force time histories and a Single-Input Multiple-Output (SIMO) modal state-space approach when using the drop hammer force time histories.
- The ML shaker drive point displacements and velocities showed that neither the shaker displacement nor velocity limits were exceeded and thus verified this open-loop approach was valid and that a close-loop simulation involving detailed modeling of ML shakers was not needed.
- Modal damping levels of 1%, 2%, and 3% were evaluated.

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t),$$

$$\Phi^T M \Phi \ddot{q}(t) + \Phi^T C \Phi \dot{q}(t) + \Phi^T K \Phi q(t) = \Phi^T F(t)$$

$$\ddot{q}(t) + CC\dot{q}(t) + KKq(t) = \Phi^T F(t)\,,$$

$$\begin{bmatrix} \dot{q}(t) \\ \ddot{q}(t) \end{bmatrix} = \begin{bmatrix} 0_n & I_n \\ -KK & -CC \end{bmatrix} \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix} + \begin{bmatrix} 0_n \\ \Phi^T \end{bmatrix} F(t)$$

$$[\ddot{q}(t)] = [-KK \quad -CC] \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix} + \Phi^T F(t)\,,$$

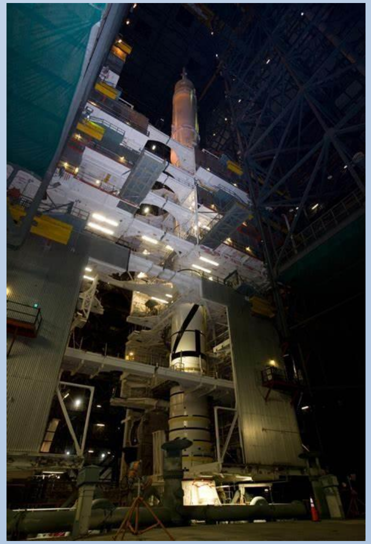
$$[\ddot{x}(t)] = \Phi[\ddot{q}(t)] = \Phi[-KK \quad -CC] \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix} + \Phi\Phi^T F(t)$$

Force To Acceleration Modal State-Space Model

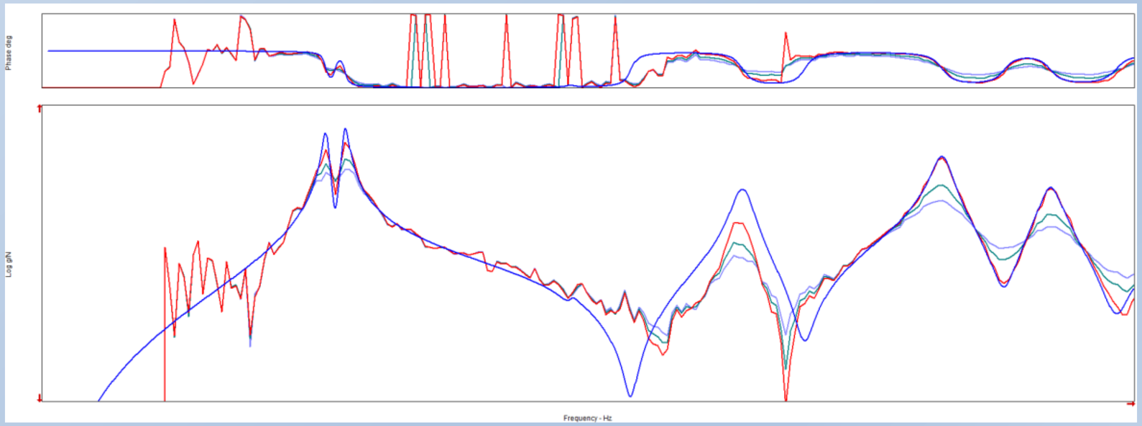
M = physical mass matrix
C = physical damping matrix
K = physical stiffness matrix
F = physical force vector

KK = modal stiffness matrix
CC = modal damping matrix
Φ = mode shape matrix
x(t) = physical displacements
q(t) = modal displacements

Force Response Analysis 2



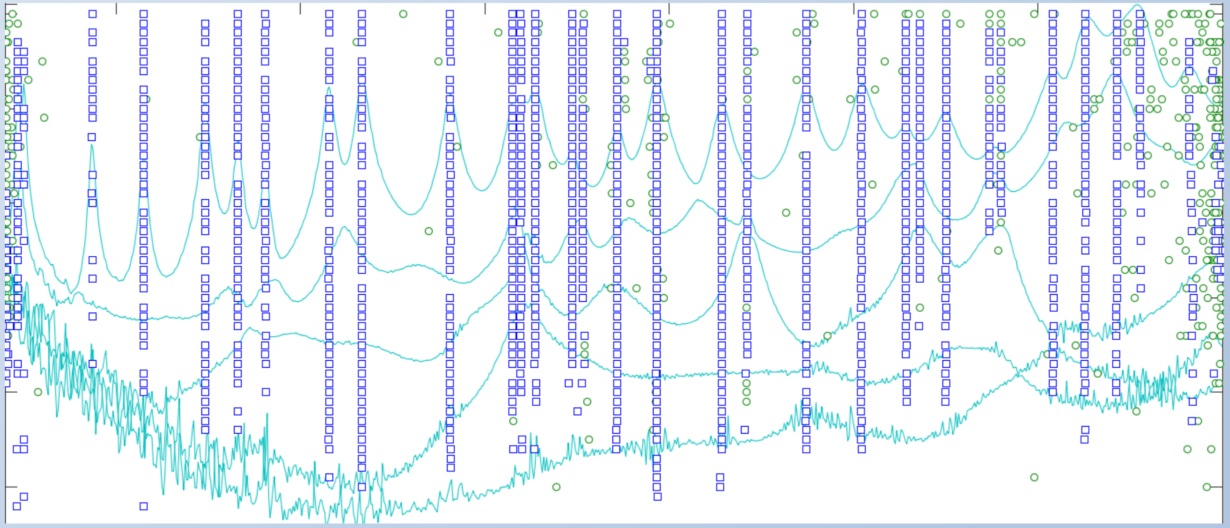
- The modal state-space model generated "clean" acceleration response time histories to which the ambient background noise and sensor noise acceleration time histories were then added in order to obtain the "test like" acceleration response time histories.
  - Accelerometer sensor noise models were based upon the accelerometer manufacture's specification data sheets.
  - Ambient background vibration levels of the ML inside the VAB were estimated from the ambient data collected during the Ares I-X Flight Test Vehicle (FTV) modal test, with the VAB doors closed, and modeled as uncorrelated zero mean Gaussian random time histories.
  - Validity of the "clean" and "test like" acceleration response time histories was verified by comparing their drive point force to acceleration (A/F) FRF to the A/F FRF computed from the ML shaker and Drop Hammer suitability study.



- No noise 1% damping (blue)
- Noisy + 1% modal damping (red)
- Noisy + 2% modal damping (green)
- Noisy + 3% modal damping (light blue)

Force Response Analysis 3

- The simulated “test like” acceleration time histories underwent standard time-domain and frequency-domain data quality checks.
- Normal Mode Indicator Function (NMIF), Multivariate Mode Indicator Function (MMIF), and Complex Mode Indicator Function (CMIF) were used to estimate the number of modes and to aid in selecting pole estimates.
- Majority of modes were extracted with time-domain polyreference techniques with a Single Degree Of Freedom (SDOF) polynomial curve fitting tool used a few times.
  - Advanced modal extraction techniques, such as mode enhancement and spatial filtering, were not used.



Force Response Analysis 4

- Self and cross-orthogonality criteria were used to determine how well the “test” primary target modes could be identified.
- If the magnitudes of the off-diagonal of the self orthogonality of the “test” primary target modes and the cross orthogonality of the “test” and FEM primary target modes being 5% (10%) or less, and the magnitudes of the diagonals of the cross orthogonality of the “test” and FEM primary target modes being 95% (90%) or greater, then the “test” primary target modes were well (adequately) identified.

FEM/Test Cross Orthogonality Table

FEM Shapes

			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	S1	S2	S3	P13	S4	P14	S5	S6	P15						P16		Test	Test	90 - 100
	Test Shapes		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	19	20	25	26	27	28	29	30	31	32	33	CRSS	CRSS	50 - 89
100	P1	1	100																												100	100	
95	P2	2		100																											100	100	
90	P3	3			100																										100	100	
85	P4	4				100																									100	100	
80	P5	5					100																								100	100	
75	P6	6						100																							100	100	
70	P7	7							100																						100	100	
65	P8	8								100																					100	100	
60	P9	9									100																				100	100	
55	P10	10										100																			100	100	
50	P11	11											100					5													100	100	
45	P12	12												100				11													100	100	
40	S1	13												8	99											5		5		5	99	100	
35	S2	14														94									7	13		11		22	94	98	
30	S3	15															88		8					9	12	12	16	21			88	95	
25	P13	16											5	11				100			7		7	5					7		100	100	
20	S4	17																	100												100	100	
15		18																								5					100	100	
10	P14	19																		100		5	7						14		100	100	
5	S5	20																7			100					5		5	5		100	100	
0		21																						10		8					100	100	
		22																									9			10	99	100	
		23																							14	10		9			98	99	
		24																						9		22	13	31		16	87	97	
	S6	25																		5		96	37			9	6	13		20	96	99	
	P15	26																8		6		36	98	5		11	6	11	13	15	98	100	
		27																6						99	5					5	99	100	
		28																							100		7				100	100	
		29																						7		100		7			100	100	
		30																				6			8		100	5		8	100	100	
		31																										100	6		100	100	
FEM		CRSS	100	100	100	100	100	100	100	100	100	100	100	100	99	94	88	100	100	100	100	97	98	99	100	100	100	100	14	22			
FEM		CRSS	100	100	100	100	100	100	100	100	100	100	100	100	100	95	93	100	100	100	100	98	99	100	100	100	100	100	25	38			

FEM/Test Cross Orthogonality Table

FEM Shapes

			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	S1	S2	S3	P13	S4	P14	S5	S6	P15						P16		Test	Test	90 - 100
	Test Shapes		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	19	20	25	26	27	28	29	30	31	32	33	CRSS	CRSS	50 - 89
100	P1	1	100																												100	100	
95	P2	2		100																											100	100	
90	P3	3			100																										100	100	
85	P4	4				100																									100	100	
80	P5	5					100																								100	100	
75	P6	6						100																							100	100	
70	P7	7							100																						100	100	
65	P8	8								100																					100	100	
60	P9	9									100																				100	100	
55	P10	10										100																			100	100	
50	P11	11											100					5													100	100	
45	P12	12												100				11													100	100	
25	P13	16											5	11				100			7		7	5					7		100	100	
10	P14	19																		100		5	7						14		100	100	
	P15	26																8		6		36	98	5		11	6	11	13	15	98	100	

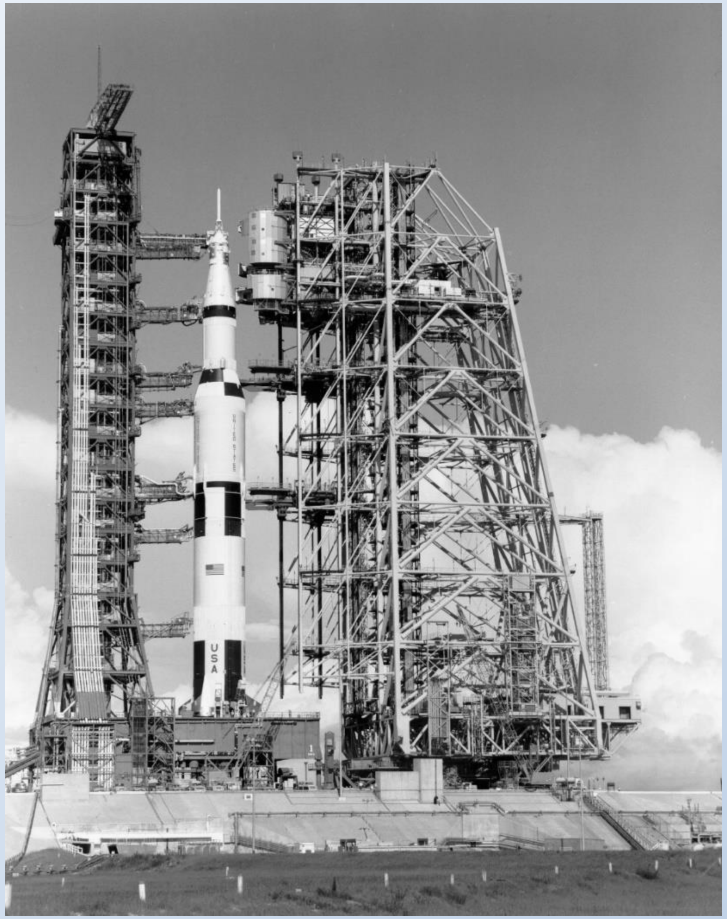
- Example shows a subset of the test DOF adequately identify the first 11 primary target modes.

Conclusion

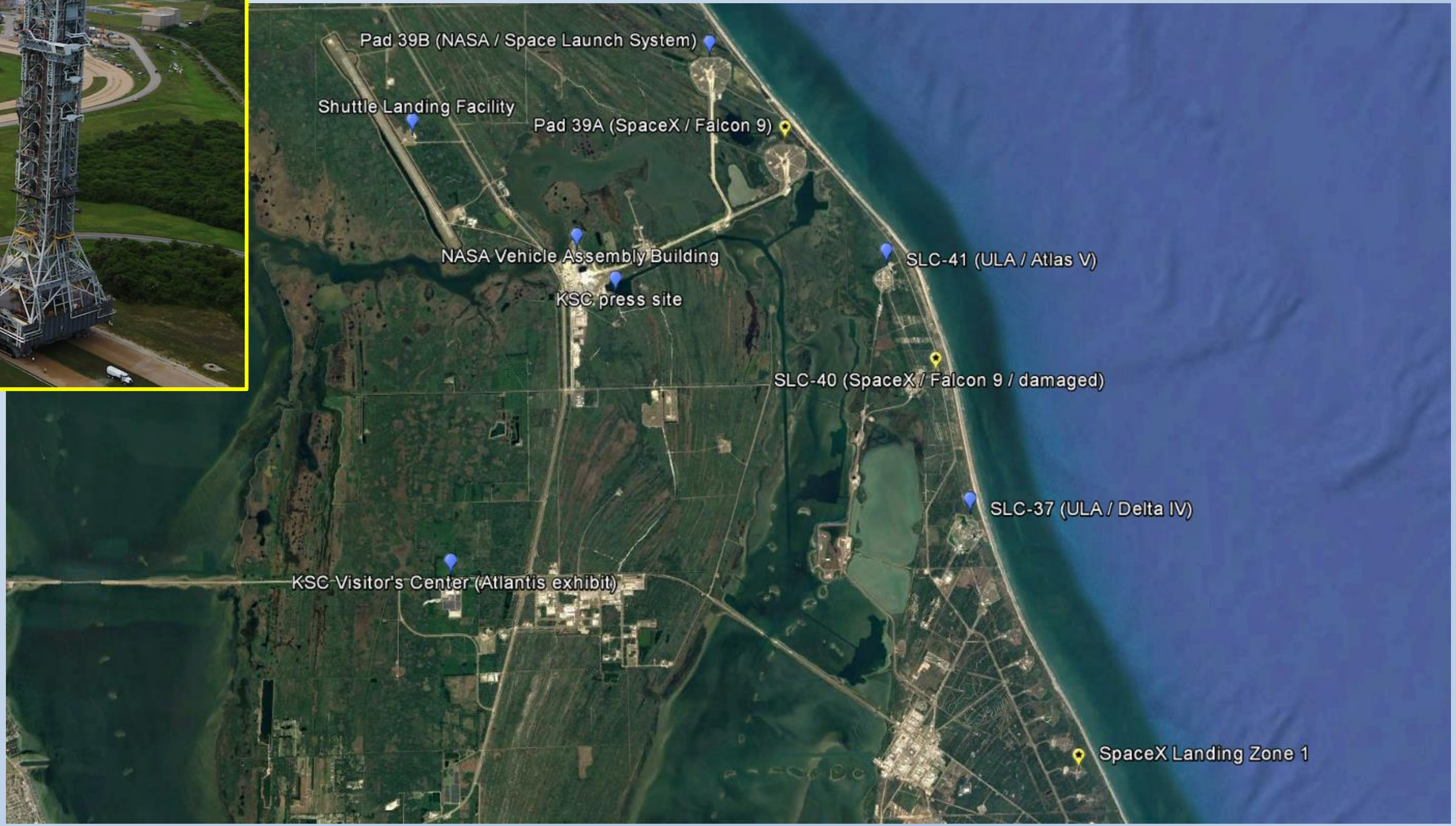
- Primary target modes for all three test configurations can be adequately identified, and many times well identified for 1% - 2% modal damping values.
  - However, this requires running the ML shakers at their full force levels.
- Running the ML shakers at 50% and 20% of their full levels was investigated for the ML on VAB Support Posts test configuration to determine if multi-force linearity studies (i.e. shakers run at 20%, 50%, 100% levels) were feasible.
  - Running the ML shakers at 20% of their full level is insufficient if the modal damping is 3% or greater.
  - Due to ML shakers operating as inertial reaction mass shakers and the lowest frequency primary target modes being significantly below the shaker force corner frequency.
- Hence multi-force level linearity studies for all three test configurations may require multi-point sine sweeps or normal mode tuning techniques.

Backup Slides

Mobile Launcher Evolution



Mobile Launcher Rollout Fall 2018



End