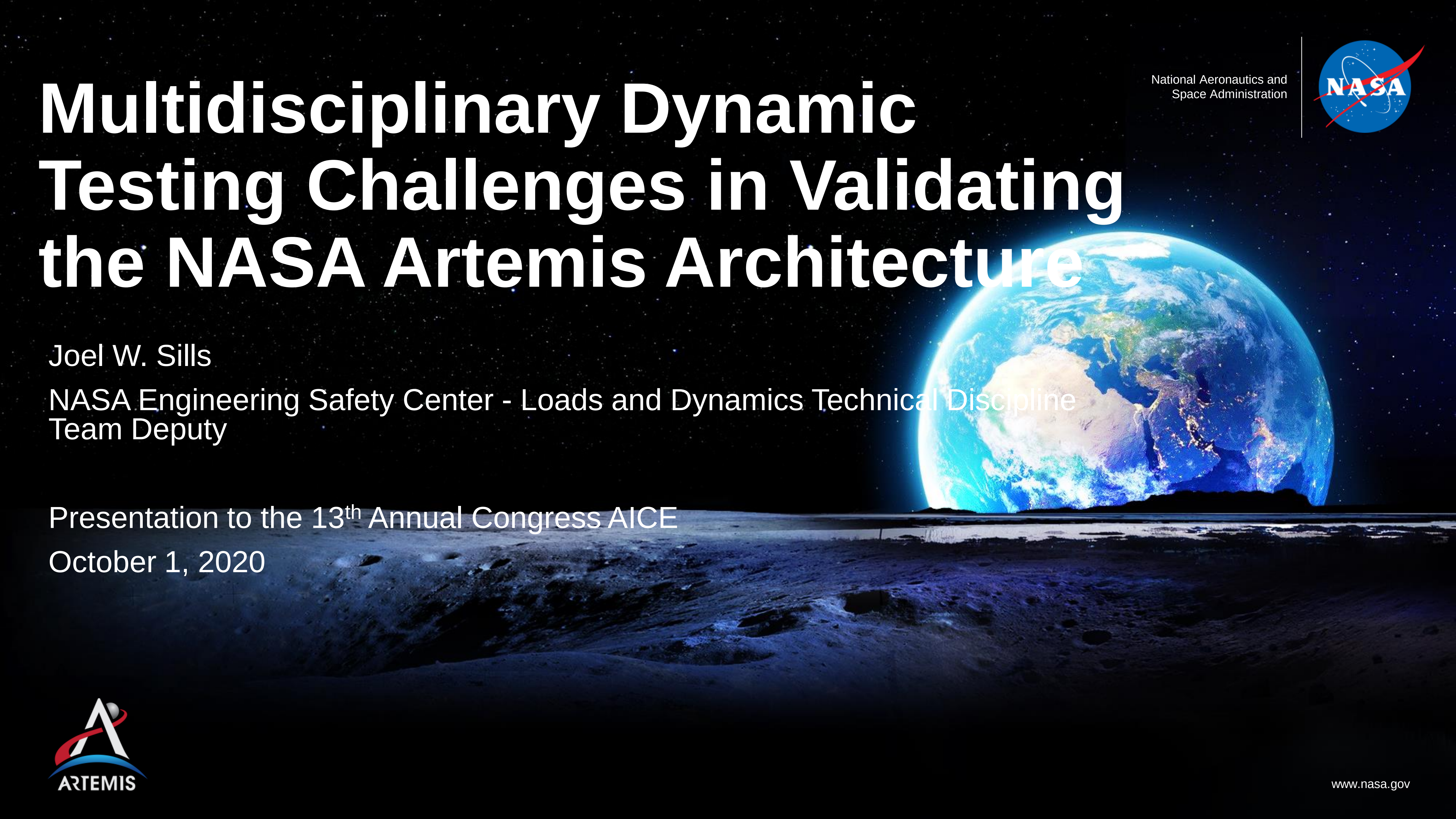


National Aeronautics and
Space Administration

Multidisciplinary Dynamic Testing Challenges in Validating the NASA Artemis Architecture

Joel W. Sills

NASA Engineering Safety Center - Loads and Dynamics Technical Discipline Team Deputy

Presentation to the 13th Annual Congress AICE

October 1, 2020

An Introduction to the NASA Engineering Safety Center (NESC)

NESC Background and Mission

Space Shuttle

International Space Station

Exploration

- NESC was established in July 2003 in response to the Columbia accident
- NESC highlights NASA’s traditional safety philosophy:
  - *Strong in-line checks and balances*
  - *Healthy tension between organizational elements*
  - *Value-added independent assessment*
- NESC provides independent assessment of technical issues for NASA programs and projects

NESC is cultivating a Safety culture focused on ***engineering and technical excellence***, while fostering an ***open environment*** and attacking challenges with ***unequalled tenacity***

NESC Model

- Institutionalized “Tiger Team” approach to solving problems
- Agency-recognized NASA Technical Fellows lead Technical Discipline Teams (TDT)
    - *“Ready” experts from across NASA, industry, academia and other agencies*
    - *Diverse, expert technical teams provide robust technical solutions*
- Assemble independent, diverse, expert technical teams that provide robust technical solutions to the Agency’s highest-risk and most complex issues
    - *NESC involvement ranges from supporting reviews, augmenting project teams, and solving problems through independent test and analysis, to exploring alternate design concepts*
- Strong Systems Engineering and Integration function for proactive trending and identification of problem areas before failures occur

Artist Concept of Orion, Space Launch System (SLS), and Mobile Launcher (ML) Rolling Out of VAB

Focus on technical rigor and engineering excellence

EXPLORE
MOON to MARS

An Introduction to Artemis

We Are Going to the Moon

https://www.youtube.com/watch?v=vl6jn-DdafM

Why go to The Moon?

Proves technologies and capabilities for sending humans to Mars

Establishes American leadership and strategic presence

Inspires a new generation and encourages careers in STEM

Leads civilization changing science and technology

Expands the U.S. global economic impact

Broadens U.S. industry and international partnerships in deep space

Moon Before Mars

On the Moon, we can take reasonable risks while astronauts are just three days away from home.

There we will prove technologies and mature systems necessary to live and work on another world before embarking on what could be a 2-3 year mission to Mars.

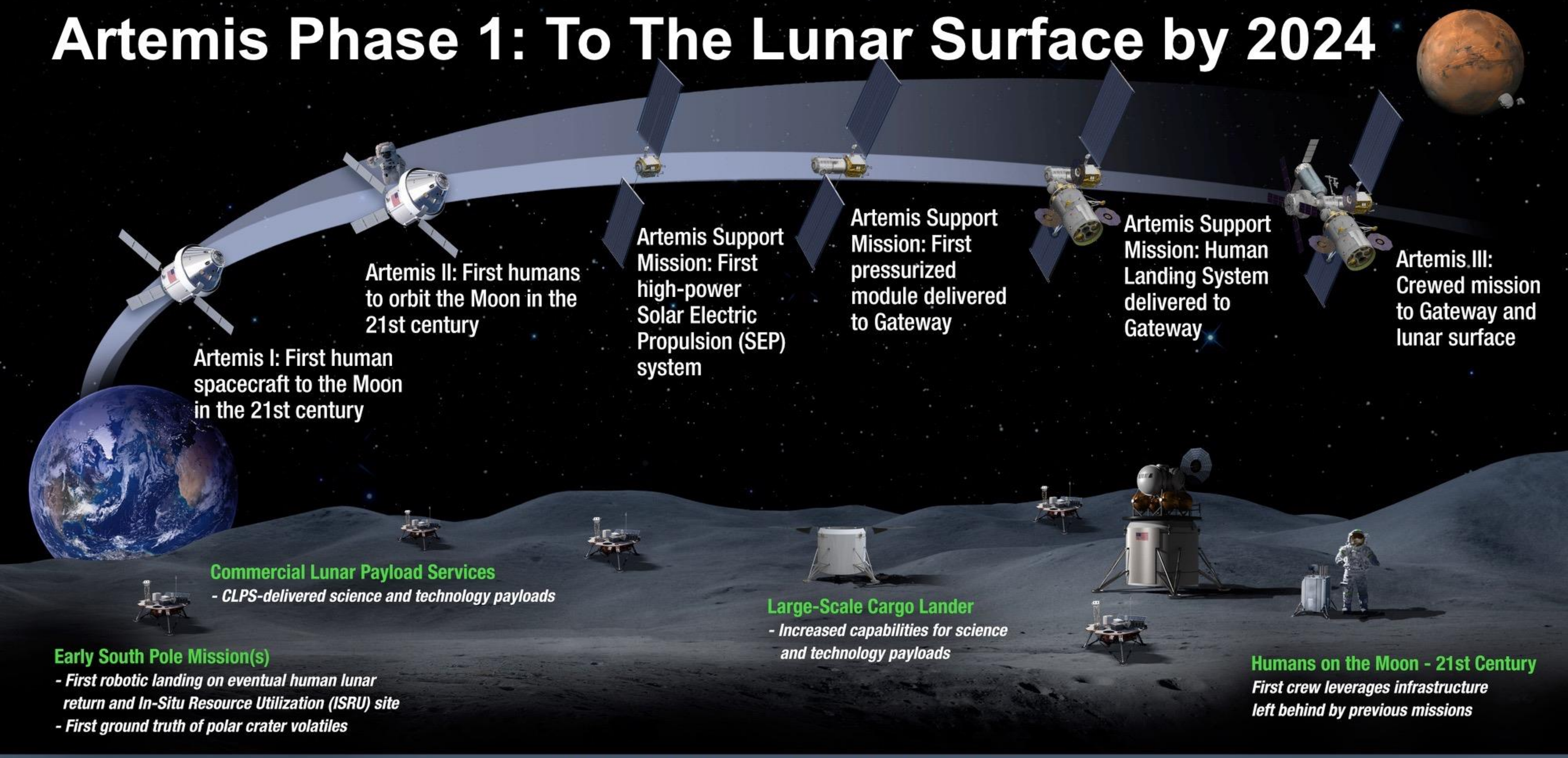
The Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies our path to the Moon as the name of NASA’s program to return astronauts to the lunar surface by 2024.

When they land, Artemis astronauts will step foot where no human has ever been before: the Moon’s South Pole.

With the horizon goal of sending humans to Mars, Artemis begins the next era of exploration.

Artemis Phase 1: To The Lunar Surface by 2024



Artemis I: First human spacecraft to the Moon in the 21st century

Artemis II: First humans to orbit the Moon in the 21st century

Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system

Artemis Support Mission: First pressurized module delivered to Gateway

Artemis Support Mission: Human Landing System delivered to Gateway

Artemis III: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services

- CLPS-delivered science and technology payloads

Early South Pole Mission(s)

- First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site

- First ground truth of polar crater volatiles

Large-Scale Cargo Lander

- Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century

First crew leverages infrastructure left behind by previous missions

LUNAR SOUTH POLE TARGET SITE

2020 2024

Technology Drives Exploration

Reference: https://www.youtube.com/watch?v=wJ0ia4M2dxs

Overarching Challenges – What are Key Drivers?

- **The Artemis mission architecture presents unprecedented and competing technical and programmatic challenges ahead that inherently increased mission risk compared to low Earth orbit (LEO) mission**
  - Mission complexities (e.g., lunar orbit operations, multiple docking events, multiple elements, multiple launch vehicles, etc.)
  - Hazards and critical failure modes
  - Distance from Earth-time to get home
  - Unprecedented mass and volume constraints
  - Budget and schedule constraints, and the new 2024 Human Lunar Landing timeline

- **The distance from Earth, especially in a Mars class missions presents a challenge for safe haven capability**
  - Partially offset in the lunar architecture with some flexibility offered by the combination of Gateway
  - Orion and the human landing system ascent vehicles all providing crew habitable capabilities for a safe haven
- **Mass of spacecraft and systems can significantly drive launch vehicle performance requirements, or conversely, realistic launch vehicle performance capabilities will significantly constrain spacecraft mass**

There is a need for high reliability in systems and in processes, and a need to better understand and reduce uncertainties while increasing margins, to deal with unknowns in order to achieve the necessary robustness for this bold endeavor

What are the technical needs driven by the ARTEMIS Missions? (1 of 2)

- **A design philosophy of simplicity is required**

  “Complications arose, ensued, were overcome.” – Captain Jack Sparrow, Pirates of the Caribbean: Dead Man’s Chest

- **It begins with a system engineering process:**
  - Utilize top down functional allocation considering other systems to provide capabilities and control hazards before adding component or system level redundancy with associated increase in mass and complexity
- **Quantifying margin is necessary and important, but current design approaches use “factors of safety” and “uncertainty factors” that may be sequentially applied by multiple teams**
  - This approach stacks conservatism, inefficiencies and manifests itself in system cost growth
  - Appropriate factors for new technologies (e.g., components produces with additive manufacturing, composites, etc.) are less known?, so using existing factors may not be conservative nor appropriate
  - Verification and validation testing is expensive and has no consistent quantified metric across the Agency
  - Many probabilistic tools exist but best practices for their use and implementation in design and operations is lacking maturity and a standard process

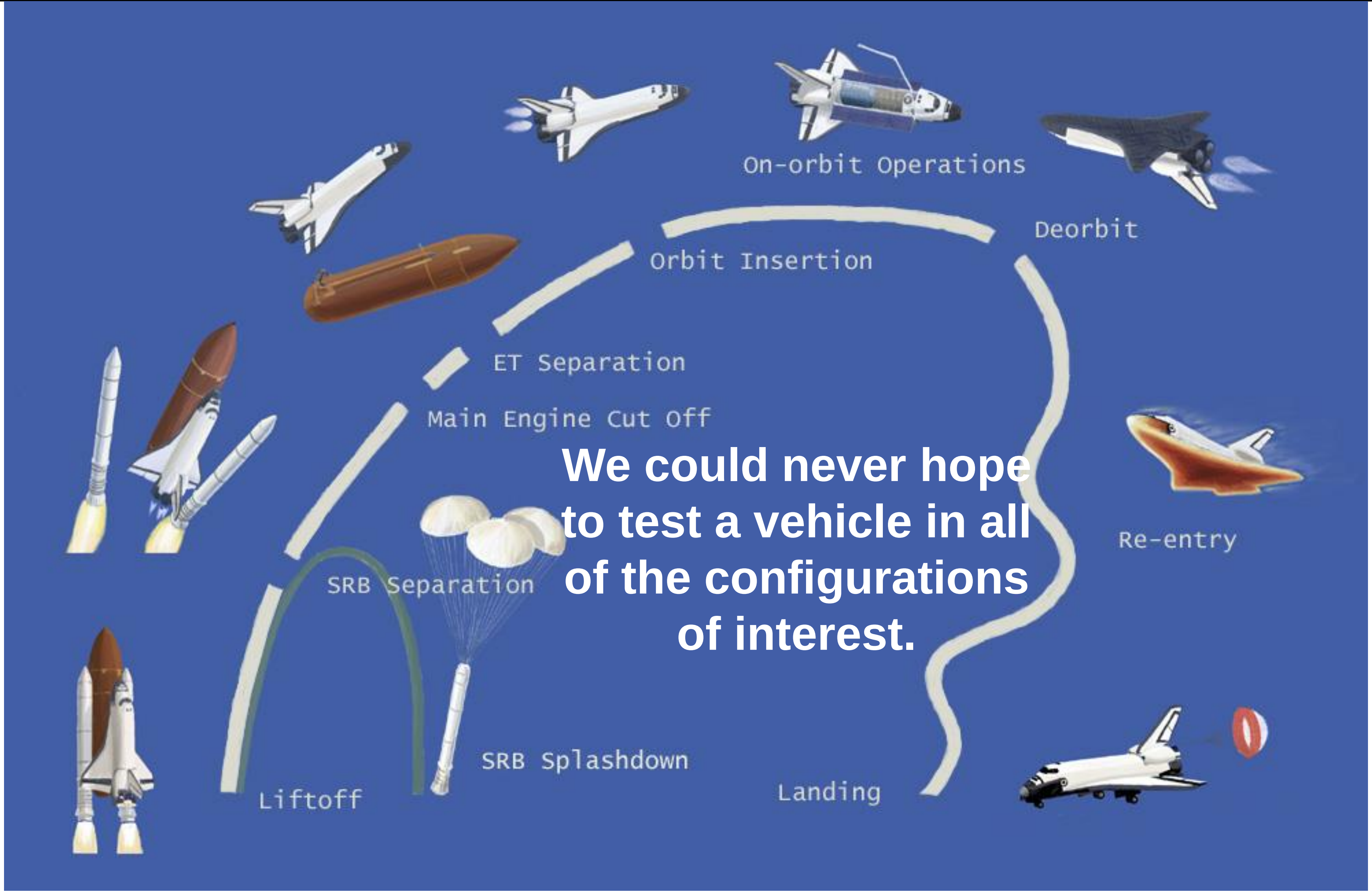
What are the technical needs driven by the ARTEMIS Missions? (2 of 2)

- **NASA missions will require new technologies for which the heritage factor-of-safety structural design approaches (based on historical experience with materials like aluminum) have no technical foundation**
  - The same is true in the development of uncertainty factors used in load, dynamic, and controls analyses as reliance on full vehicle testing diminishes and becomes heavily reliable on element testing
- **An integrated approach to development of flight systems based on a reliability methodology with uncertainty quantification (UQ) is required**
- **A reliability metric and reliability/UQ design methodology can place all structural materials/concept, and loads and dynamics on a common basis**

What is Required?

- **A combination of testing and analysis will be key to dealing with these challenges**
- **Building block approaches are required that provide the right balance between component, system, and/or element level testing that satisfies verification and validation objectives and where, uncertainties are quantified and minimized**
  - The approach to understanding these systems is steeped in using a building block approach to understanding the fundamental physics of the integrated structural systems and developing test validated models for use in system analyses
  - Successful implementation of the building block approach requires that uniform criteria are implemented across the elements to gauge the success of the test and model correlation/correction.
  - Adherence to standards and implementation of a structural verification plan that specifies consistent test and model correlation requirements for all the elements.
    - Mode survey test completeness and mode shape orthogonality criteria, model to test frequency and mode shape comparison criteria
  - Require that all finite element model (FEM) changes made to improve agreement with test data must be consistent with the drawings and the hardware

Why do we need a building block approach?



We could never hope to test a vehicle in all of the configurations of interest.

Artemis I First Flight

The first test of SLS in a free-free configuration will be during its first flight!

The Building Block approach allows us to use tests and correlation of subcomponents to gain confidence that this flight will be successful.

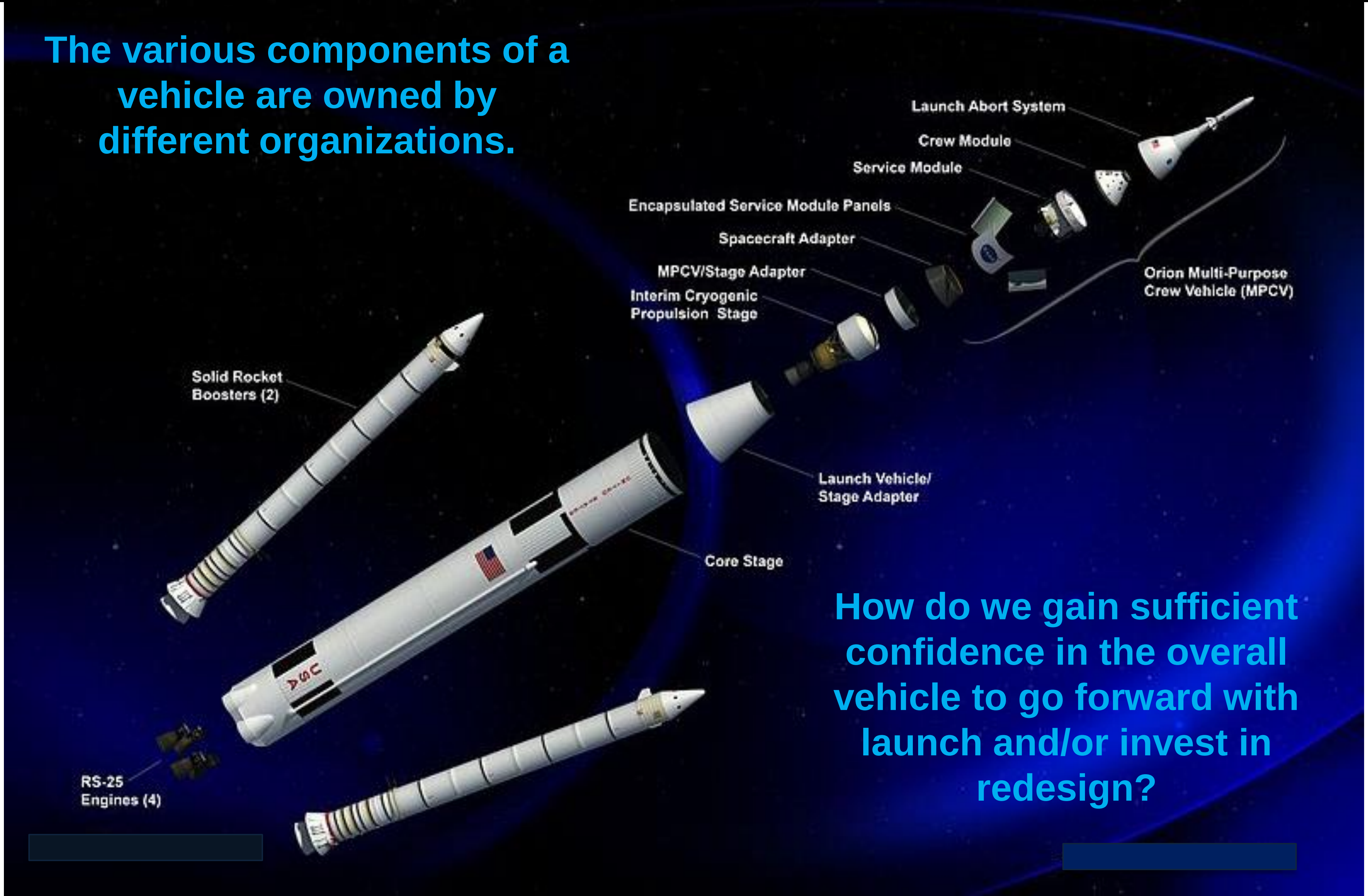
Design for Loads and Dynamics

- **The design of a launch vehicle is an iterative process:**
- **→ Structural Dynamic Properties depend on the design.**
- **→ Design iterated to meet loads requirements.**
- **→ etc…**

- **The loads (i.e. stresses, environments for components, etc…) are a function of the structural dynamic properties (i.e. natural frequencies, mode shapes, etc…) and the launch environment (i.e. propulsive forces, aerodynamics, etc…).**

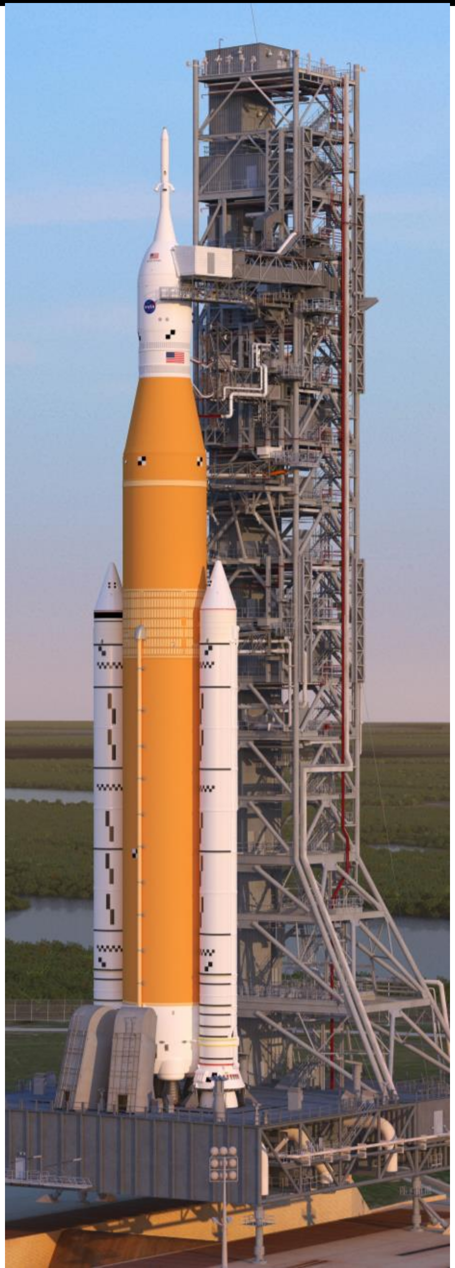
- **Modal and static testing and the subsequent model correlation are important tools used to reduce the uncertainty in the structural dynamic properties.**

Building Blocks are Owned by Different Organizations


The various components of a vehicle are owned by different organizations.

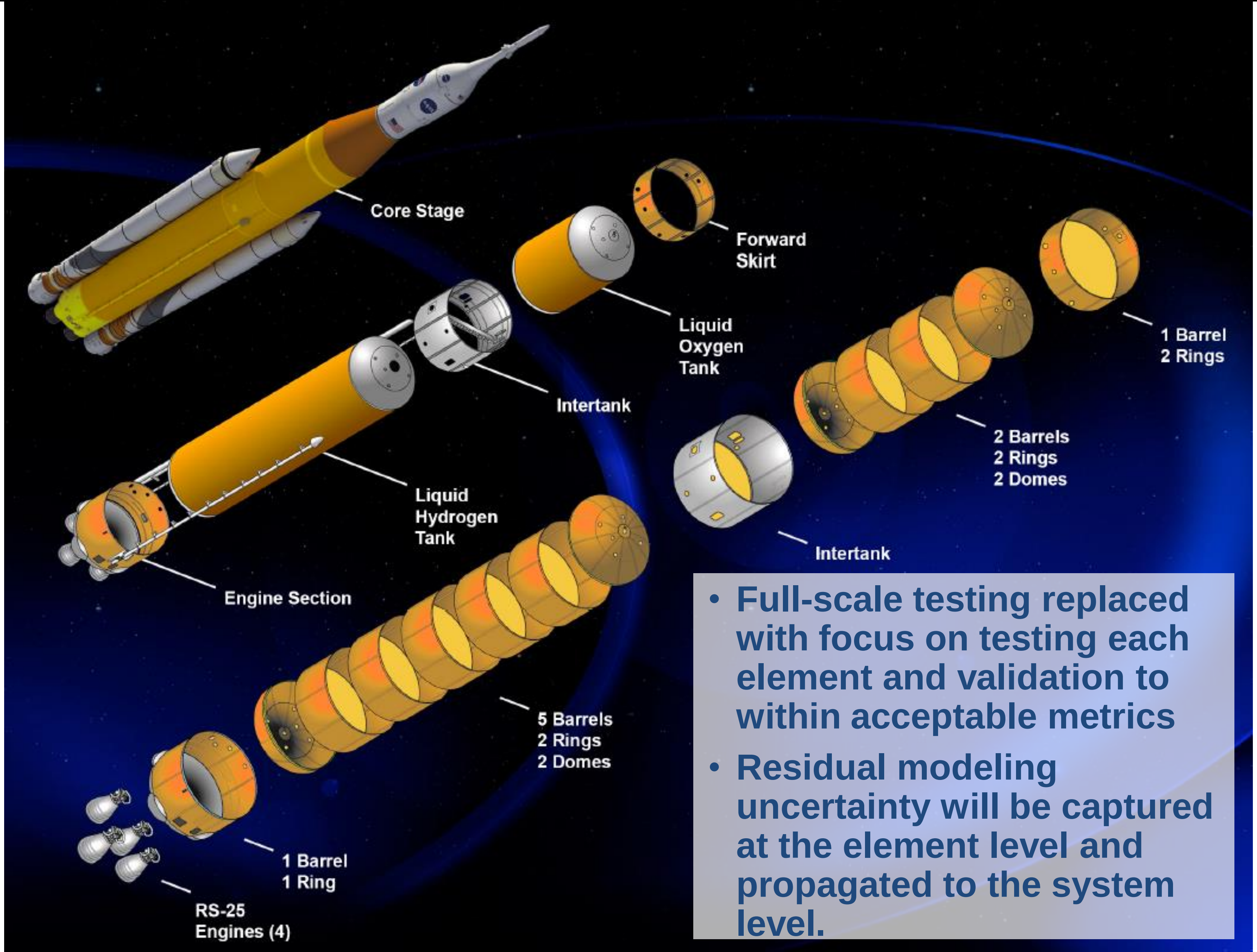
How do we gain sufficient confidence in the overall vehicle to go forward with launch and/or invest in redesign?

Experience and Plans for Space Launch System (SLS)



- **Events of interest are varied:**
  - Rollout from the Vertical Assembly Building (VAB) to the pad
  - Liftoff, Ascent
  - Landing and recovery operations
  - Etc…
- **There is not one test or model that can address all of these!**
- **Current Building Block approach represents a departure from past programs.**
  - Computer limitations (size, speed, etc…) are no longer the constraining factor
  - Some issues, such as Hydro-elastic modeling and visco-elastic propellant modeling are now well understood
  - Instead, facilities/budget/ability to accommodate tests has become a limiting factor.
    - Example: no dynamic/static testing is planed for the complete system in the liftoff or boost configurations

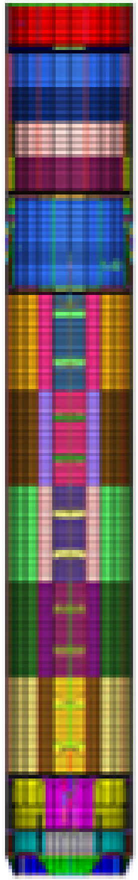
SLS Represents a True Building Block Approach



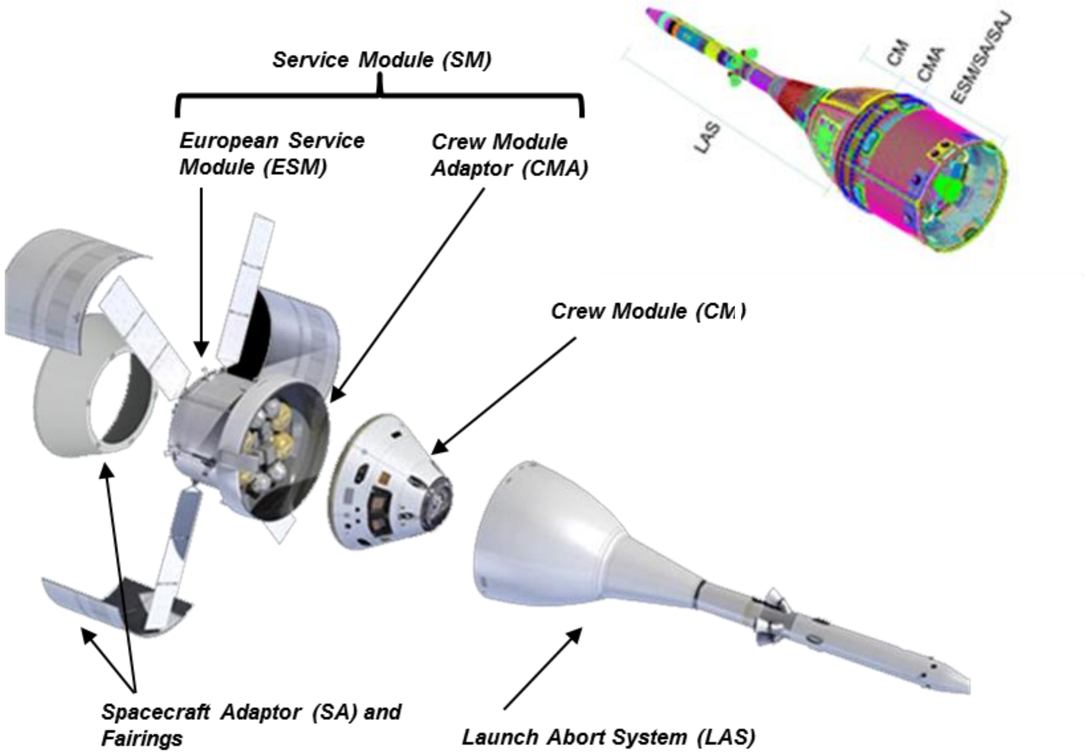
- **Full-scale testing replaced with focus on testing each element and validation to within acceptable metrics**
- **Residual modeling uncertainty will be captured at the element level and propagated to the system level.**

Finite Element Models for SLS


Core Stage and Solid Rocket Boosters

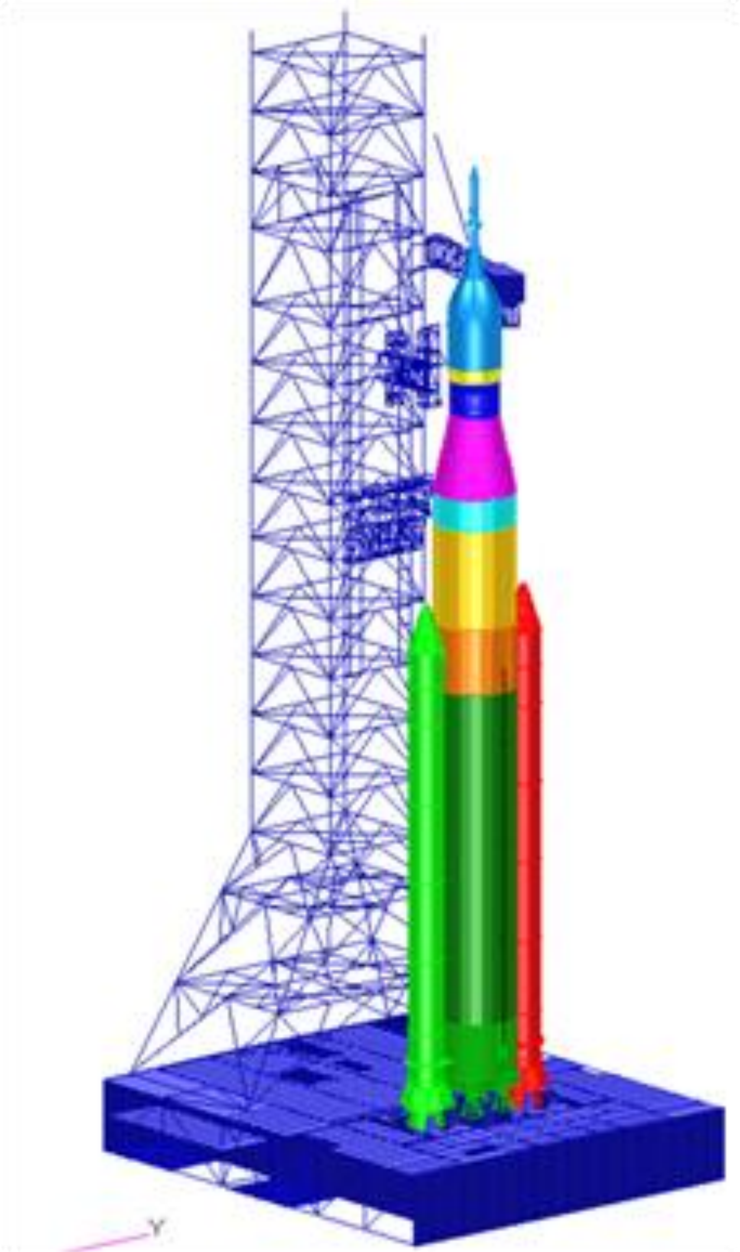

Core Stage


Solid Rocket Booster



- Typical model for the SLS has >165,000 nodes, >176,000 elements.
- Individual subcomponent models are larger, typically reduced to Hurty/Craig-Bampton models for the assembly.

FEMs for SLS and Mobile Launcher (ML)



Models are far more detailed, but many of the challenges encountered with the Apollo Saturn V and Space Shuttle Space Transportation System are still of concern:

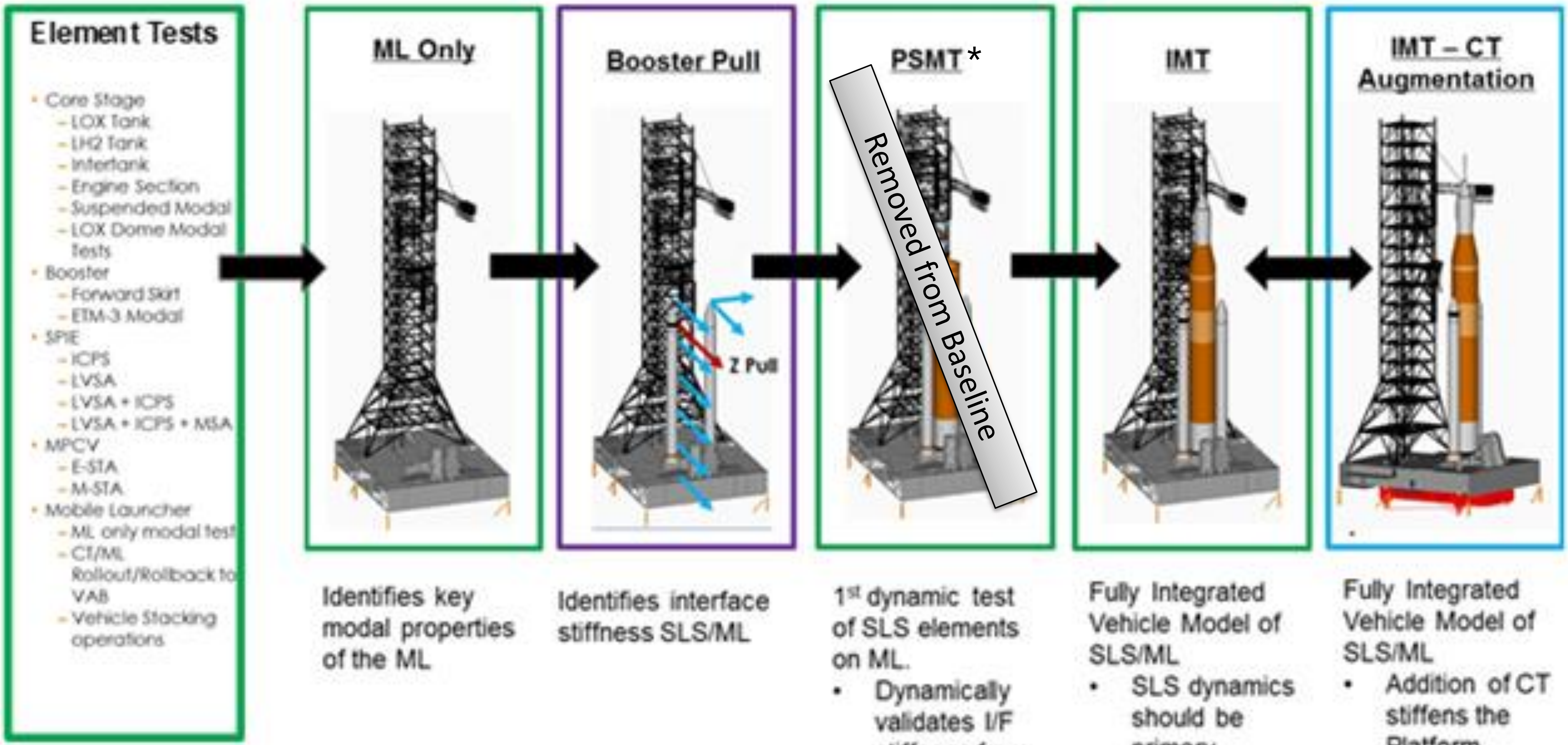
1. Interface (joint) models are not generally predictive and may introduce nonlinearities
2. Orthogrid and Isogrid structures may have uncertain properties
3. Reducing the models (i.e. using H/CB method) may introduce errors or uncertainties.

Many modes (i.e., ~1000s entire SLS) in the 0-60 Hz frequency band - a much smaller set of target modes must be selected.

Because some of the validation tests will be performed with the SLS mated to the ML, both must be modeled and validated.

- Strong coupling present between >0.5 Hz modes of SLS and ML

Original Building Block Testing Plan for Integrated SLS Systems



Element Tests

- Core Stage
  - LOX Tank
  - LH2 Tank
  - Intertank
  - Engine Section
  - Suspended Modal
  - LOX Dome Modal Tests
- Booster
  - Forward Skirt
  - ETM-3 Modal
- SPIE
  - ICPS
  - LVSA
  - LVSA + ICPS
  - LVSA + ICPS + MSA
- MPCV
  - E-STA
  - M-STA
- Mobile Launcher
  - ML only modal test
  - CT/ML Rollout/Rollback to VAB
  - Vehicle Stacking operations

ML Only: Identifies key modal properties of the ML

Booster Pull: Identifies interface stiffness SLS/ML

PSMT: 1st dynamic test of SLS elements on ML.
- Dynamically validates I/F stiffness from previous test

IMT: Fully Integrated Vehicle Model of SLS/ML
- SLS dynamics should be primary unknown in this test.

IMT – CT Augmentation: Fully Integrated Vehicle Model of SLS/ML
- Addition of CT stiffens the Platform

* Note: The PSMT test has been removed from the baseline test plan.

Takeaways and What is Required

- **While the size of Finite Element Models has increased dramatically, many of the challenges faced in the Saturn V and Space Shuttle (STS) programs are relevant today.**
  - Prior models were extremely limited in size, and errors were encountered due to modeling approximations.
  - Today's models, though orders of magnitude larger, still employ assumptions about joints or structural properties that need to be checked via test.
  - Furthermore, the models are larger and more complicated and there are many places where errors may occur (e.g. when mating parts from different contractors, or approximating interfaces between components, etc…).
- **Tests planned for the SLS seek to leverage new computational capabilities while also obtaining sufficient data to address uncertainties.**
- **Given the significant cost and time required to implement qualification test programs, there needs to be agreement on methodologies very early in the development cycle**
- **Consideration for investing in lower cost early development testing of the more critical and complex components and systems is important to gain valuable early insight into the fundamental physics, assumption and uncertainties, and will help buy down the potential for future schedule risk in more expensive qualification test programs**

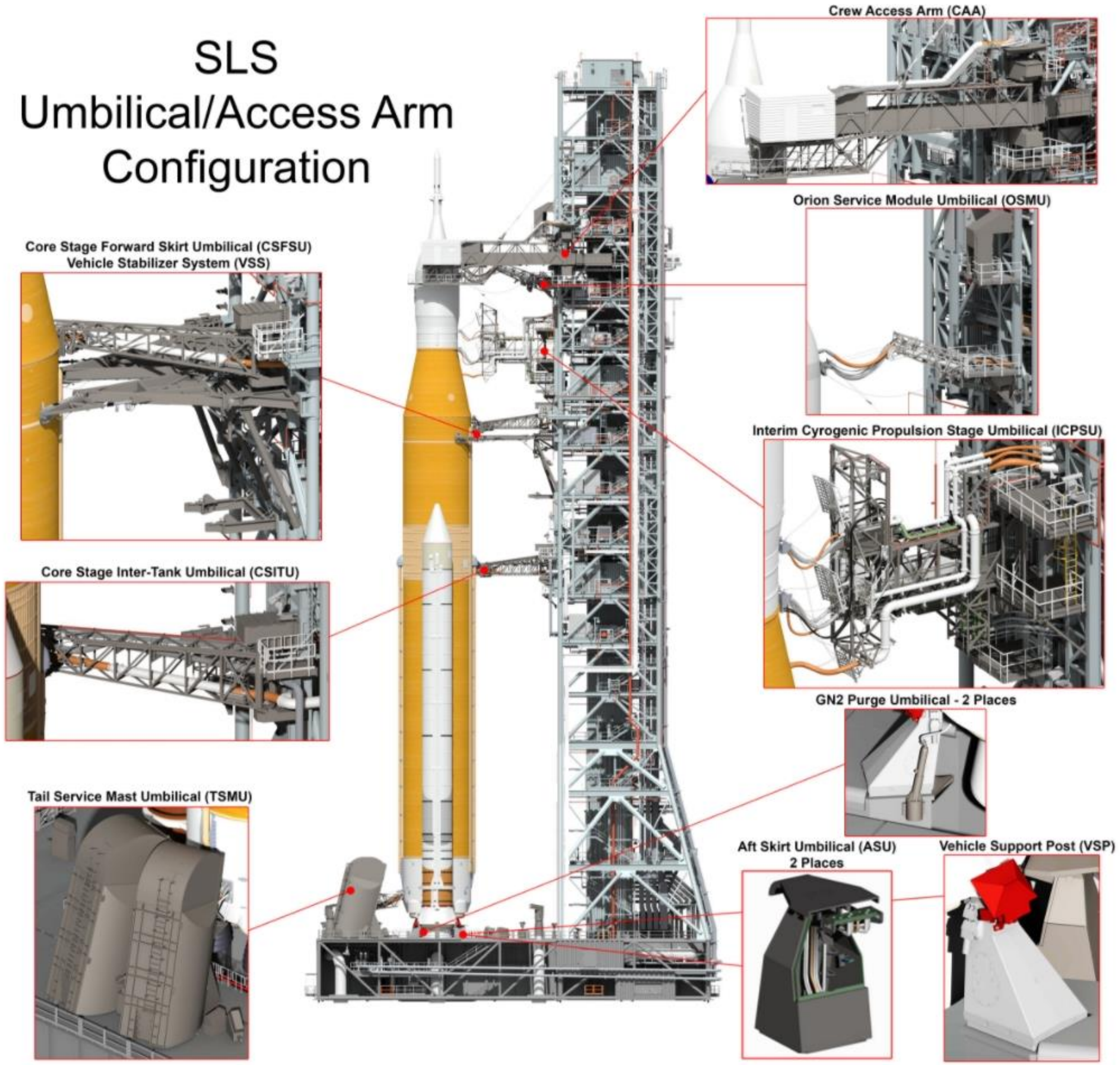
Other Considerations?

- **Nonlinear mechanisms and materials required for higher performance systems**
    - How do we advance nonlinear methods and tools in a predominant linear analysis and test world
- **Structural health monitoring**
    - What sensors are to be used given mass constraints?
    - What algorithms are used to process the data?
- **As Aerospace systems increase in size, tests to understand important modal characteristics approach the magnitude of modal testing of Civil Engineering structures**
    - Testing regimes exist where the input forces cannot be measured and we are looking more and more at using an OMA approach to extract modal parameters.
    - Civil Engineering has leveraged the use of FEM's and fluid dynamic modeling that came out of Aerospace Engineering in the Analysis of taller more flexible buildings and longer more flexible bridges.
    - Now Aerospace Engineering is leveraging OMA that came out of Civil Engineering to analyze systems where the input forces cannot be measured. This not only includes static structures like the ML but is also being applied to analyzing flight data.
- **Other key topical areas that will require focus in testing and analytical techniques include:**
    - Pogo, and other fluid-structural coupling phenomenon
    - Turbomachinery rotodynamic modes/critical speeds and turbine wheel blade harmonic/flutter modes
- **Analytical techniques that combine multi-physical phenomenon enabling evaluation of system-of-systems performance and interactions should be pursued and leveraged for speed and to reduce compounding conservations with uncertainty factors**

A Look at Multidisciplinary Fusion: Mobile Launcher (ML)

Mobile Launcher Evolution

Mobile Launcher (ML)



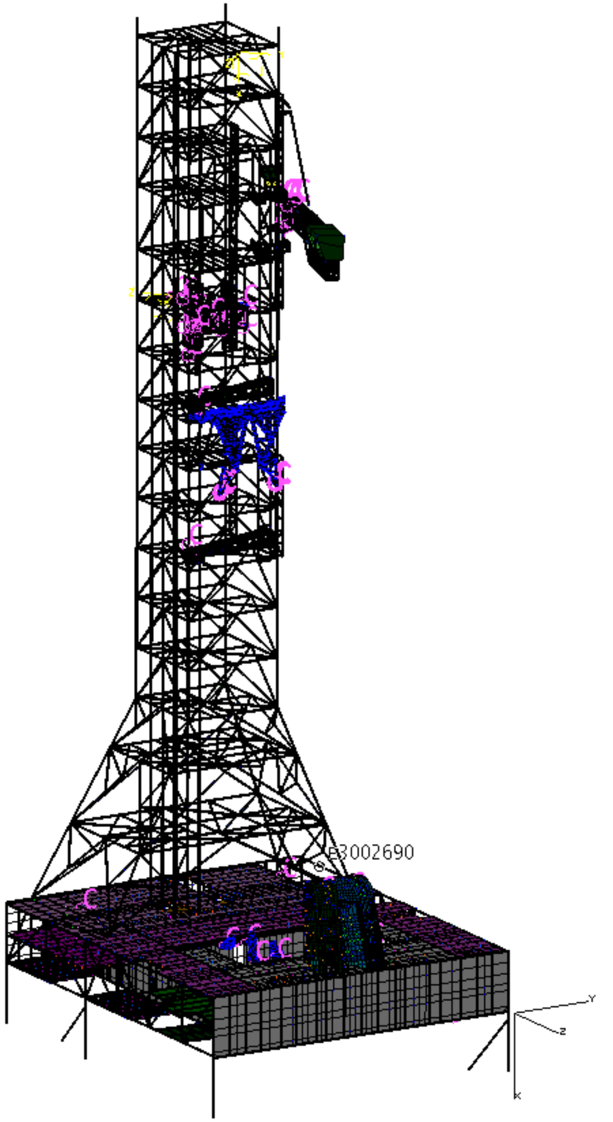
SLS Umbilical/Access Arm Configuration

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.
- **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.**
  - Will 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.**
- **Target modes are very low in frequency and closely spaced**
- **Testing is complete and correlation efforts are completing**

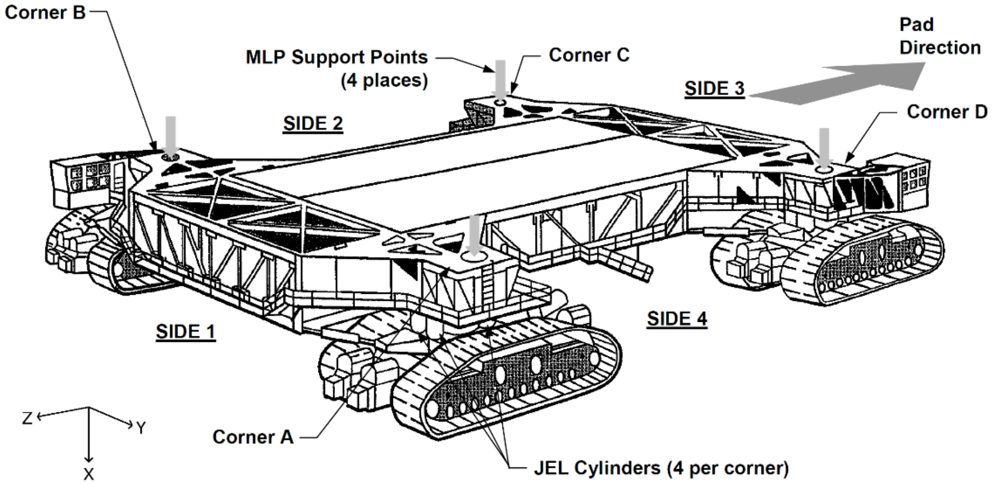


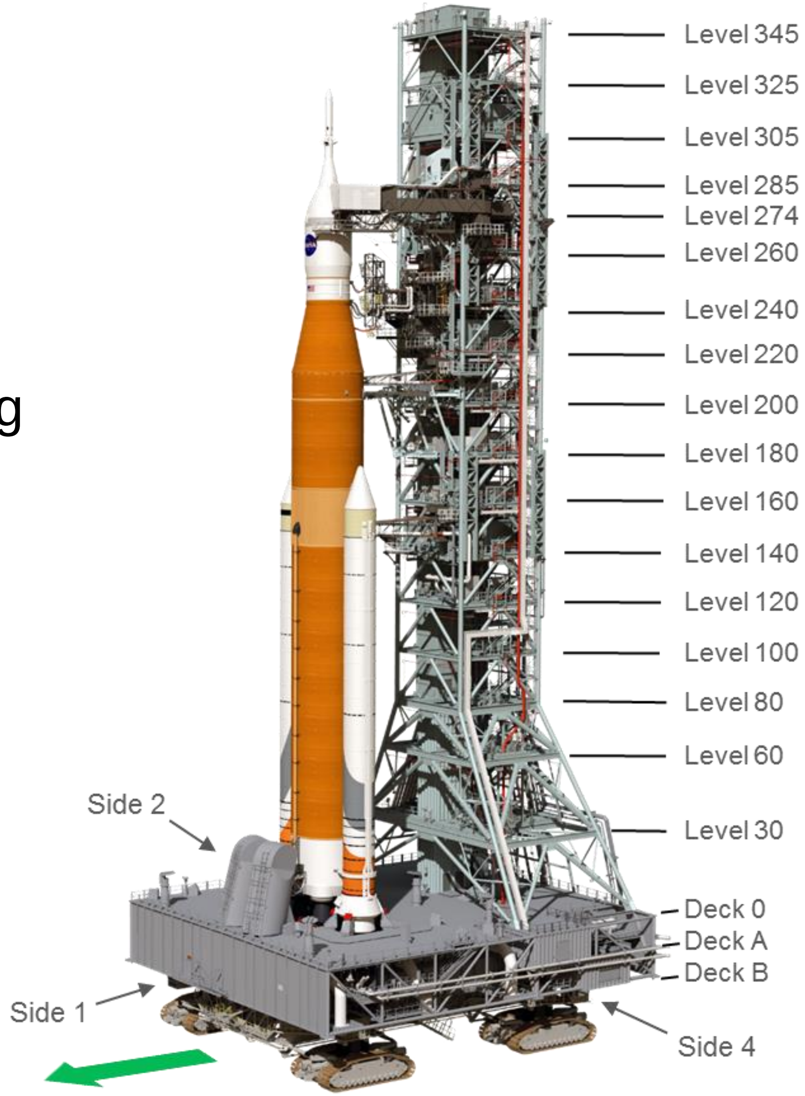
EXPLORE MOON to MARS

A Look at Multidisciplinary Fusion: Crawler Transporter

ML/CT Rollout Operational Modal Analysis (OMA)

- **As part of the Mobile Launcher (ML) system Verification and Validation (V&V), two ML on Crawler Transporter (CT) rollouts to Launch Pad 39B were conducted**
  - These were Kennedy Space Center (KSC) Exploration Ground System (EGS) tests designed to demonstrate using the CT to transport the ML from the Vehicle Assembly Building (VAB) to Launch Pad 39B.



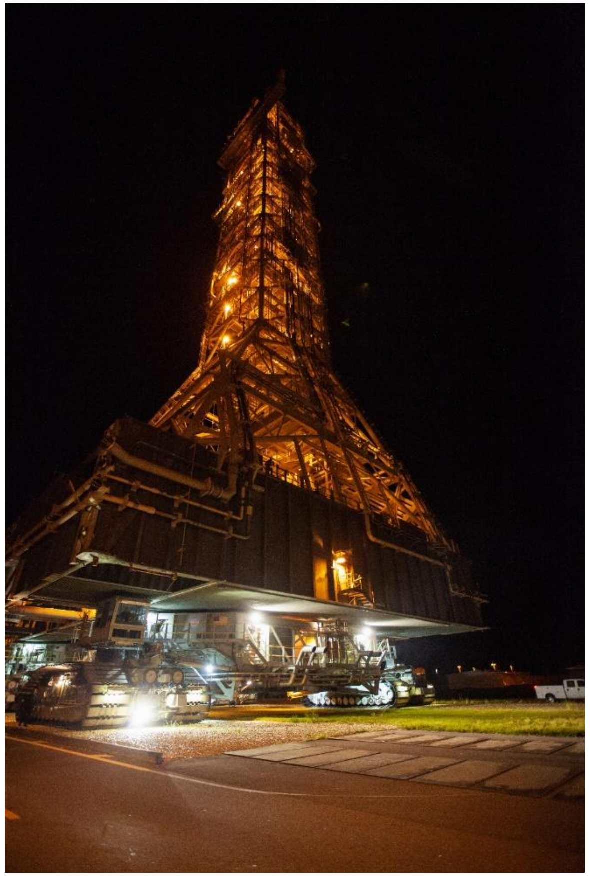


Rollout from VAB to Launch Pad 39B

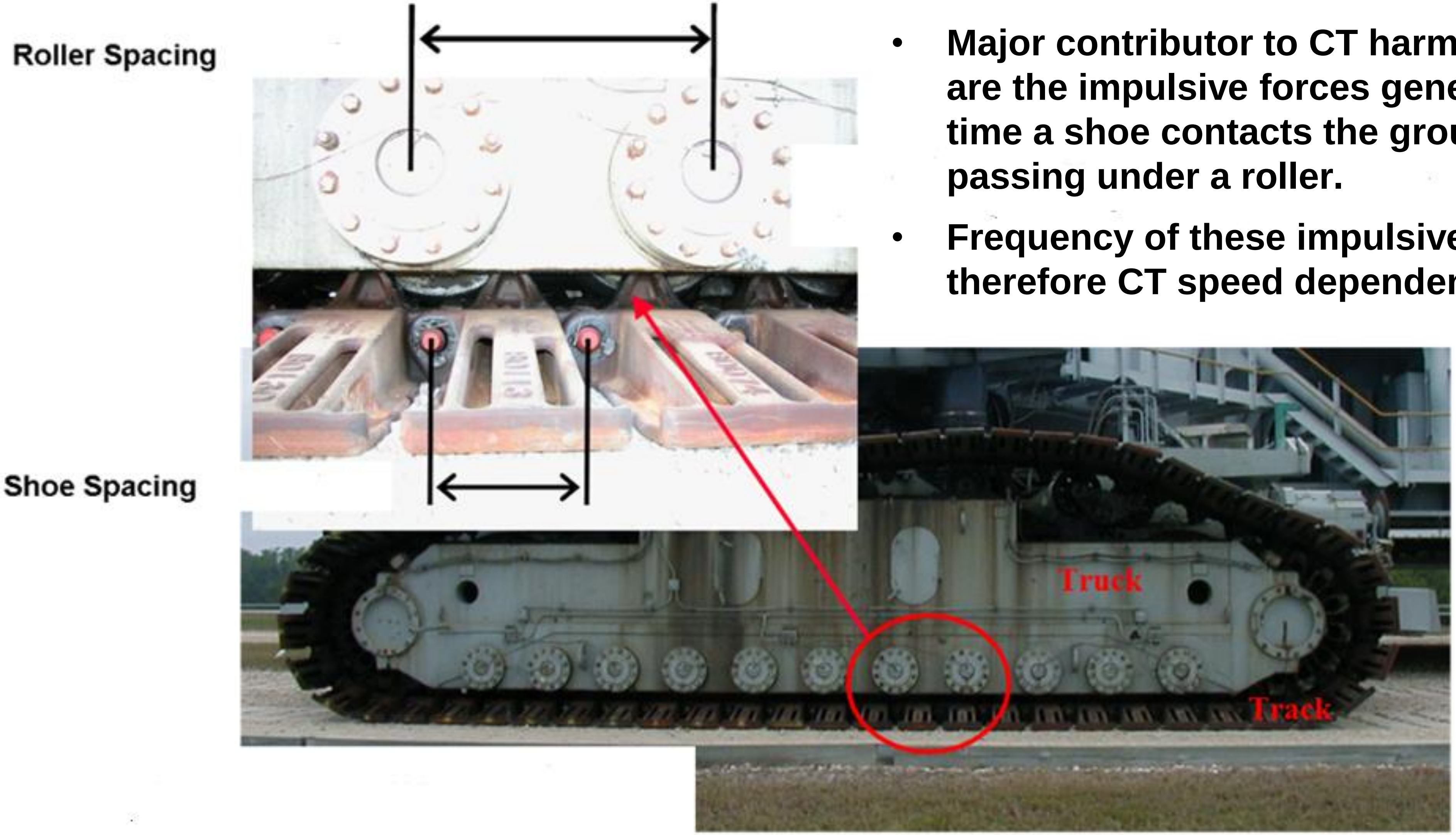
- Rollout of ML on CT from the Vertical Assembly Building (VAB) takes on the order of ~8 and ¾ hours one way
- Rollout data collected from departing the VAB to arriving at gate of Launch Pad 39B

Rollout from VAB to Launch Pad 39B

- ML weighs 10.6 million pounds (Tower weighs 4 million pounds, Deck weighs 6 million pounds.
- CT weighs 6.3 million pounds (2.2 million pounds suspended weight).
- CT during rollout carried a total of static load of 12.8 million pounds at a top speed of 0.95 mph.



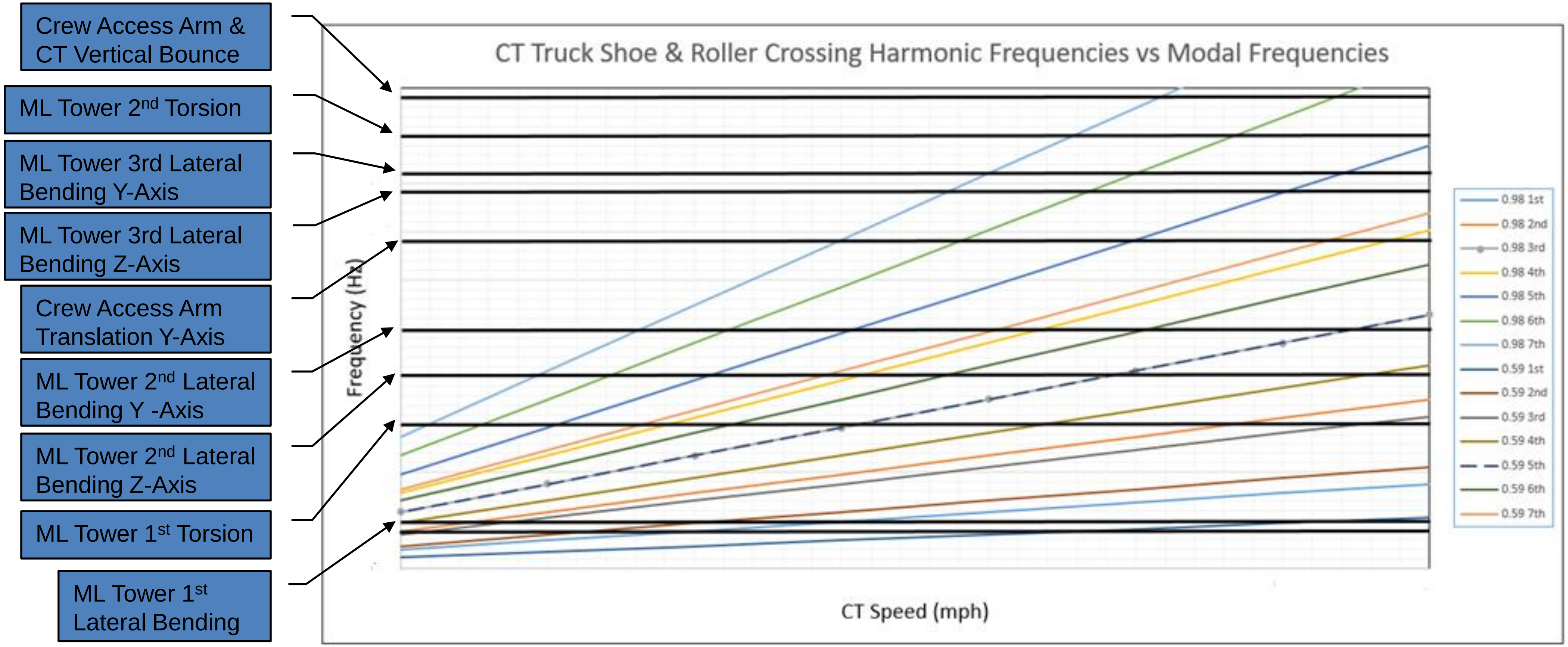
CT Truck Shoe & Roller Crossing Harmonics



- Major contributor to CT harmonic forces are the impulsive forces generated every time a shoe contacts the ground and when passing under a roller.
- Frequency of these impulsive forces is therefore CT speed dependent.

CT Truck Shoe & Roller Crossing Harmonics vs Modal Frequencies

- **The presence of the CT Truck shoe and roller crossing harmonics significantly hampers identifying the ML on CT modes if CT speed is constant.**
- **Varying CT speeds mitigates the detrimental effects of these CT harmonics.**



Crew Access Arm & CT Vertical Bounce

ML Tower 2nd Torsion

ML Tower 3rd Lateral Bending Y-Axis

ML Tower 3rd Lateral Bending Z-Axis

Crew Access Arm Translation Y-Axis

ML Tower 2nd Lateral Bending Y -Axis

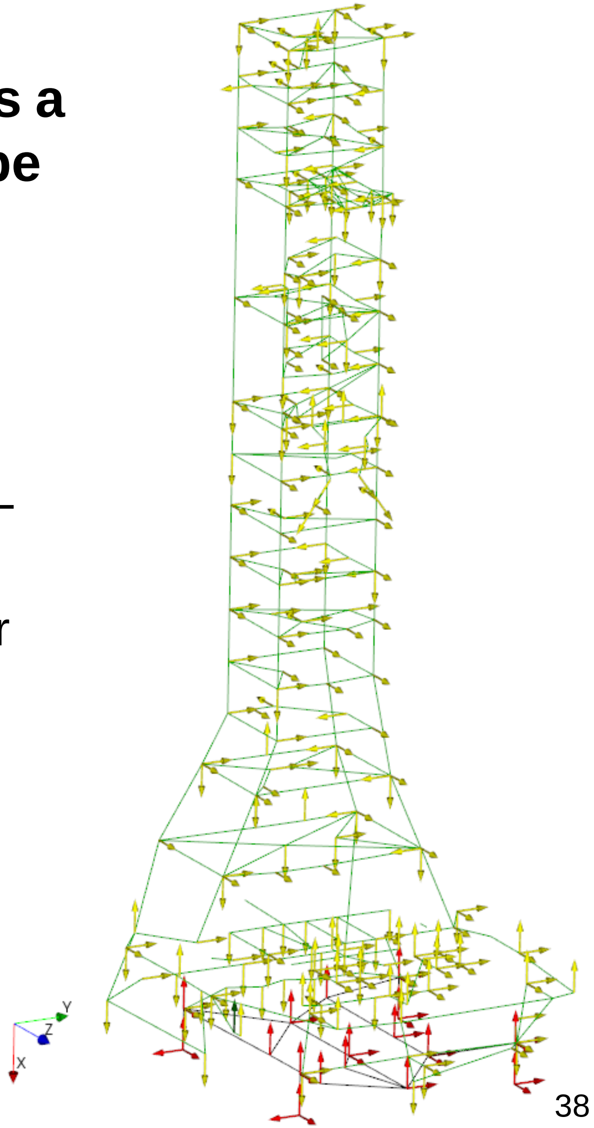
ML Tower 2nd Lateral Bending Z-Axis

ML Tower 1st Torsion

ML Tower 1st Lateral Bending

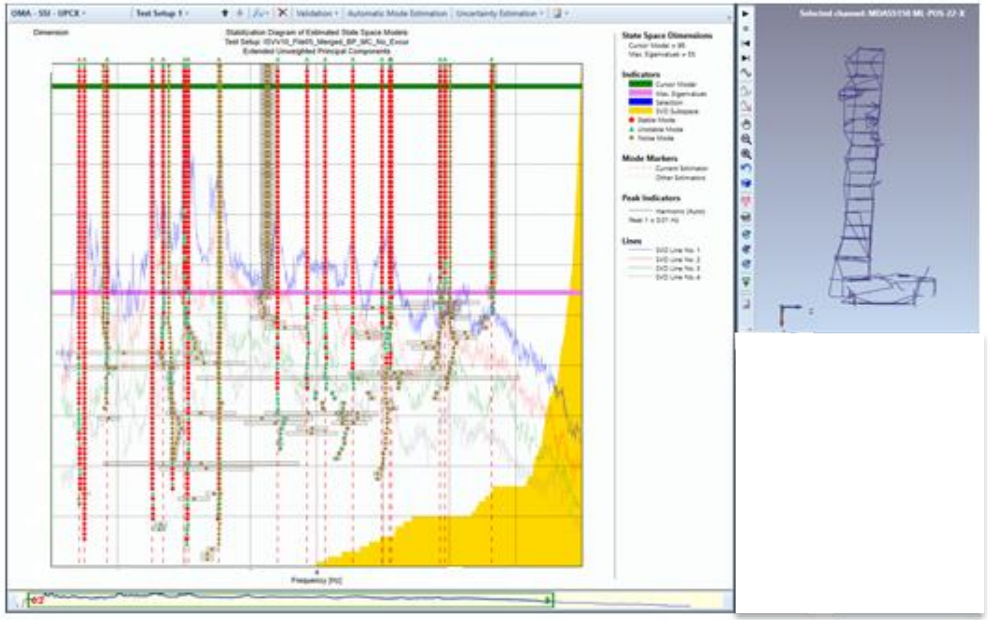
Rollout OMA Data Assessment

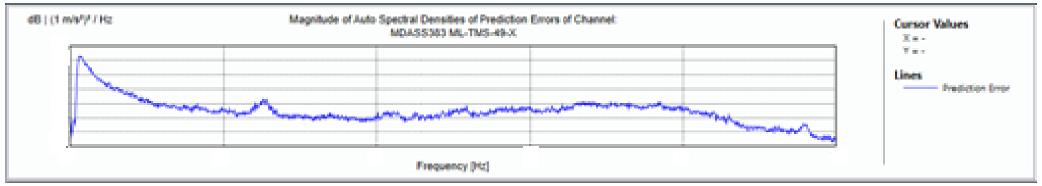
- **OMA techniques used on the rollout acceleration time histories shows a significant number of fundamental ML on CT modes up to ~7 Hz can be identified.**
  - Predominantly lower frequency modes below 4 Hz – 5 Hz that are dominated by ML Tower deflection.
  - Identifying modes above 4 Hz – 5 Hz becomes progressively more challenging due to increasing modal density and relatively low acceleration levels on the ML Deck.
  - The 1-hour time interval where the CT speed was gradually increasing in a stair step fashion was most conducive to identifying modes.

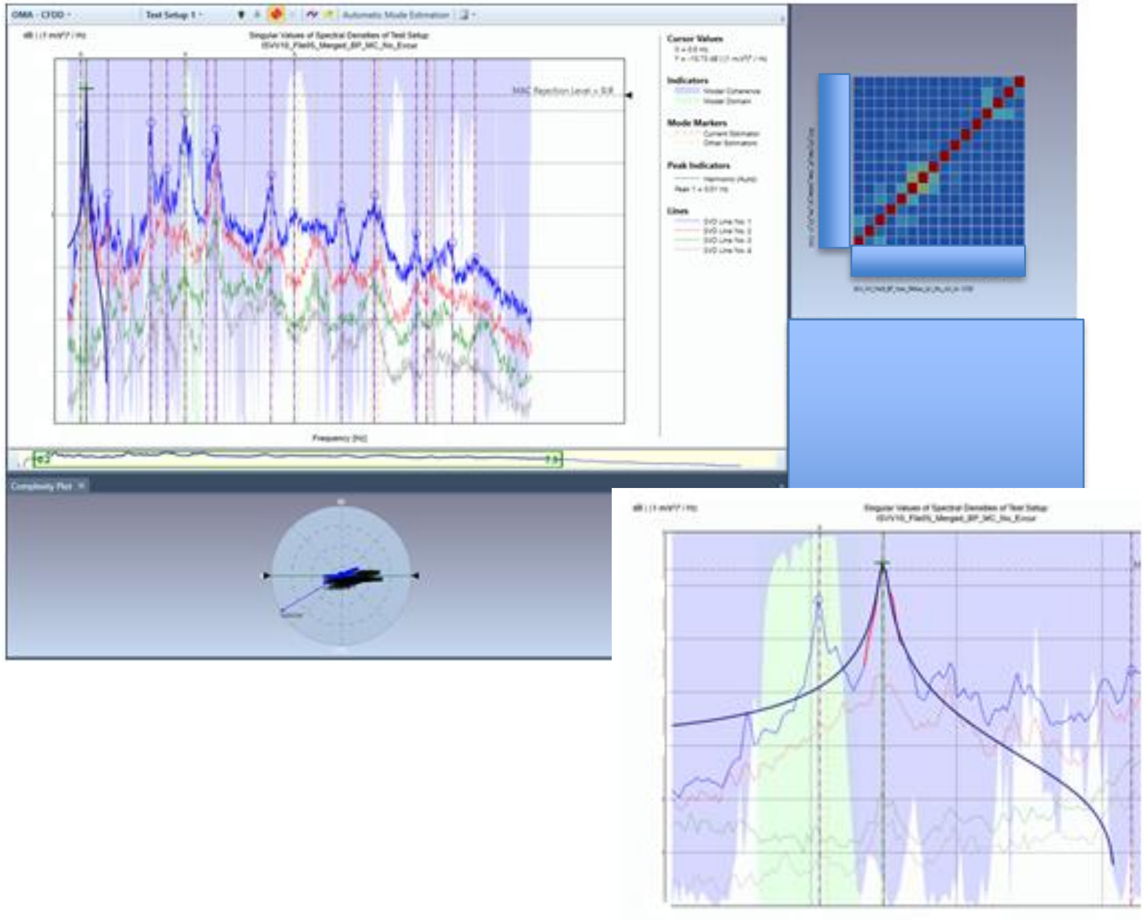


Rollout OMA Data Assessment (cont.)

- **Time-domain (Subspace Identification) and frequency-domain OMA techniques used to identify the fundamental ML on CT modes up to ~7 Hz.**





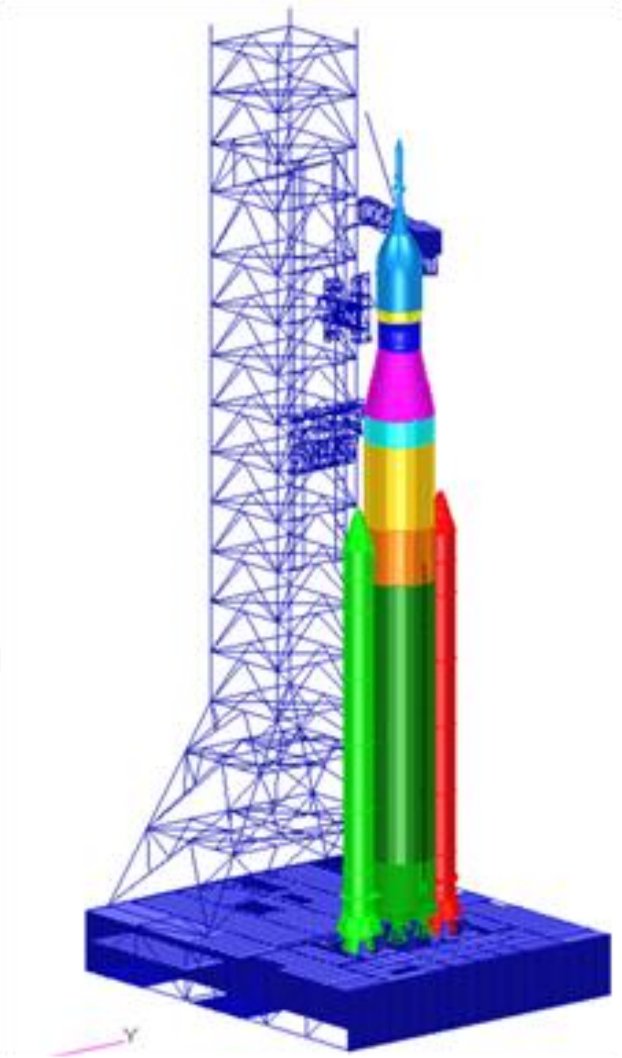


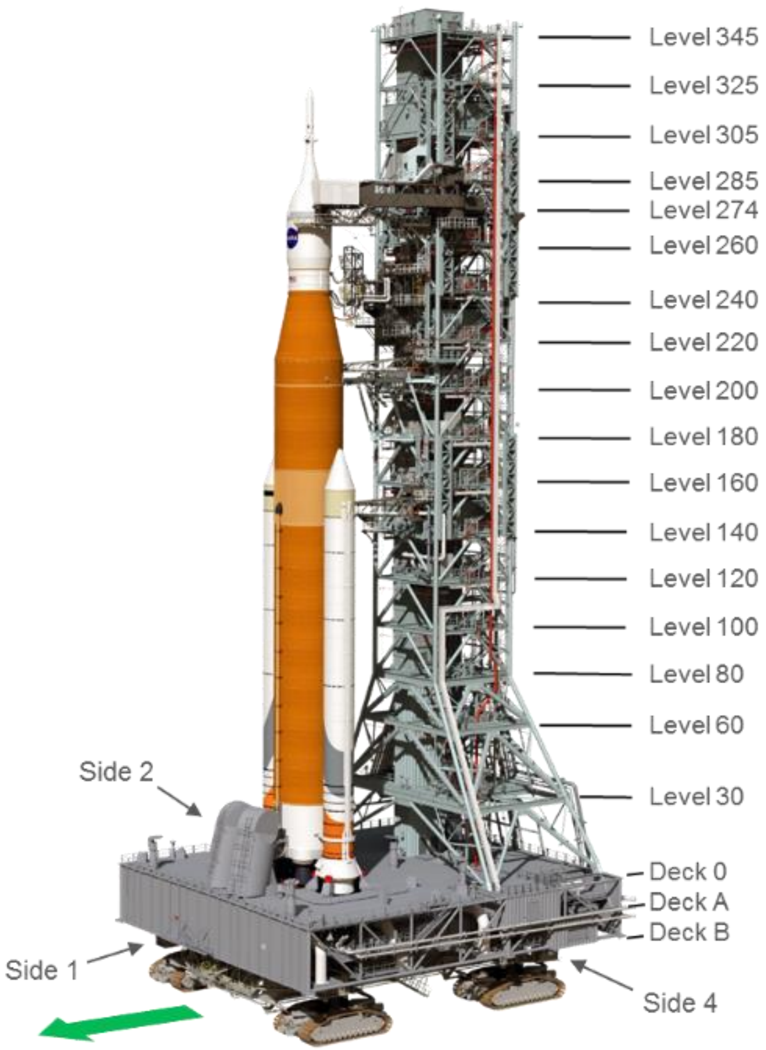
Rollout OMA Observations to Date

- **OMA techniques will not replace traditional modal testing with modal shakers and modal hammers, but provides important supplemental information and insights into the structural dynamics of hardware in its operational environment**
  - The effectiveness of OMA techniques is highly dependent on the quality of the rollout data
  - Best practices need to be followed.
- **Streamlining the data acquisition and transfer process, especially time synchronization of the data channels, will play a critical roll in the timeliness and effectiveness of analyzing the DRT rollout data**
  - Time synchronization is critical to being able to identify modes and compute transfer functions with correct phase information.
  - Data acquisition systems not intended for long period data acquisition and may have time drift

Challenges for the Dynamic Rollout Test (DRT)

- **The ML and Artemis I dynamics during DRT will differ significantly from the Integrated Modal Test (IMT) due to the umbilicals and the Vehicle Stabilizer System (VSS) connecting Artemis I to the ML Tower**
  - VSS has a known nonlinear characteristic based upon its original design
  - The remaining umbilicals influenc is unknown at this time.
- **DRT and ML/CT only dynamics are very different due to DRT having Artemis 1 present and the umbilicals deployed instead of stowed**





The ARTEMIS Opportunity (1 of 2)

- **The Artemis mission architecture will challenge the structural dynamics discipline, and other disciplines, to improve current methods in both test and analysis and physics based understanding of large complex flexible structures**
- **The challenge is:**
  - To develop analysis and testing techniques that can define nonlinear systems and provide for analysis tools to describe the system
  - Find innovative and affordable methods to not only enhance testing and analysis within the structural dynamics discipline, but also in ways that combine the physics of multiple interacting disciplines, a systems-of-systems methodology philosophy
  - Re-focus on the merger of analysis and test – need to find the right balance

    "No-one believes computer predictions except the person who has done the analysis, while …. Everyone believes the results from a test, except the person who has made the measurements." Dr. McNeal

  - Current trends have a heavy reliance on analysis versus balanced approach of test and analysis for certification
    - Analysis models are not an adequate representation of as-built hardware

      "All models are wrong, but some are useful." Professor George E.P. Box, University of Wisconsin

    - There is an over-confidence in analytical model results as accurate representation

The ARTEMIS Opportunity (2 of 2)

- **The challenge is:**
  - Consider probabilistic approaches to quantifying system margins/safety factors rather than more conservative deterministic approaches
    - One must still understand the physics and distributions of individual parameters.
  - Consider a new paradigm that leverages model base system engineering (MBSE) and the use of intelligent learning algorithms as appropriate to help increase modeling efficiency and configuration management.

At the end, the question that still needs answering is, how do we best build confidence in systems and system-of-systems performance capabilities and margins and understand uncertainties?

Summation

- **The challenge is to find the appropriate balance between analysis tools, complexity, cases run, etc. to arrive at good reliable answer/solution with knowledge of product use**

- **Continue to build on and leverage the advancing analytical approached (appropriately test anchored) to increase our speed to obtain and resolution of answers**

However, we must avoid paralysis by analysis

We Are NASA

Let’s go. *The Time is Now.*

We have the capability

We have the purpose

We have the charge

We have the responsibility