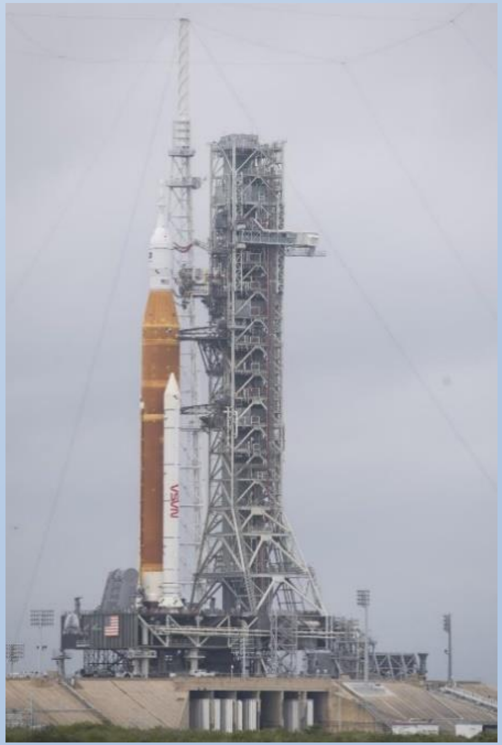
Operational Modal Analysis of the Artemis I Dynamic Rollout Test and Wet Dress Rehearsal

IMAC XLII



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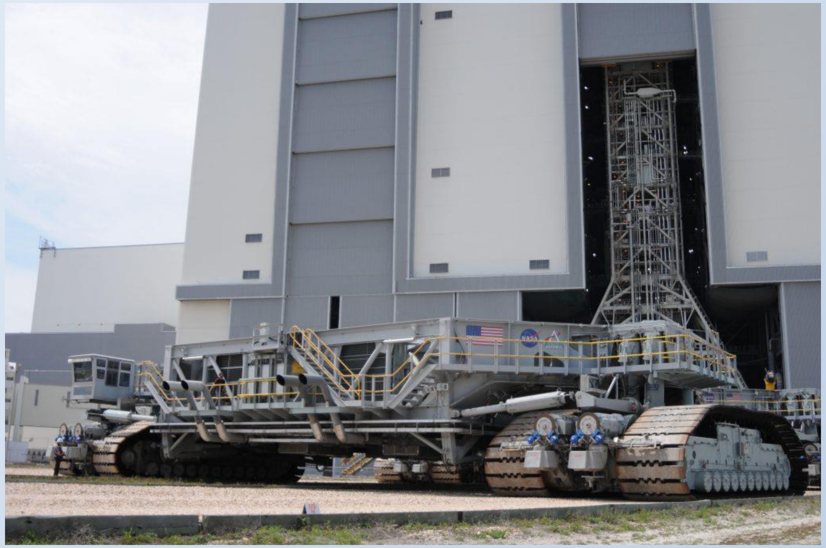
Matthew Allen – ATA Engineering

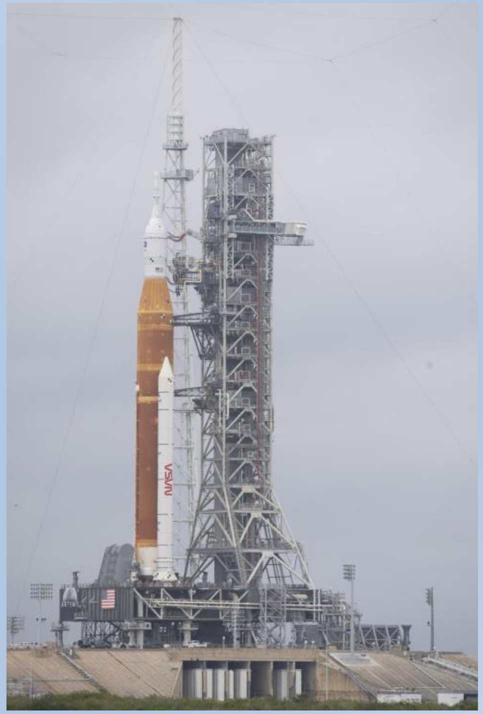
Artemis I Rollout from VAB to Launch Pad 39B

- NASA is developing an expendable heavy lift launch vehicle capability, the Space Launch System (SLS), to support lunar and deep space exploration.
- The Artemis I Dynamic Rollout Test (DRT) recorded accelerations on Artemis I, the Mobile Launcher (ML), and Crawler Transporter (CT), during its rollout from the Vehicle Assembly Building (VAB) to Launch Pad 39B in March 2022 and back in April 2022.



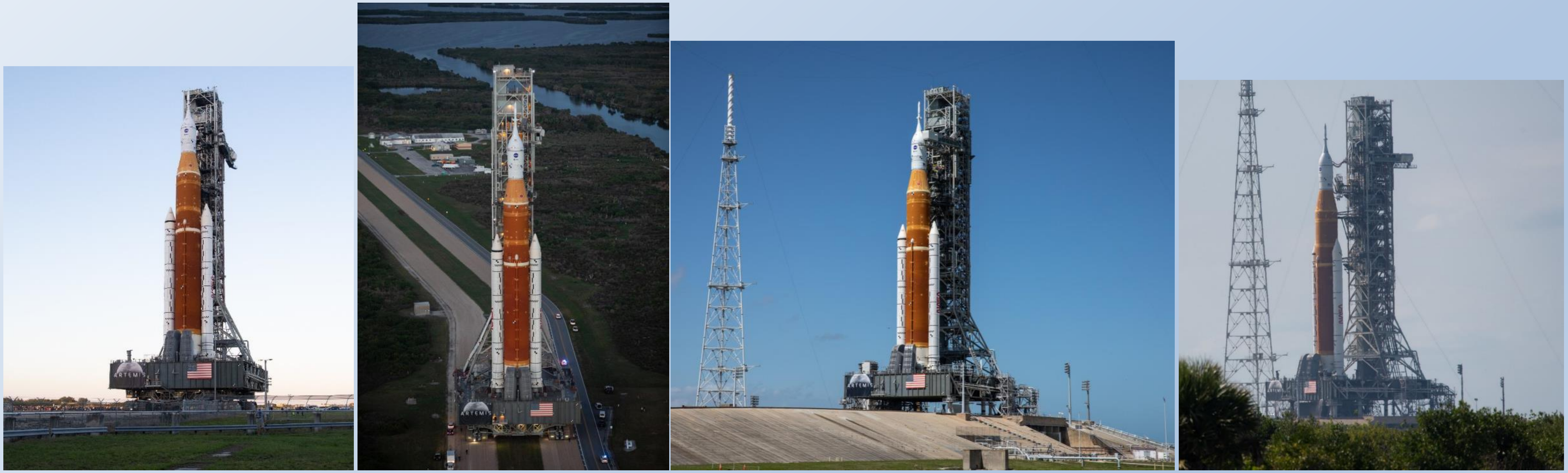
Wet Dress Rehearsal

- While Artemis 1 was at Launch Pad 39B, between the DRT rollout and rollback, the Wet Dress Rehearsal (WDR) was performed to demonstrate launch readiness, which was to include running through the planned launch countdown timeline and automated sequences all the way down inside of T-10 seconds before stopping.
  - Provided an opportunity to acquire modal characteristics of Artemis I in a partially fueled state.



Artemis I DRT & WDR Supports Model Correlation

- The dynamic characteristics extracted from DRT will be used to support Space Launch System (SLS) Integrated Modal Test (IMT) math model correlation efforts, Exploration Ground System (EGS) ML model verification and validation (V&V), and development of generic rollout forcing functions.

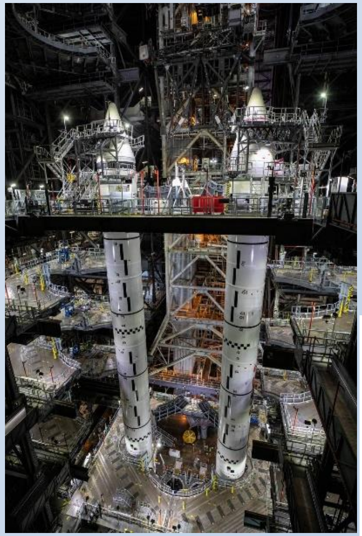


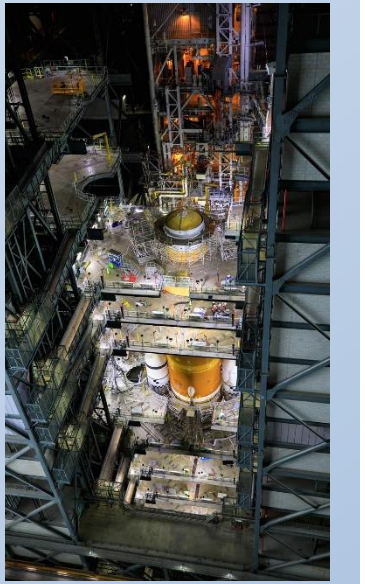
Artemis I At Launch Pad 39B WDR

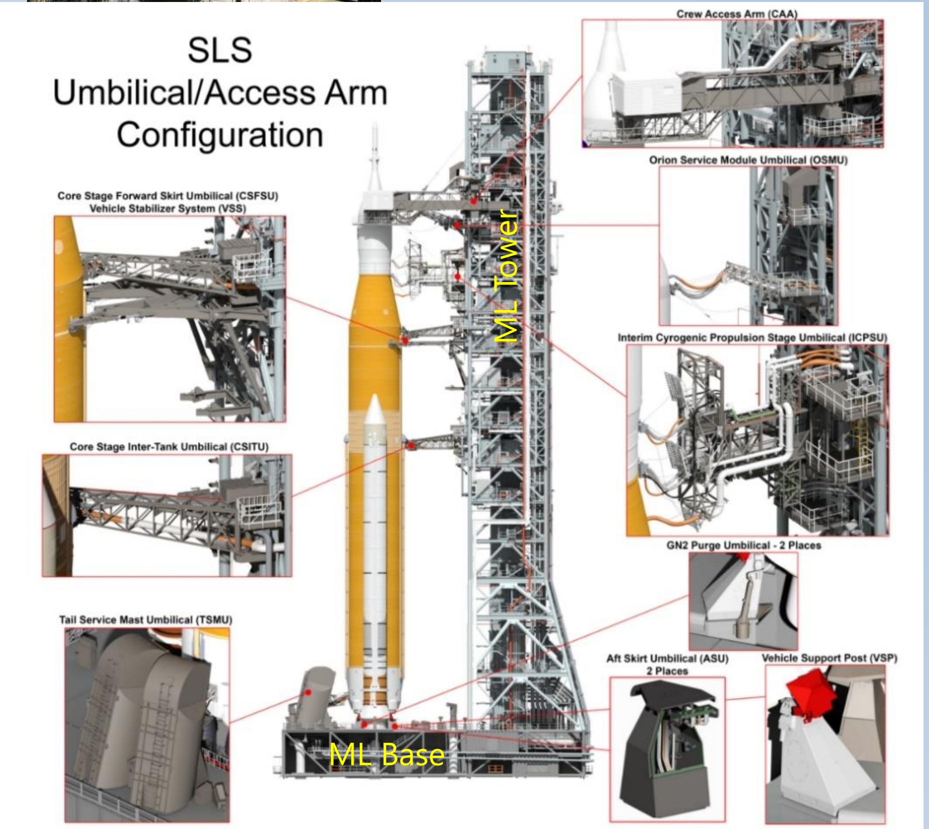
- ML supported on the six Vertical Support Posts at Launch Pad 39B with four Extensible Columns positioned near the perimeter of the flame hole providing additional vertical support to the ML Deck.
  - Extensible Columns provide additional vertical support to the ML Deck.

Mobile Launcher

- ML supported the integration of Artemis 1 inside the VAB and served as the Integrated Modal Test (IMT) test fixture.
- ML Base supports the SLS at the eight Vehicle Support Posts (VSP), 4 located at the bottom of each of the two boosters.
- Vehicle Stabilization System (VSS) provides lateral support to SLS.
- ML Tower supports fuel, power, and data umbilicals to SLS and the Multi-Purpose Crew Vehicle (MPCV) Orion.
- ML Tower also provides crew access to the MPCV Orion Crew Module (CM) via the Crew Access Arm (CAA).



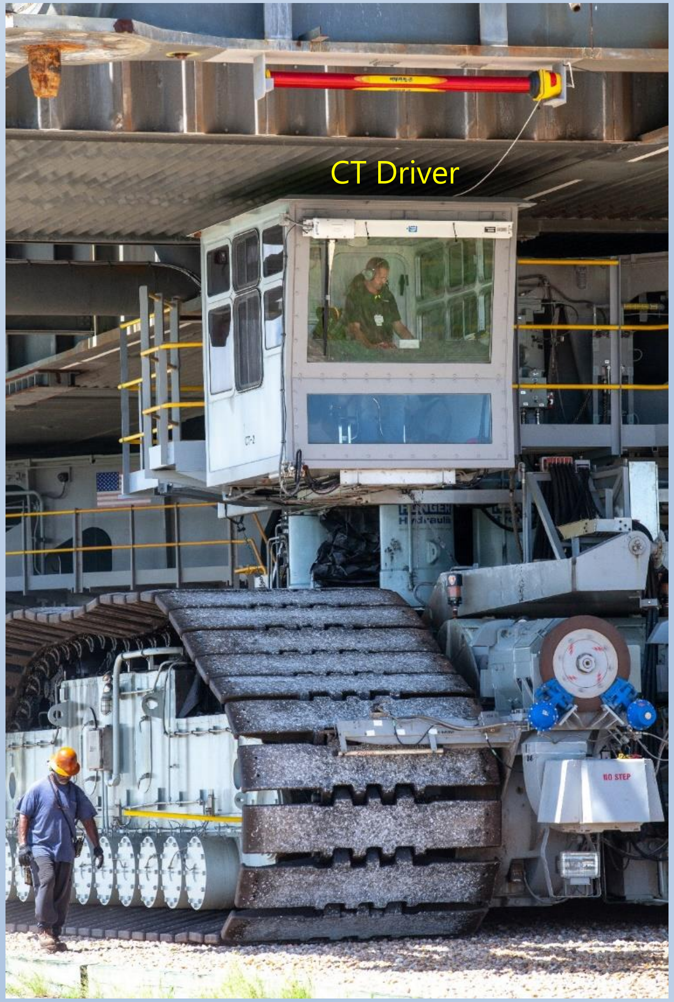




Crawler Transporter (CT)


4 Jacking, Equalizing, and Leveling (JEL) hydraulic cylinders.

Height between 20 ft – 26 ft


CT Driver

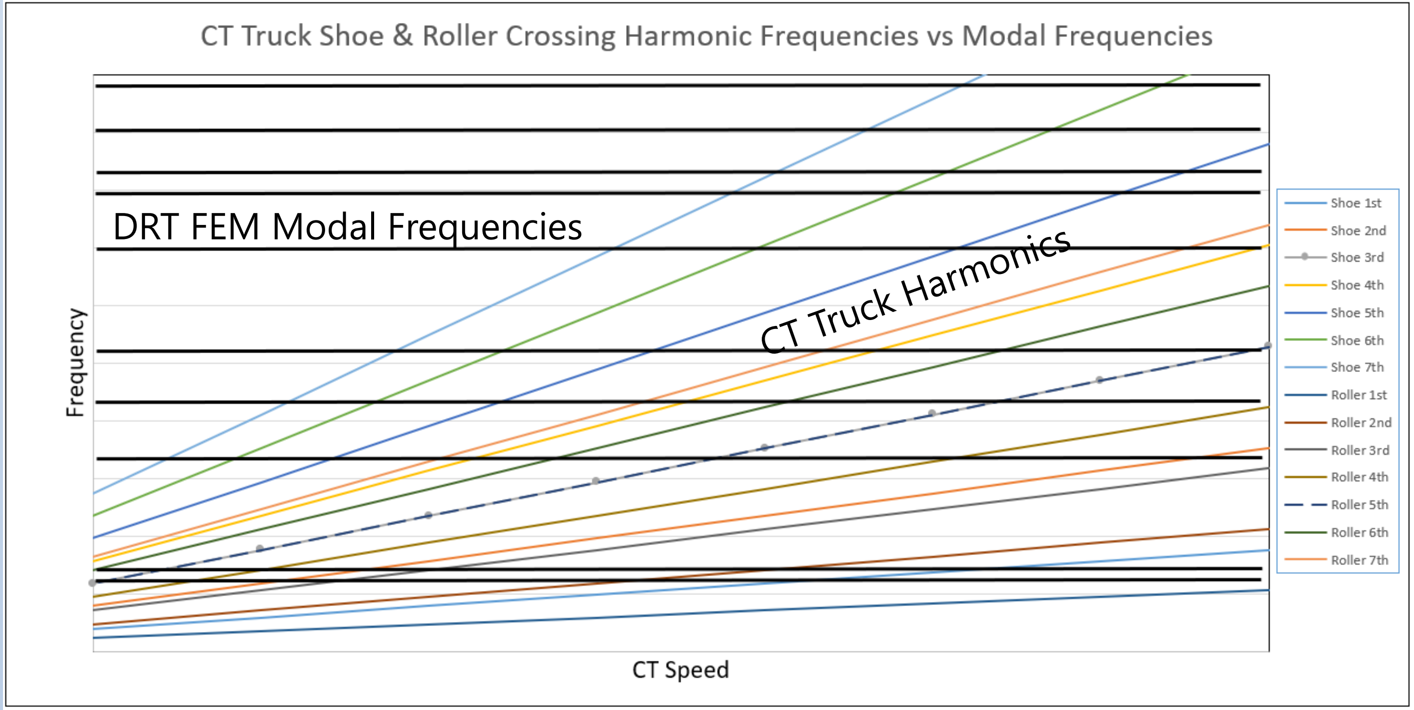
Ground Forces During Rollout & At Launch Pad 39B

- The rollout ground forces generated by the CT are the primary low frequency excitation into the ML and SLS when the CT is moving.
  - CT Truck Track Shoes contacting the ground and passing under the CT Truck rollers.

- When the CT is stopped or when the ML and the SLS integrated vehicle are sitting on the launch pad, the primary excitation consists of wind loading on the ML Tower and the SLS integrated vehicle.

CT Truck Harmonics

- A dominant CT harmonic excitation is due to the impulsive forces generated by the track shoes initial contact with the ground, “shoe slapping harmonics”. Function of CT speed and shoe spacing.
- Another dominant CT harmonic excitation is due to the impulsive forces generated when the track shoes pass underneath the 11 support rollers of each truck, “roller crossing harmonics”. Also, a function of the CT speed and the spacing between the support rollers.

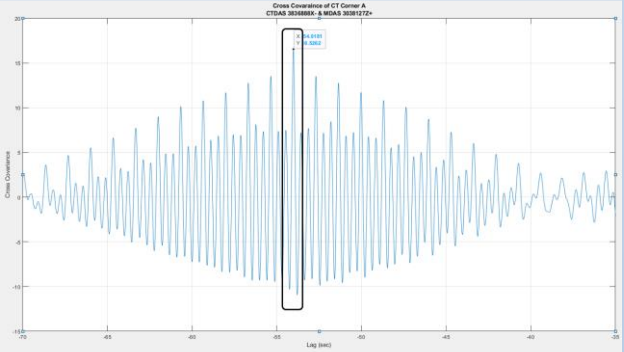

CT Truck Shoe & Roller Crossing Harmonic Frequencies vs Modal Frequencies

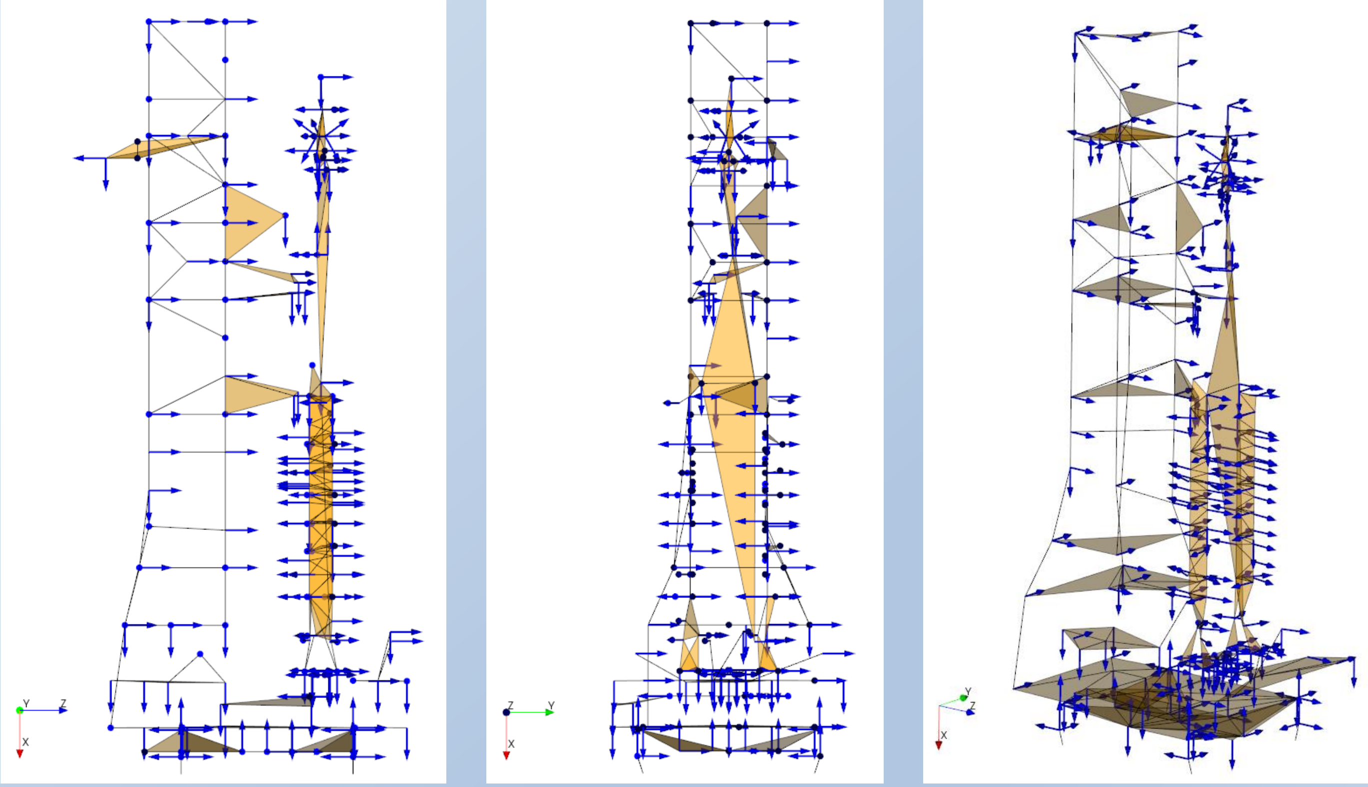
DRT and WDR OMA Challenges

- Operational Modal Analysis (OMA) assumptions:
  - Linear time invariant structure.
  - Excitation is spatially distributed, uncorrelated, stationary, broadband (i.e., no harmonics or tones).
  - Time histories have sufficient duration (i.e., ~1,000 x T).
- DRT/WDR challenges these assumptions.
  - Structure is nonlinear (e.g., Vehicle Stabilizing System and umbilicals).
  - When CT is moving the excitation is not spatially distributed (i.e., comes up from the CT), has a high density of harmonics, and not perfectly stationary.
  - When the CT is stopped, wind acting on the ML and SLS integrated vehicle, the primary excitation, which may be nonstationary. Possible vortex shedding.
  - Data duration is limited with respect to how closely spaced the modes are.

DRT Instrumentation

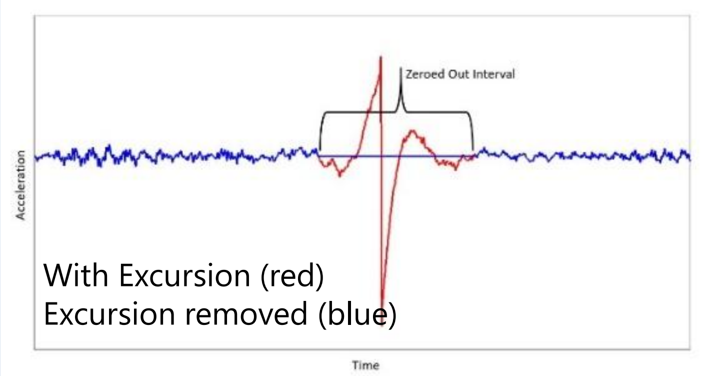
- ~ 350 low frequency highly sensitive accelerometers distributed over Artemis 1, ML, and CT.
- 4 CT JEL pressures (one in each corner).
- CT speed.
- Multiple data acquisition systems required acceleration time histories to be time synchronized post test.

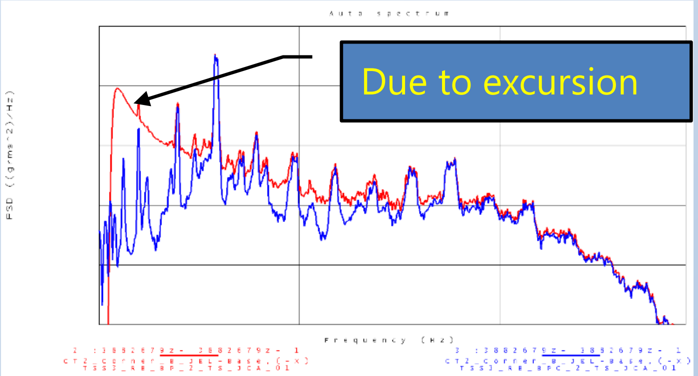


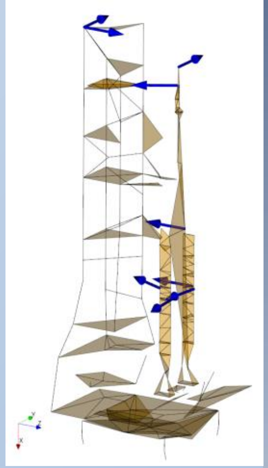


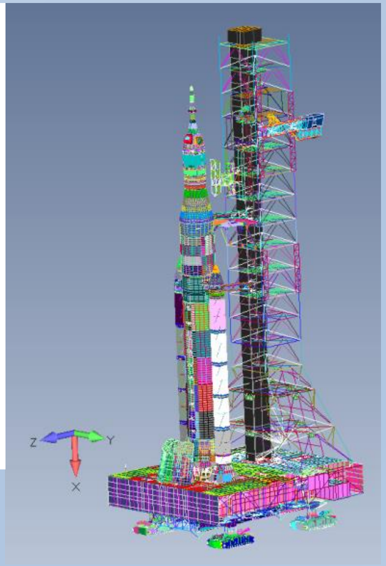
OMA Analysis I

- Finite Element Model (FEM) was tremendously helpful.
- Rigorous time-domain and frequency-domain data quality checks identified bad/questionable channels and remove spurious data effects.

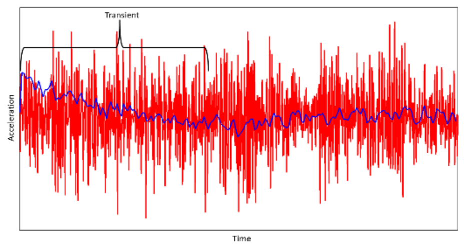








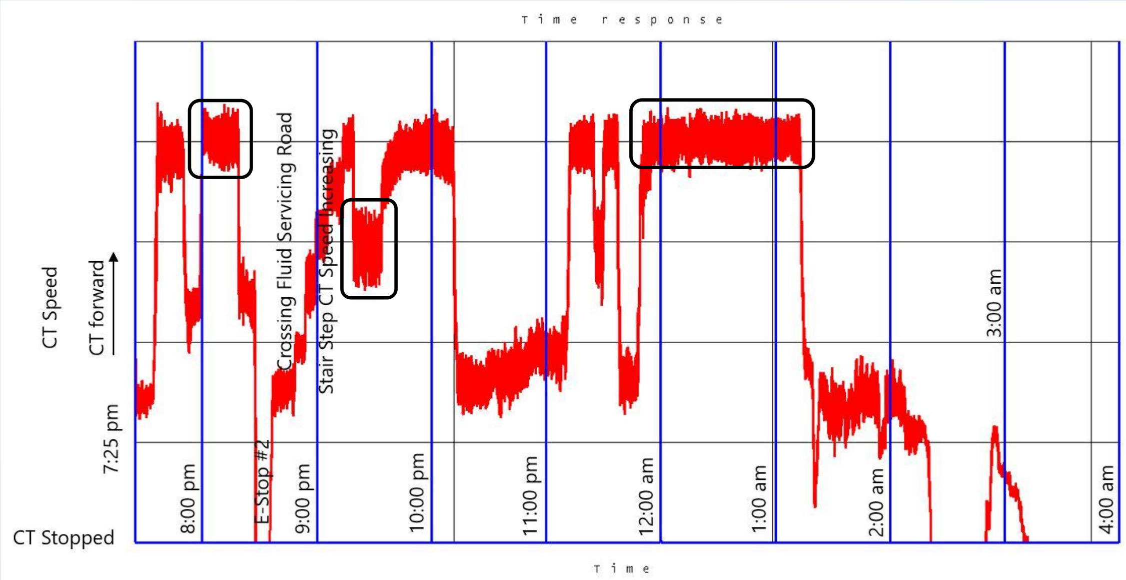
- Proper selection of projection channels is important.
- Bandpass filtered and decimated test data to only having frequency content in the range of interest is important.
  - Careful to exclude filter transients.



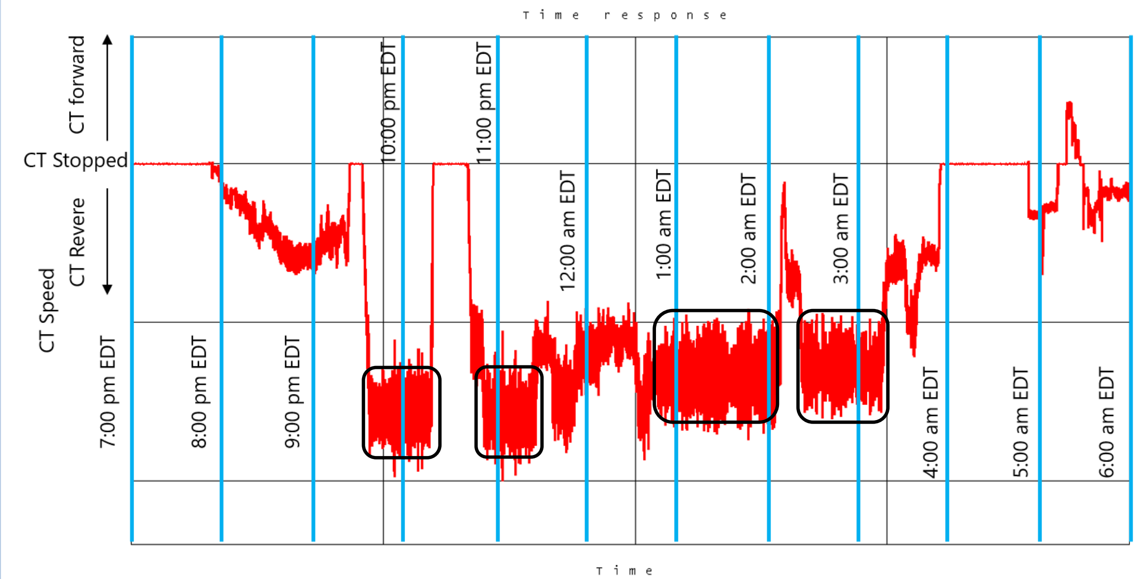
OMA Analysis I

- Modes identified from time segments with different constant CT speeds were used to identify true structural modes.
  - Helps separate modes due to CT harmonics from those due to true structural modes.
  - Nonlinearities in the Artemis I DRT configuration result in some differences in the true structural modes identified at different CT speeds.

DRT Rollout Starting on March 12, 2022



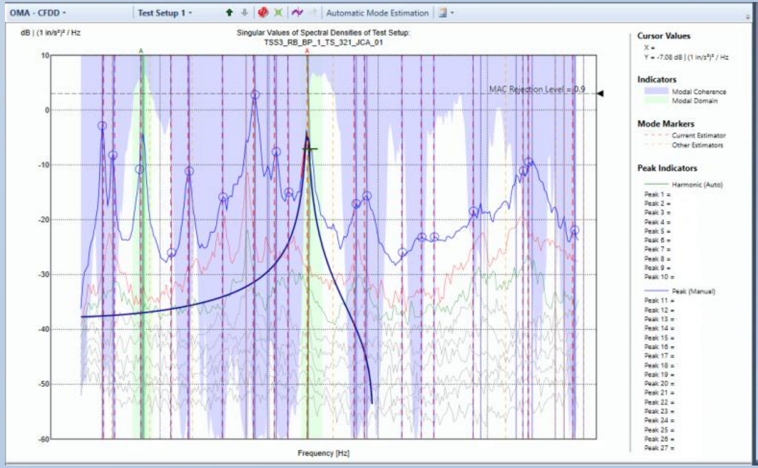
DRT Rollback Starting on April 25, 2022



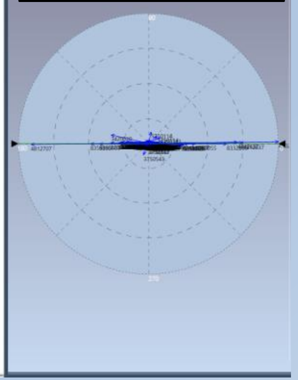
OMA Time & Frequency Domain Modal Extraction Techniques 1

- Multiple OMA techniques needed to identify all target modes.
- Started with time-domain technique (i.e., SSI-UPCX) then moved to the frequency-domain techniques in the order of Curve-Fit Frequency Domain Decomposition (CFDD), Enhanced Frequency Domain Decomposition (EFDD) and finally Frequency Domain Decomposition (FDD) to verify the modes already identified and to identify modes not already identified.
  - SSI-UPCX could not identify all modes associated with the dominant peaks in the SVD.
  - SSI-UPCX, CFDD, and EFDD techniques estimated mode shapes, modal frequency, and modal damping.
  - FDD can only estimate mode shapes and modal frequency.

Frequency-domain: Curve-Fit Frequency Domain Decomposition Method (CFDD)

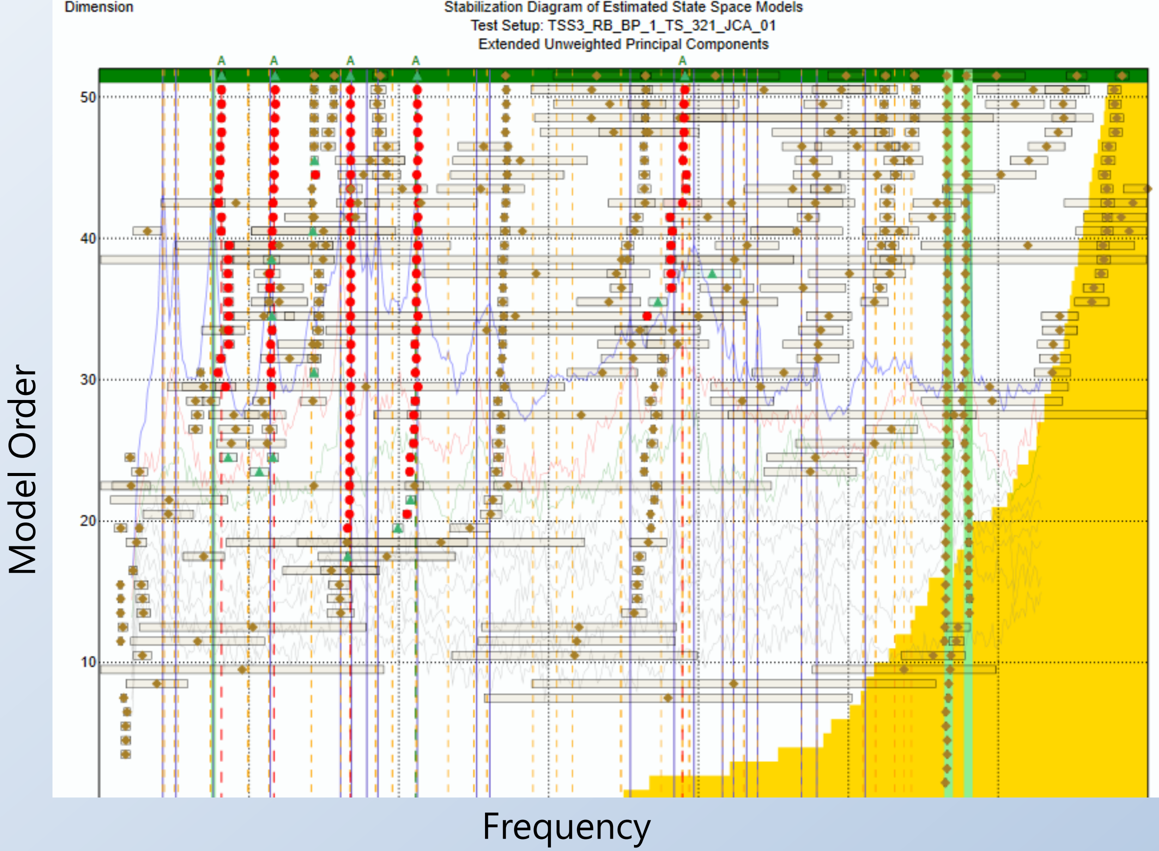


Phase Rotation Normalized Complex Mode Shape

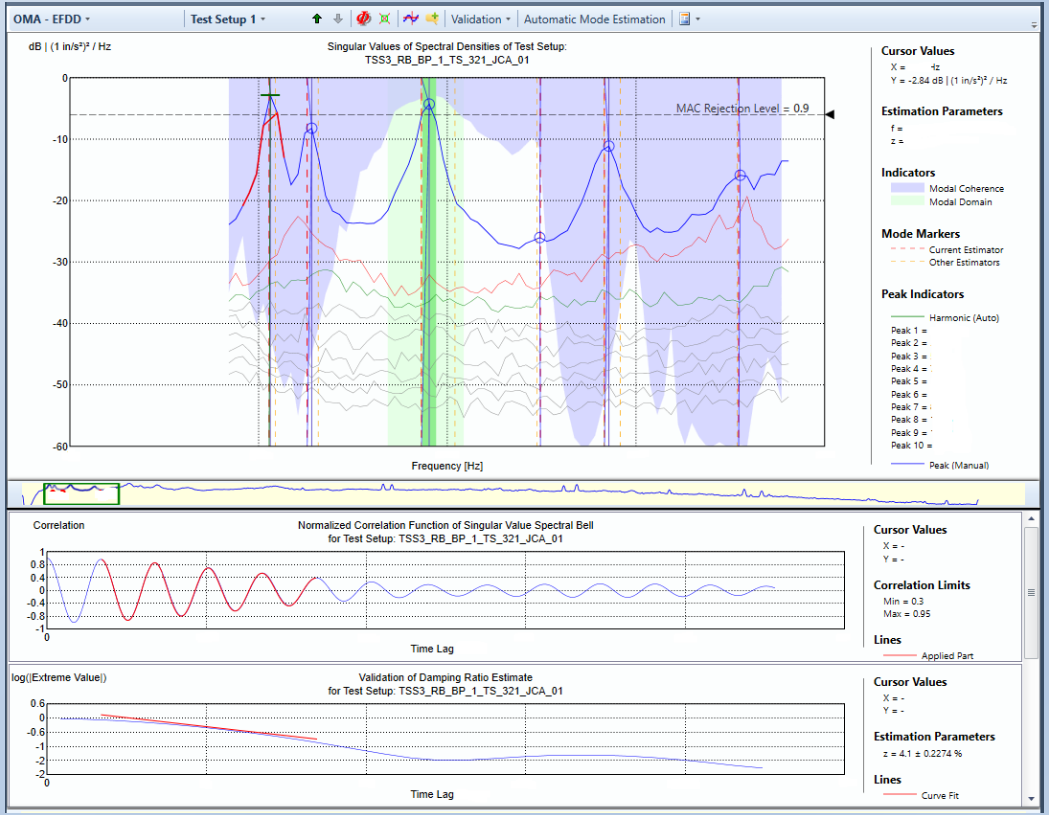


OMA Time & Frequency Domain Modal Extraction Techniques 2

Time-domain: Subspace Identification Extended Unweighted Principal Component Method (SSI-UPCX)

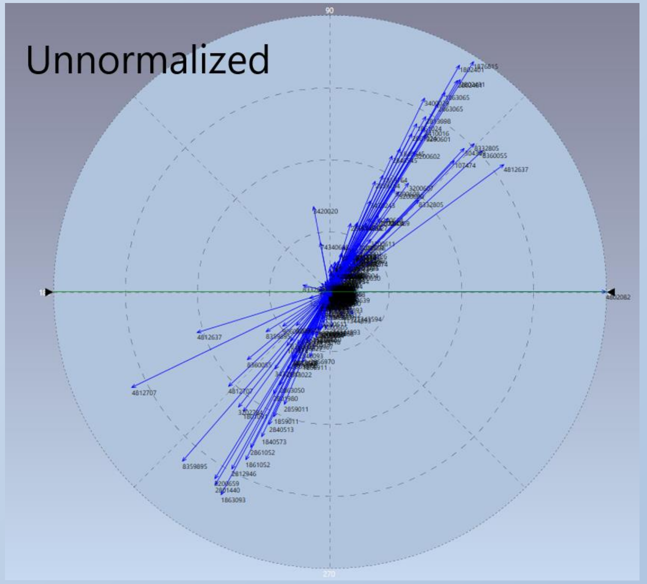


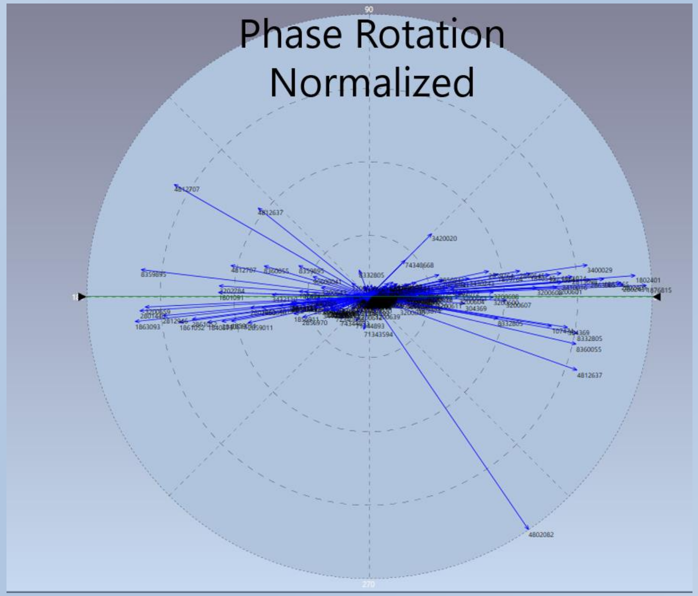
Frequency-domain: Extended Frequency Domain Decomposition Method (EFDD)



Complex Valued To Real Valued Mode Shape Conversion

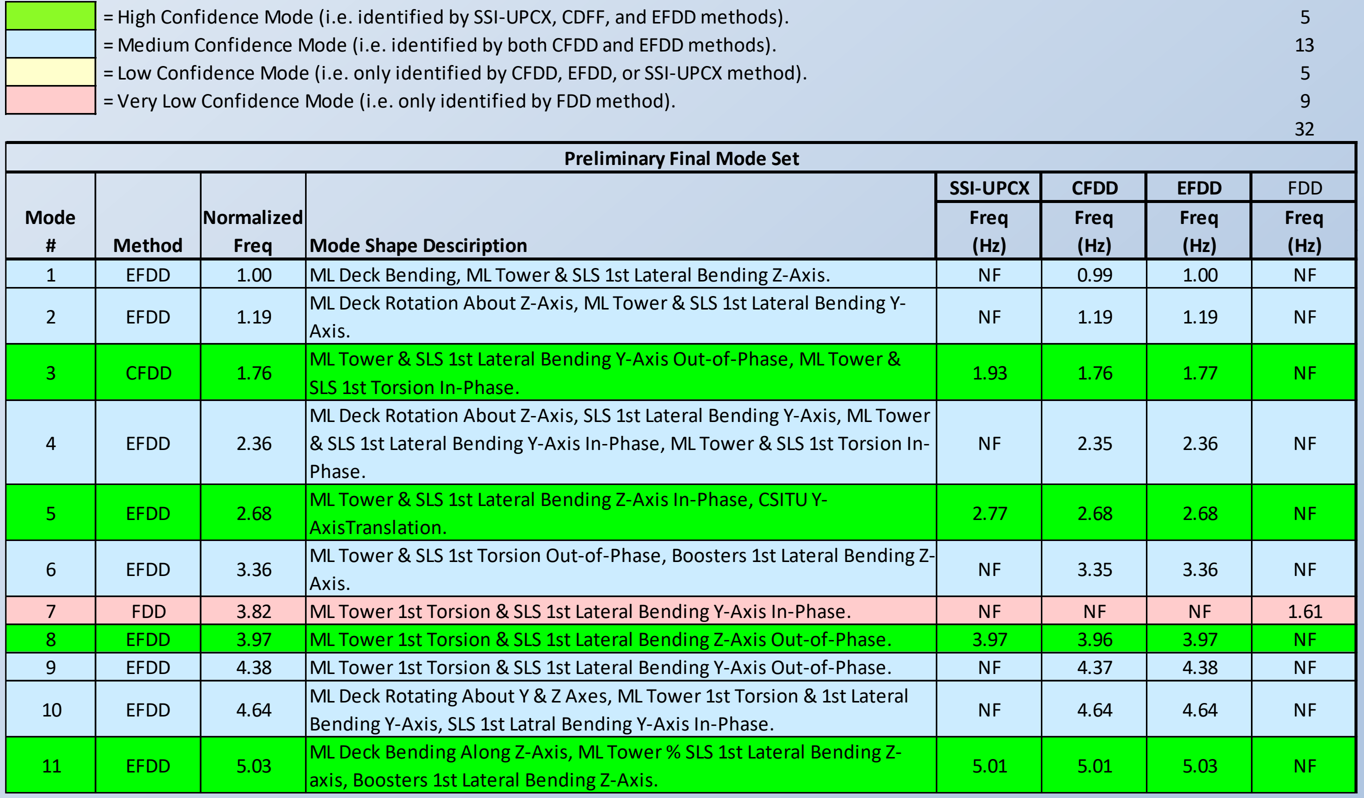
- Care needs to be exercised in this conversion process.
  - Want the real valued mode shapes to retain the dominant characteristics of the complex valued mode shapes.
  - Phase Rotation normalization used to rotate the complex valued mode shape coefficients to "best" lie on the real axis.
  - Real portion taken for the real valued mode shape coefficients.





DRT Rollback CT Stopped Identified Modes

- Computed cross-orthogonalities between the real-valued modes extracted from the OMA techniques.
- Higher confidence in modes identified with larger number of techniques.



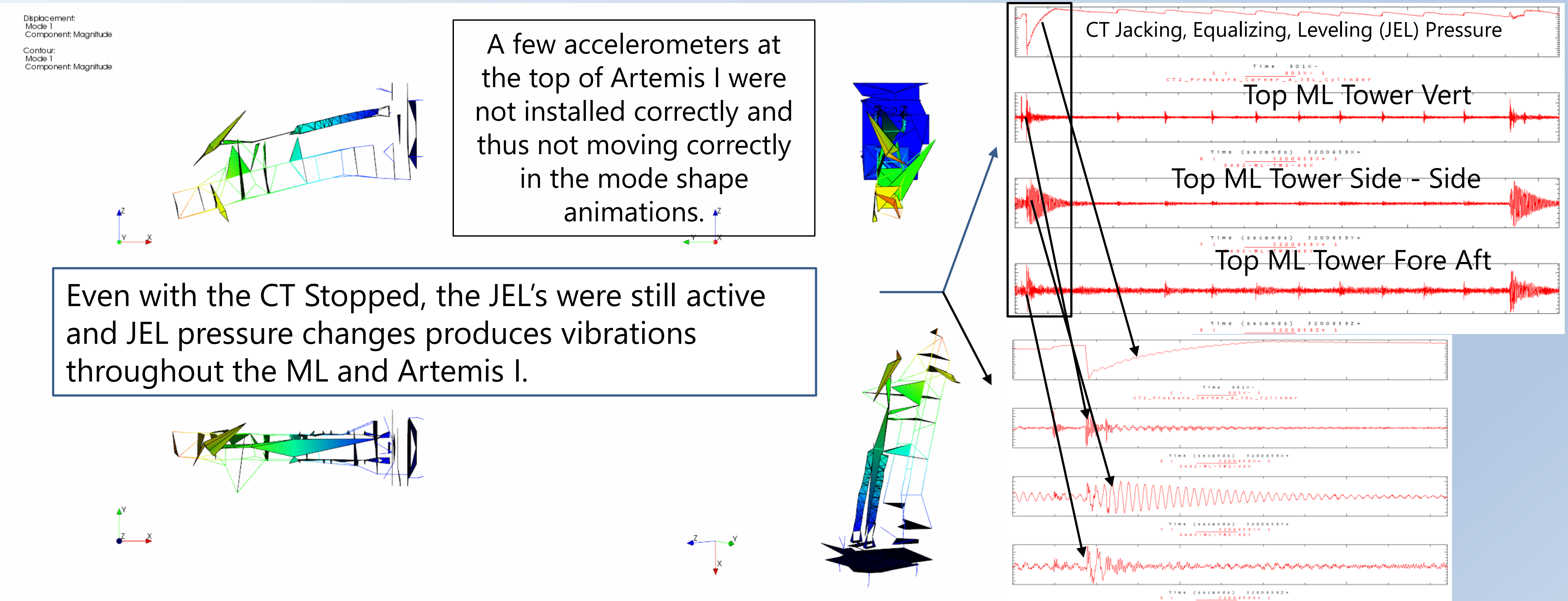
🟩	= High Confidence Mode (i.e. identified by SSI-UPCX, CDFF, and EFDD methods).	5
🟦	= Medium Confidence Mode (i.e. identified by both CFDD and EFDD methods).	13
🟨	= Low Confidence Mode (i.e. only identified by CFDD, EFDD, or SSI-UPCX method).	5
🟥	= Very Low Confidence Mode (i.e. only identified by FDD method).	9
		32

Preliminary Final Mode Set

Mode #	Method	Normalized Freq	Mode Shape Desciription	SSI-UPCX Freq (Hz)	CFDD Freq (Hz)	EFDD Freq (Hz)	FDD Freq (Hz)
1	EFDD	1.00	ML Deck Bending, ML Tower & SLS 1st Lateral Bending Z-Axis.	NF	0.99	1.00	NF
2	EFDD	1.19	ML Deck Rotation About Z-Axis, ML Tower & SLS 1st Lateral Bending Y-Axis.	NF	1.19	1.19	NF
3	CFDD	1.76	ML Tower & SLS 1st Lateral Bending Y-Axis Out-of-Phase, ML Tower & SLS 1st Torsion In-Phase.	1.93	1.76	1.77	NF
4	EFDD	2.36	ML Deck Rotation About Z-Axis, SLS 1st Lateral Bending Y-Axis, ML Tower & SLS 1st Lateral Bending Y-Axis In-Phase, ML Tower & SLS 1st Torsion In-Phase.	NF	2.35	2.36	NF
5	EFDD	2.68	ML Tower & SLS 1st Lateral Bending Z-Axis In-Phase, CSITU Y-AxisTranslation.	2.77	2.68	2.68	NF
6	EFDD	3.36	ML Tower & SLS 1st Torsion Out-of-Phase, Boosters 1st Lateral Bending Z-Axis.	NF	3.35	3.36	NF
7	FDD	3.82	ML Tower 1st Torsion & SLS 1st Lateral Bending Y-Axis In-Phase.	NF	NF	NF	1.61
8	EFDD	3.97	ML Tower 1st Torsion & SLS 1st Lateral Bending Z-Axis Out-of-Phase.	3.97	3.96	3.97	NF
9	EFDD	4.38	ML Tower 1st Torsion & SLS 1st Lateral Bending Y-Axis Out-of-Phase.	NF	4.37	4.38	NF
10	EFDD	4.64	ML Deck Rotating About Y & Z Axes, ML Tower 1st Torsion & 1st Lateral Bending Y-Axis, SLS 1st Latral Bending Y-Axis In-Phase.	NF	4.64	4.64	NF
11	EFDD	5.03	ML Deck Bending Along Z-Axis, ML Tower % SLS 1st Lateral Bending Z-axis, Boosters 1st Lateral Bending Z-Axis.	5.01	5.01	5.03	NF

DRT Rollback CT Stopped Modes (cont)

- Mode #1: ML Deck Bending, ML Tower & SLS 1st Lateral Bending Z-Axis.

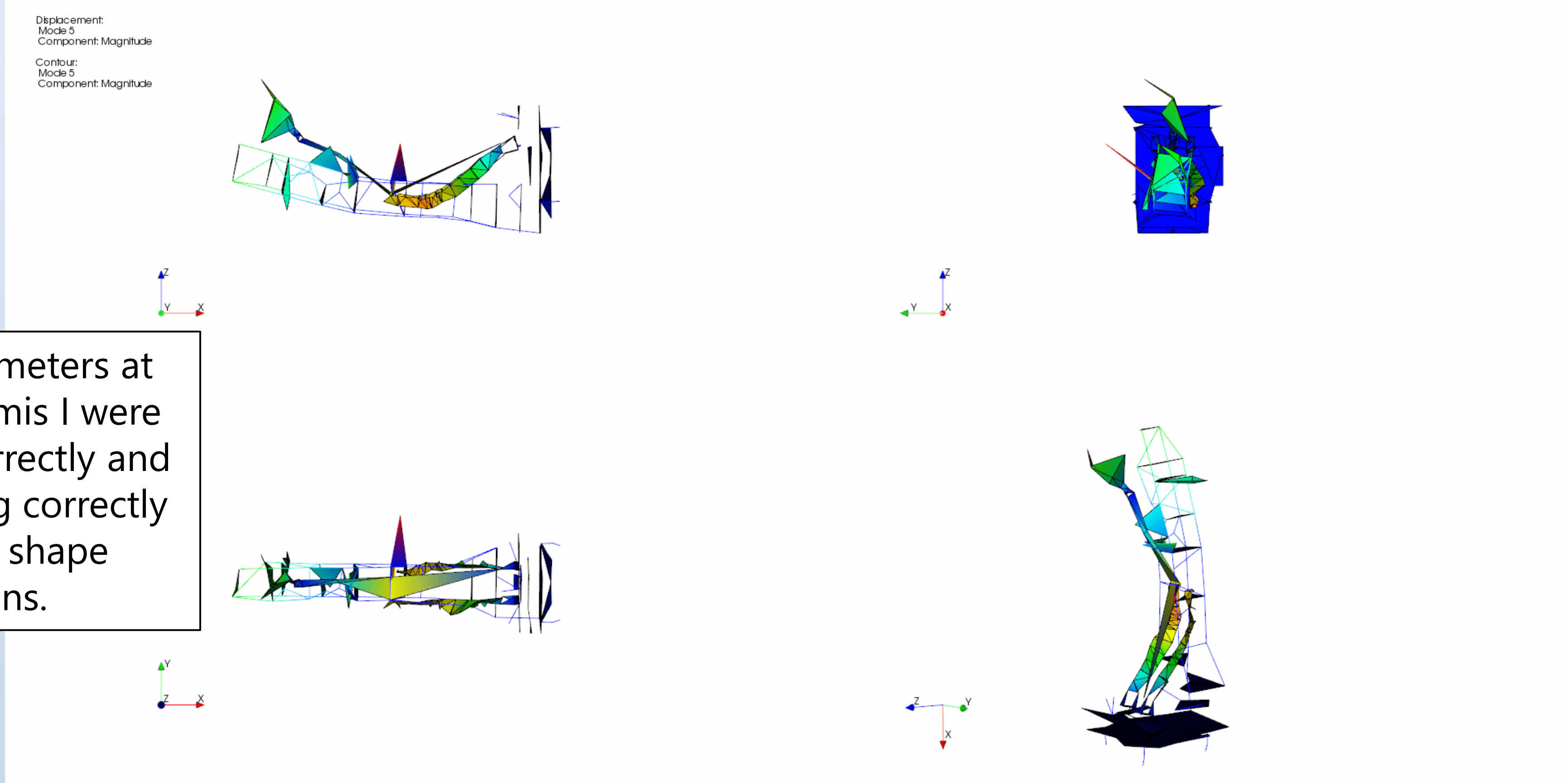


A few accelerometers at the top of Artemis I were not installed correctly and thus not moving correctly in the mode shape animations.

Even with the CT Stopped, the JEL's were still active and JEL pressure changes produces vibrations throughout the ML and Artemis I.

DRT Rollback CT Stopped Modes (cont)

- Mode #5: ML Tower & SLS 1st Lateral Bending Z-Axis In-Phase, Core Stage Intertank Umbilical (CSIT) Y-Axis Translation.



A few accelerometers at the top of Artemis I were not installed correctly and thus not moving correctly in the mode shape animations.

DRT Rollback CT Stopped Test Modes Self ORTHO

Test Self Orthogonality Table

Test Shapes

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Ott	**Test Shapes**		1.00	1.19	1.76	2.36	2.68	3.36	3.82	3.97	4.38	4.64	5.02	5.52	5.93	6.14	6.86	7.48	8.25	8.88	9.22	9.34	9.85	10.02	10.19	10.19	10.41	11.10	11.34	12.09	12.28	12.57	12.71	12.83
100	1	1.00	100				11						7	7	5			5																
95	2	1.19		100	13									6				5				5		6										
90	3	1.76		13	100	40			8		7	8																						6
85	4	2.36			40	100	69	13	11			15	7	19	19	8	23	18	24	15	13	9		6	9	7		6			7	11		5
80	5	2.68	11			69	100	7				9	6																					
75	6	3.36				13	7	100	9	16		9		12	6	7	7	7	11		7	10	12	13	10		7							
70	7	3.82			8	11		9	100		17	7							6	11	21	22	15	24	21		9							
65	8	3.97						16		100	13	14		13					9	8	15	20	18	25	23		7		8					5
60	9	4.38			7				17	13	100	58	13				8			17	27	25	18	28	28	5	25							
55	10	4.64			8	15	9	9	7	14	58	100	57	13	17	17	11	8	18	19	26	24	11	20	31	14	21	5				6	6	
50	11	5.02	7			7	6				13	57	100	67	8		10				10	15	18	17	18		17		6					
45	12	5.52	7	6		19		12		13		13	67	100	51	39	33	12	33	22	7	5	26	10		20	15	9	10	6	10	12	5	5
40	13	5.93	5			19		6				17	8	51	100	53	13	10	5		7		8	5	6									7
35	14	6.14				8		7				17		39	53	100	42	28	12	18	11			6	7	6	8			7				
30	15	6.86				23		7			8	11	10	33	13	42	100	21	57	43	25	8	23	7	21	39		15	16	12	12	15	16	6
25	16	7.48	5	5		18		7				8		12	10	28	21	100	74	25	13		17		13	27	6	10	9	9		7		
20	17	8.25				24		11	6	9		18		33	5	12	57	74	100	20	5	7	31	7	11	47		11	16				10	5
15	18	8.88				15			11	8	17	19		22		18	43	25	20	100	67	42		45	60	55	19	7	9				9	
10	19	9.22				13		7	21	15	27	26	10	7	7	11	25	13	5	67	100	80	34	84	91	42	29		10				7	5
5	20	9.34		5		9		10	22	20	25	24	15	5			8		7	42	80	100	57	89	82	15	48		9					
0	21	9.85						12	15	18	18	11	18	26	8		23	17	31		34	57	100	68	33	48	35				5		6	
	22	10.02		6		6		13	24	25	28	20	17	10	5	6	7		7	45	84	89	68	100	87	16	39		13	6	8	6		
	23	10.19				9		10	21	23	28	31	18		6	7	21	13	11	60	91	82	33	87	100	51	36	6			11	9		6
	24	10.19				7					5	14		20		6	39	27	47	55	42	15	48	16	51	100	6	24	8	21	28	26	5	8
	25	10.41						7	9	7	25	21	17	15		8		6		19	29	48	35	39	36	6	100	8	22	7			8	5
	26	11.10				6						5		9			15	10	11	7					6	24	8	100	39		5		8	
	27	11.34								8			6	10			16	9	16	9	10	9		13		8	22	39	100	7	18	16		
	28	12.09												6		7	12	9						6		21	7		7	100	30	43	23	17
	29	12.28				7								10			12						5	8	11	28		5	18	30	100	86	40	
	30	12.57				11						6		12			15	7						6	9	26			16	43	86	100	61	12
	31	12.71										6		5			16		10	9	7		6			5	8	8		23	40	61	100	61
	32	12.83			6	5				5				5	7		6		5		5				6	8	5			17		12	61	100

DRT Rollback CT Stopped Test vs FEM Modes XORTHO

FEM/Test Cross Orthogonality Table

FEM Shapes

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Otg	**Test Shapes**		1.02	1.22	1.54	1.87	2.12	2.12	2.12	2.12	3.12	3.22	3.56	3.77	3.86	4.61	4.67	5.09	5.40	5.44	5.67	6.12	6.67	6.78
100	1	1.00	98																					
95	2	1.19		99			34																	
90	3	1.76			97		80																	
85	4	2.36			38	63	33	68	67	68		32												
80	5	2.68				89		97	98	98		38												
75	6	3.36						20			94	23												
70	7	3.82					54						96											
65	8	3.97				31						85				33								
60	9	4.38					22							92										
55	10	4.64				20								59		26	53		24					
50	11	5.02				20						21		23		83				32				
45	12	5.52										25				42				56	38			
40	13	5.93																	25	28	90			
35	14	6.14														23			35	81	24			
30	15	6.86																		20				
25	16	7.48																		21				

MPCV Orion Service Module Slosh Modes (4 Tanks)

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq Pct Diff	Cross Ortho	CRSS XOrtho 3%	CRSS XOrtho All	90 - 100 50 - 89 0 - 49
1	1	1.00	1.02	1.7	98	98	99	
2	2	1.19	1.22	2.1	99	99	100	
3	3	1.76	1.54	-12.7	97	97	100	
4	8	2.36	2.12	-10.2	68	77	96	
5	7	2.68	2.12	-20.9	98	98	100	
6	9	3.36	3.12	-6.9	94	94	100	
7	11	3.82	3.56	-6.6	96	96	100	
8	10	3.97	3.22	-18.8	85	85	100	
9	12	4.38	3.77	-13.8	92	92	99	
10	12	4.64	3.77	-18.7	59	59	99	
11	14	5.02	4.61	-8.2	83	84	99	
12	18	5.52	5.44	-1.3	56	56	98	
13	19	5.93	5.67	-4.3	90	90	100	
14	18	6.14	5.44	-11.3	81	83	99	
15	28	6.86	7.77	13.3	51	52	98	
16	31	7.48	8.81	17.8	49	49	98	
17	28	8.25	7.77	-5.8	74	78	99	
18	31	8.88	8.81	-0.8	80	80	99	
19	22	9.22	6.78	-26.5	50	73	99	
20	25	9.34	7.30	-21.8	57	59	100	
21	32	9.85	9.49	-3.6	54	54	99	
22	22	10.02	6.78	-32.4	46	66	99	

Conclusions 1

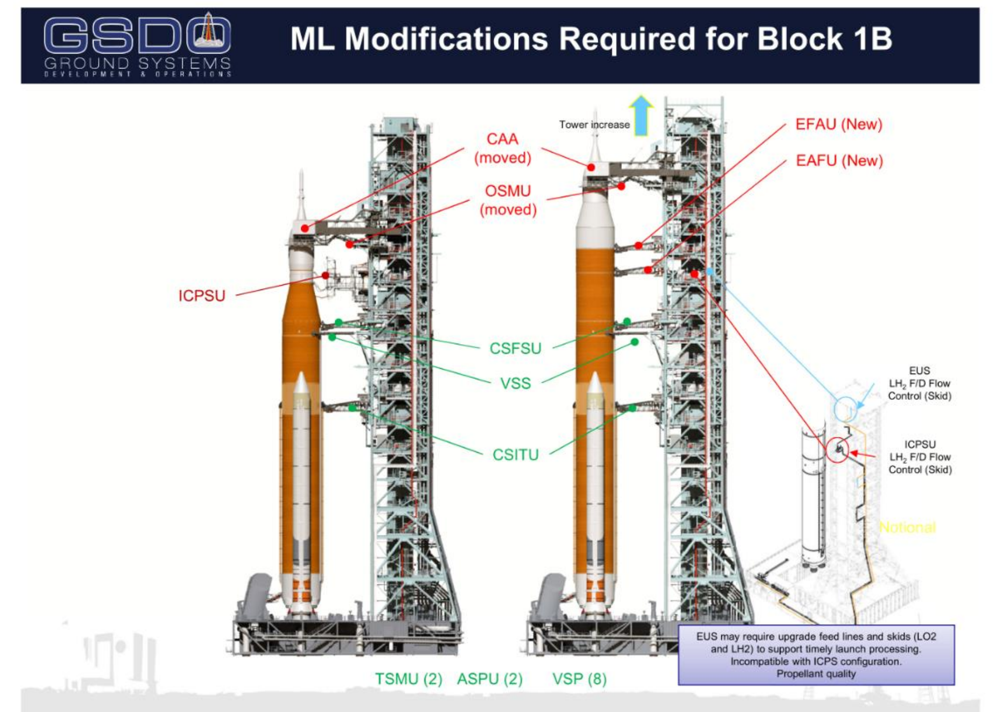
- OMA techniques successfully identified Artemis I DRT and WDR FEM target modes.
- CT harmonics lie within the frequency range of the fundamental target modes and continue to be a significant challenge when applying OMA techniques to rollout data.
- The Artemis I DRT and WDR configurations exhibited nonlinear behavior.
  - Modal parameters dependent upon CT speed and ground wind speed.
- OMA techniques will not replace traditional modal testing.
  - Provides important supplemental information and insights into the structural dynamics of hardware in its operational environment.
- Proper selection of Projection Channels is very important.

Conclusions 2

- Having a FEM, its predicted modal frequencies and mode shapes, and the associated Test Analysis Model (TAM) are tremendously helpful.
  - Helps focus the OMA Analysis.
  - Allows cross-orthogonalities for judging the similarity between FEM and test shapes.
  - Back expansion of test mode shapes to all three translational DOF at each accelerometer location (i.e., TDM grid point) facilitates visual interpretation.
- Effectiveness of OMA techniques is highly dependent on rollout data quality.
  - Time-domain and frequency-domain data quality checks and “correcting” “bad” or “corrupted” acceleration time histories prior to starting an OMA analysis are critical.

Forward Work

- Perform OMA analysis on data acquired on ML-2 as it is built up and when it is transported by the CT and to help inform and preliminarily “tune” its FEM.
  - Building block approach.
  - Artemis IV will use the larger and more powerful SLS Block 1B launch vehicle, which will require the larger and heavier ML-2 to support it.
  - It is expected that the OMA analysis of the Artemis IV rollout configuration will therefore be more challenging due to both the larger physical sizes, lower frequencies of fundamental modes, and higher modal densities.



ML Modifications Required for Block 1B

EUS may require upgrade feed lines and skids (LO2 and LH2) to support timely launch processing. Incompatible with ICPS configuration. Propellant quality

End