



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



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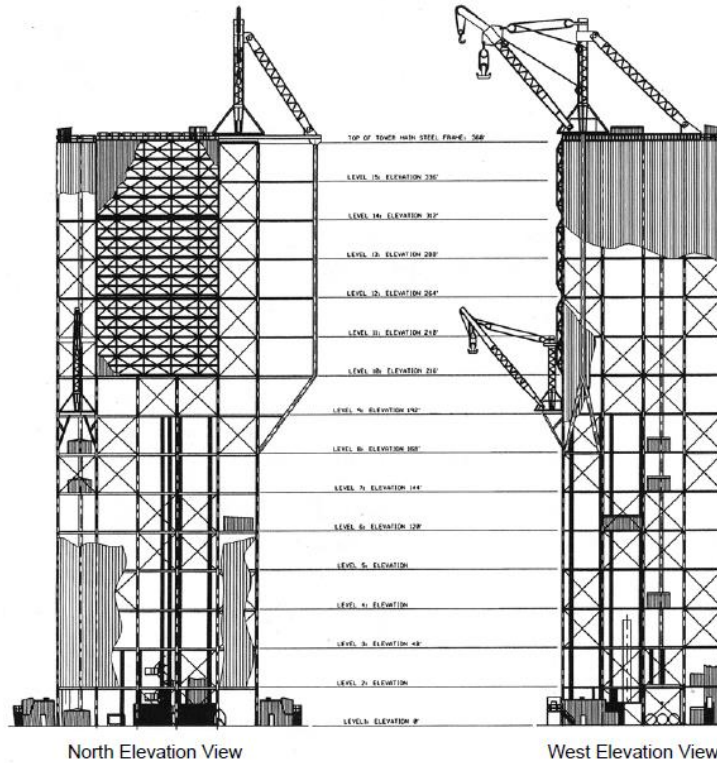
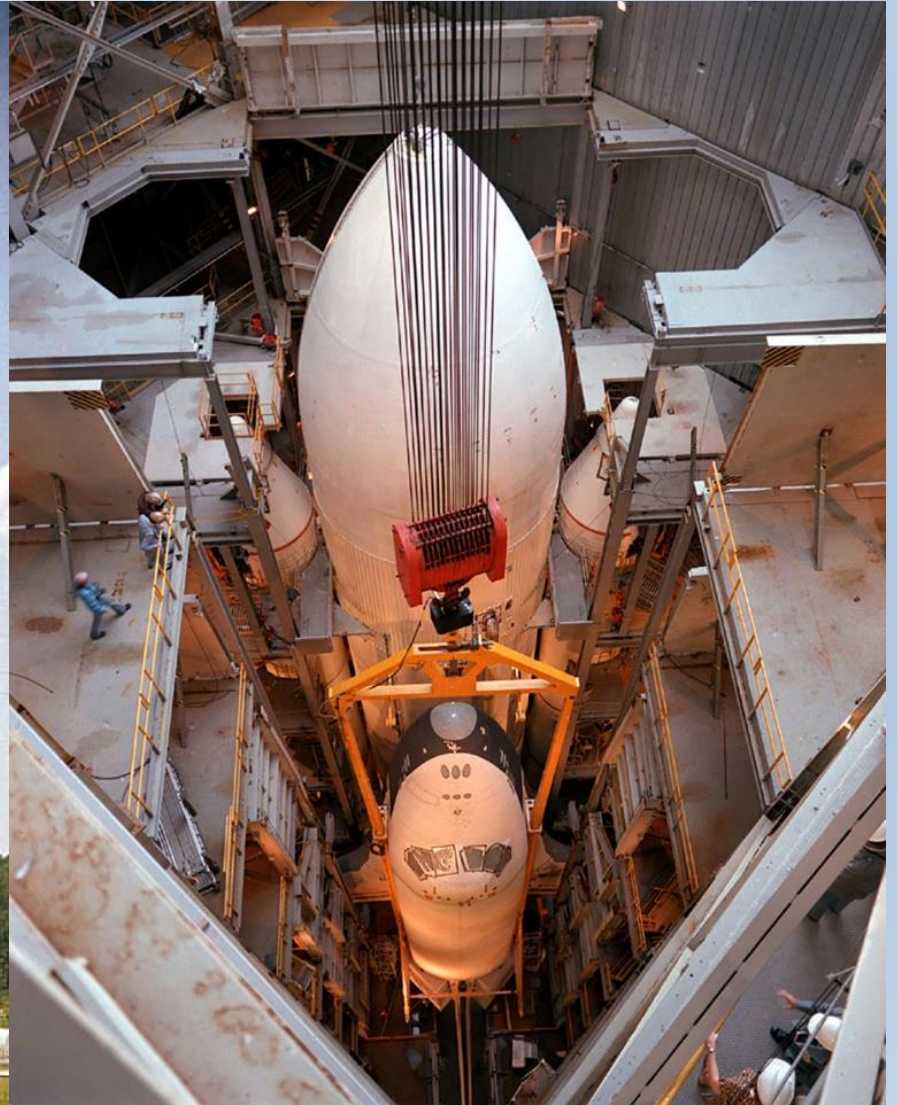


FIGURE 2-4
Test Stand 4550 Photograph
and Elevation Profiles

MSFC Test Stand 4450 & Shuttle Orbiter Enterprise



Mobile Launcher (ML)



SLS Umbilical/Access Arm Configuration

Core Stage Forward Skirt Umbilical (CSFSU)
Vehicle Stabilizer System (VSS)



Core Stage Inter-Tank Umbilical (CSITU)



Tail Service Mast Umbilical (TSMU)



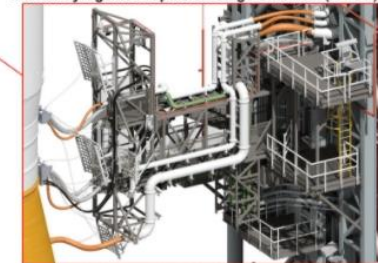
Crew Access Arm (CAA)



Orion Service Module Umbilical (OSMU)



Interim Cryogenic Propulsion Stage Umbilical (ICPSU)



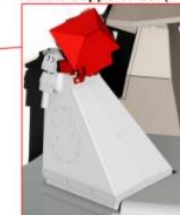
GN2 Purge Umbilical - 2 Places



Aft Skirt Umbilical (ASU)
2 Places



Vehicle Support Post (VSP)



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.

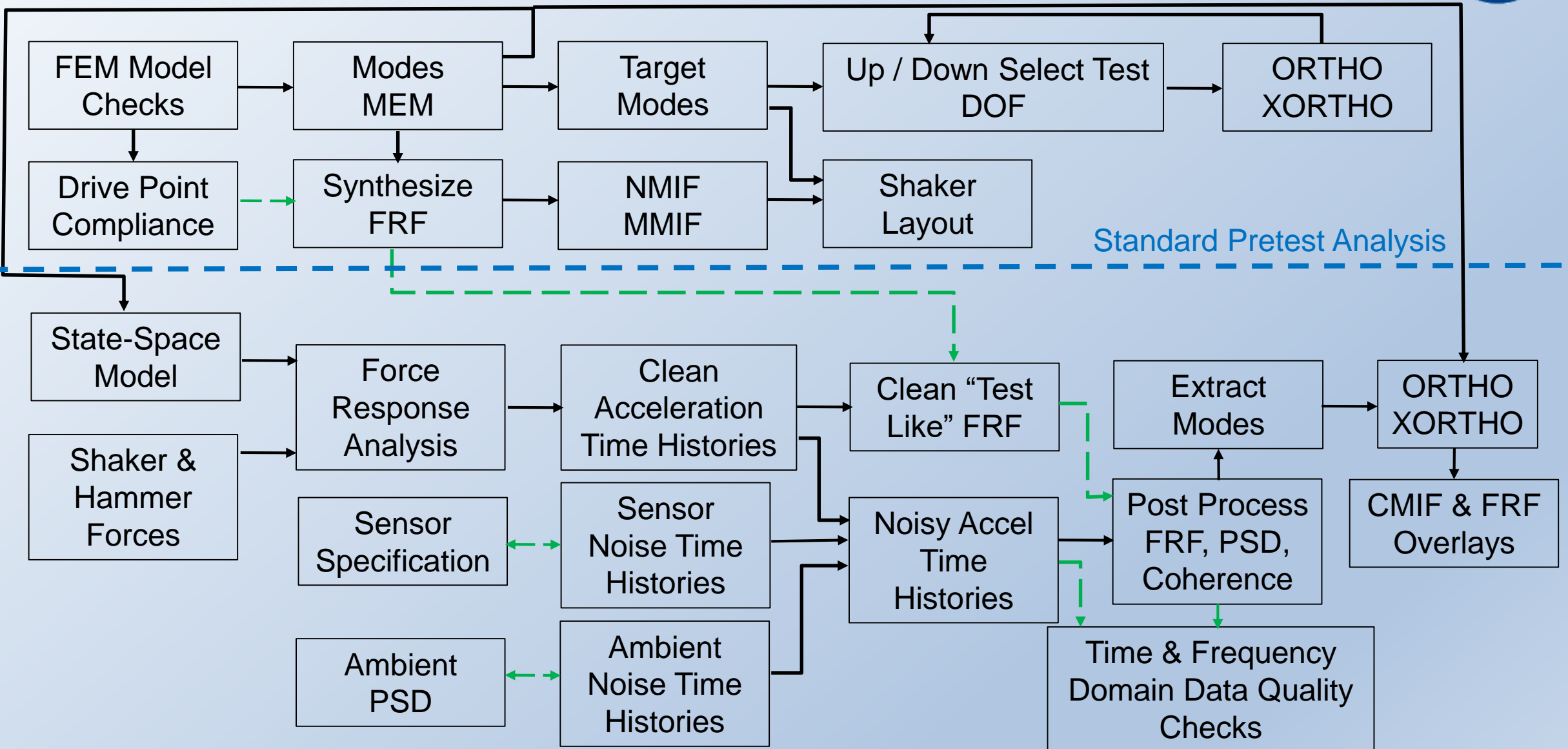




ML Only Modal Test Pretest Analysis

- 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.

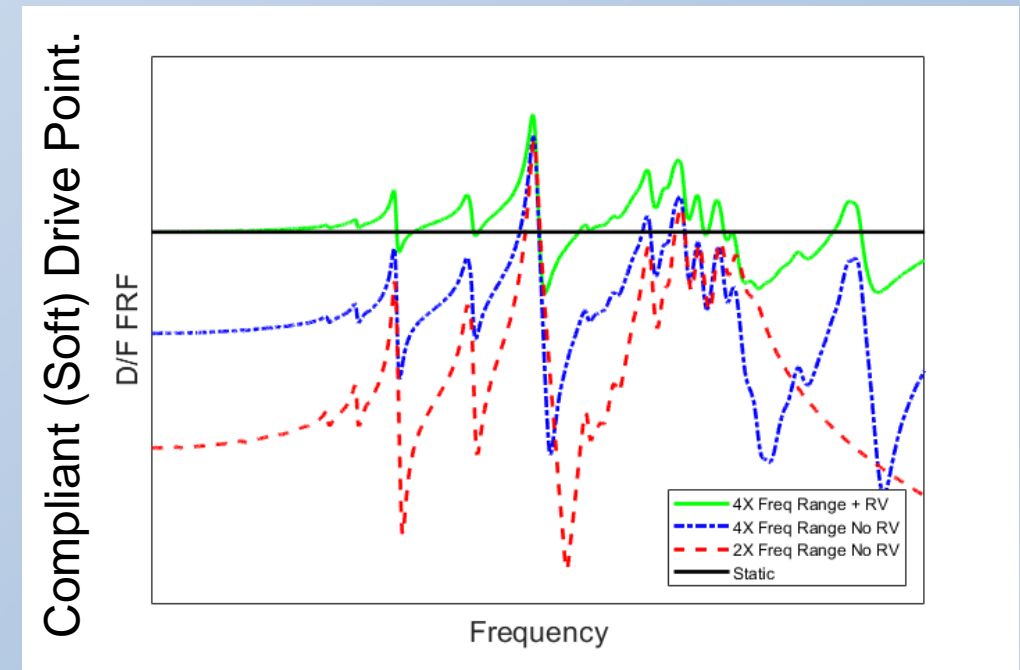
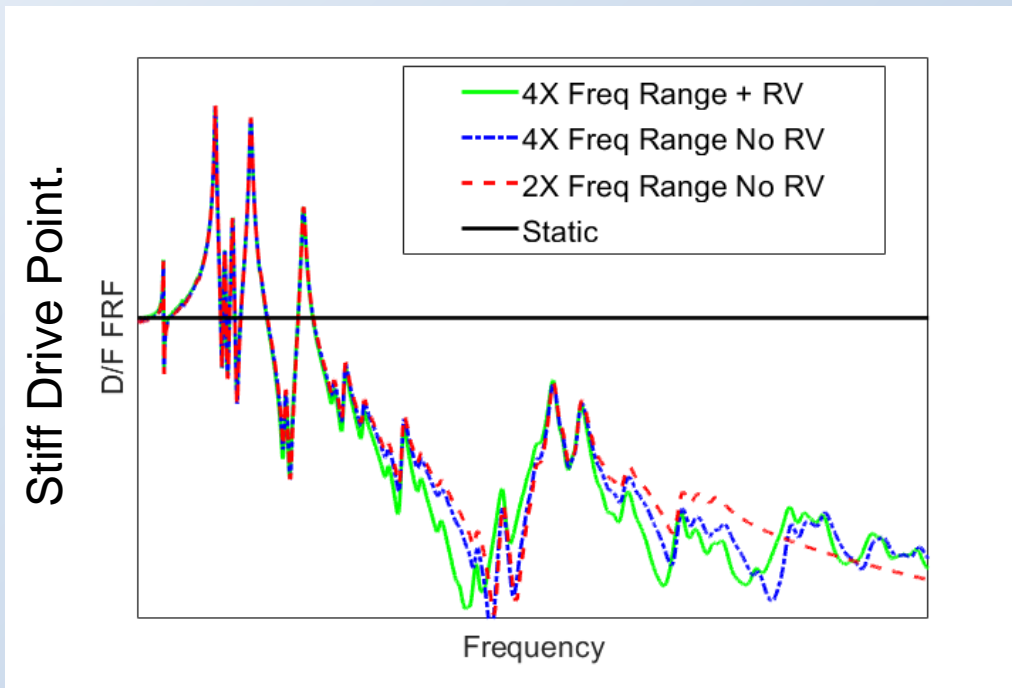
Pretest Analysis



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.

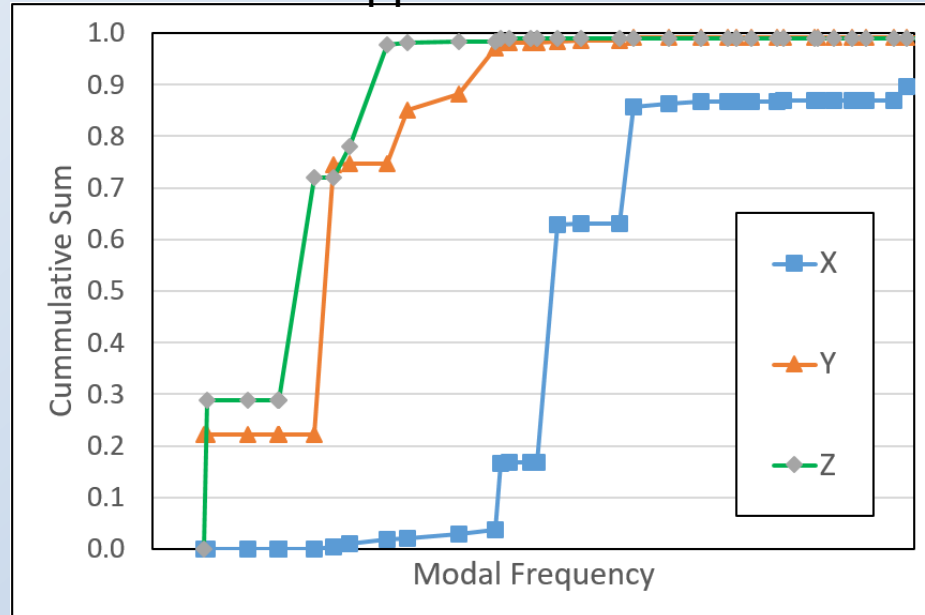




Target Mode Selection

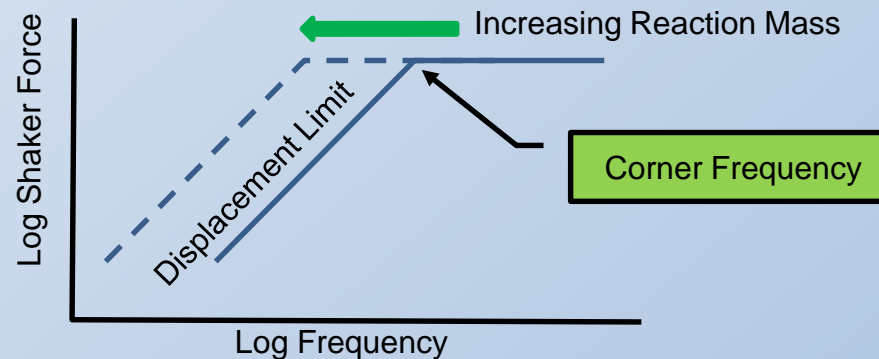
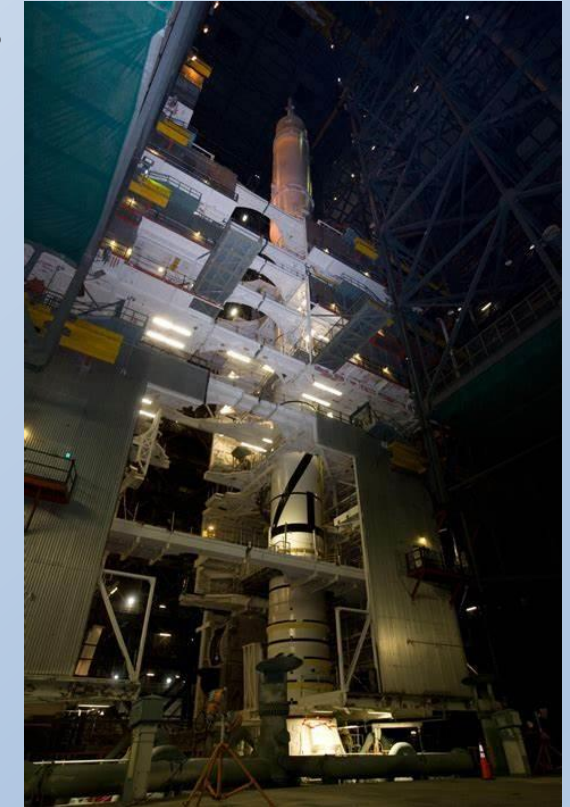
- Primary and secondary target modes selected based upon modal effective mass and engineering judgement to capture fundamental characteristics of the ML and CT-2.
 - Because the CT-2 has a significant amount of grounded mass due to the way its four trucks are modeled and constrained to ground this was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

ML on VAB Support Posts Translational



ML Shakers 1

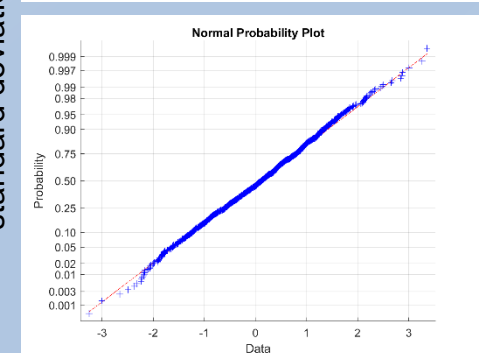
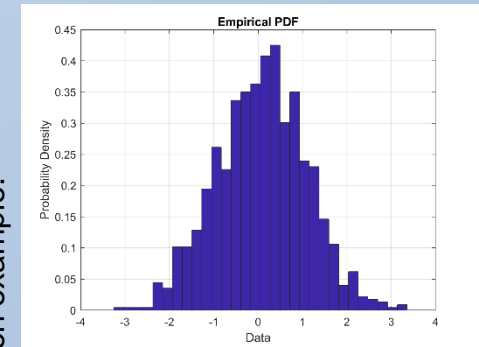
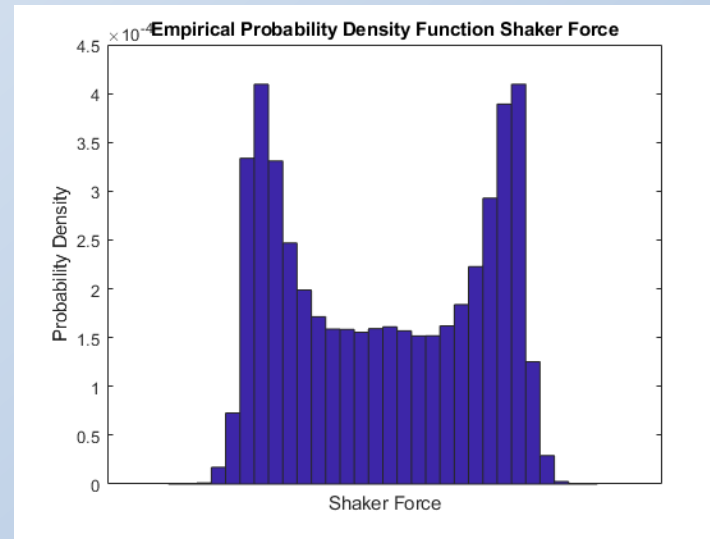
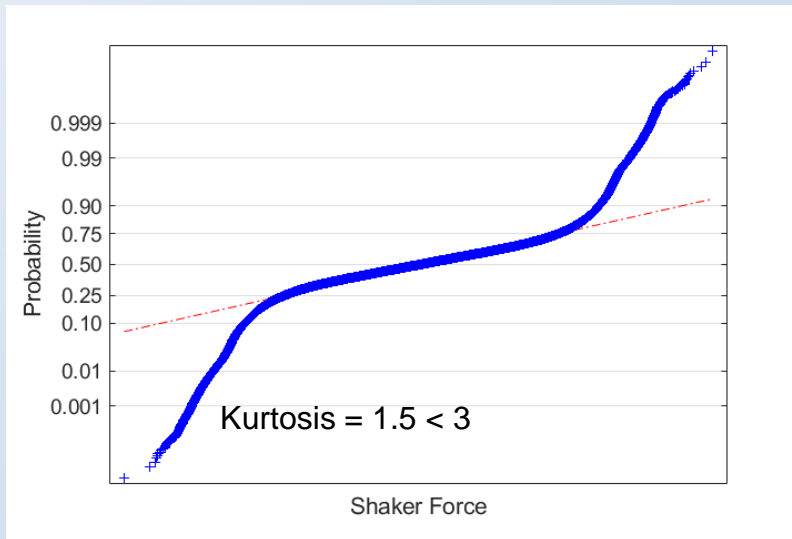
- The ML Only modal test shakers are inertial reaction mass shakers.
 - 3 lateral (horizontal) ML shakers with their inertial reaction mass riding on bearing rails.
 - 2 vertical ML shakers with their inertial reaction mass moving on vertical guide-posts.
 - NASA/Marshall Space Flight Center (MSFC) test 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.

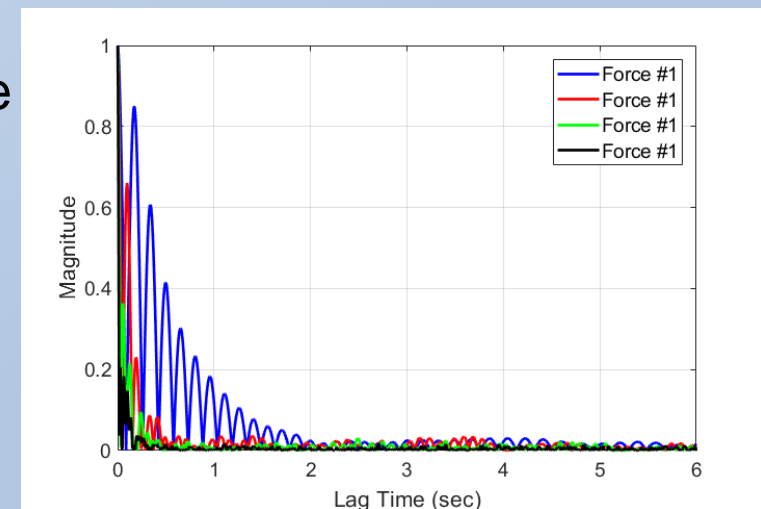


Gaussian zero mean unit standard deviation example.

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 \neq 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

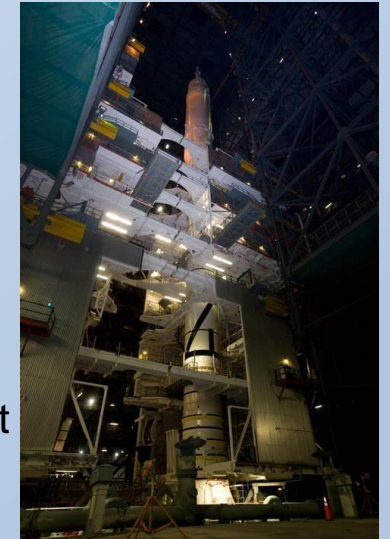
M = physical mass matrix
 C = physical damping matrix
 K = physical stiffness matrix
 F = physical force vector

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

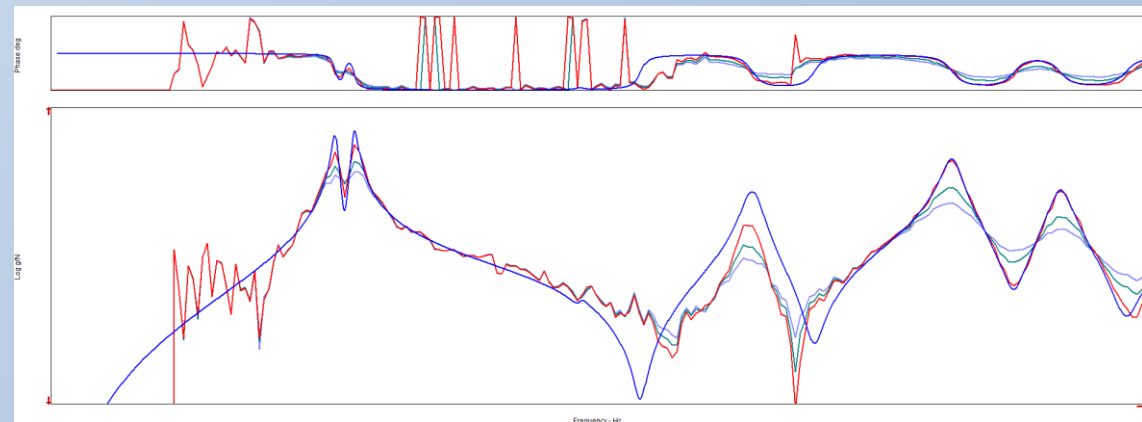
Force Response Analysis 2



- 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.



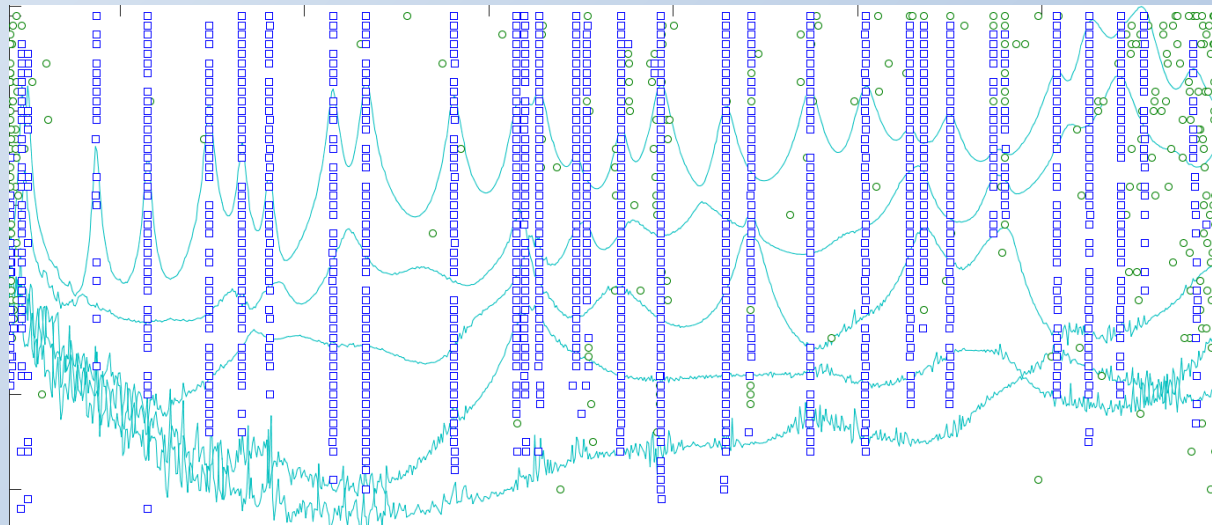
- No noise 1% damping (blue)
- Noisy + 1% modal damping (red)
- Noisy + 2% modal damping (green)
- Noisy + 3% modal damping (light blue)



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.





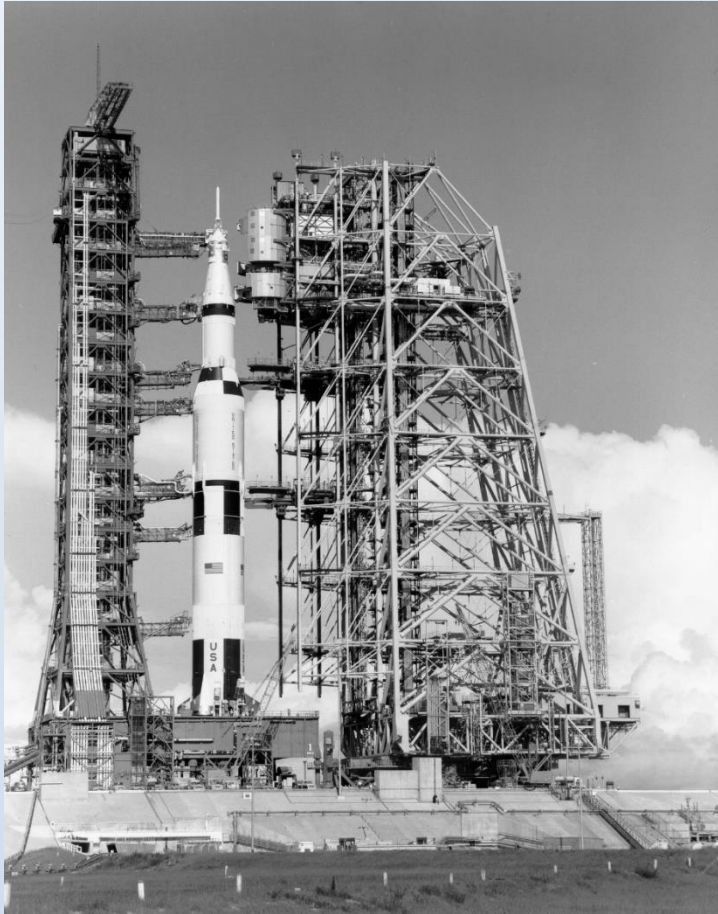
Conclusion

- 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.

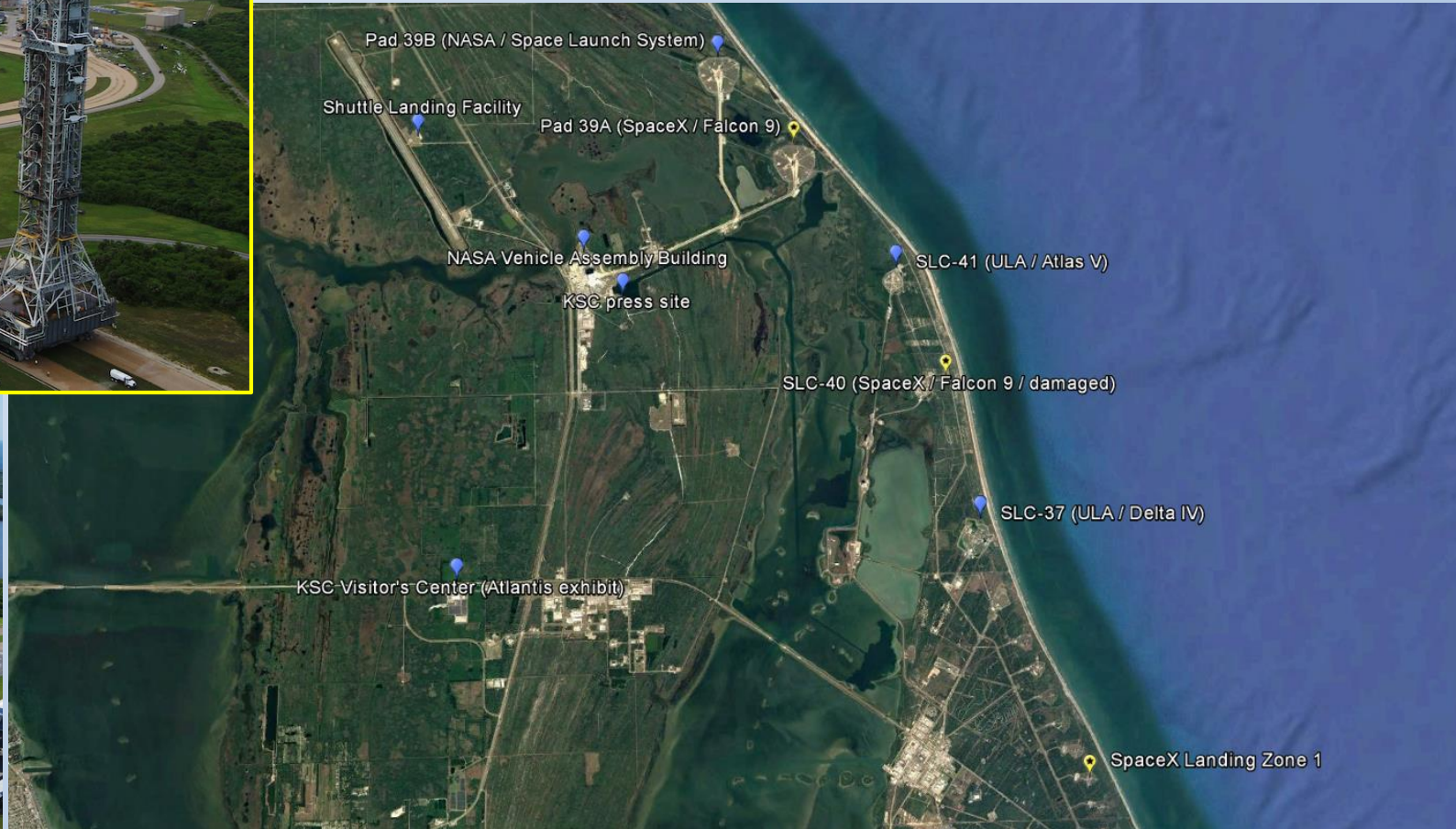


Backup Slides

Mobile Launcher Evolution



Mobile Launcher Rollout Fall 2018





End