

A Cacophony of Multidisciplinary Dynamic Testing Challenges

Joel W. Sills

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

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National Aeronautics and
Space Administration



EXPLORE MOON_{to}MARS

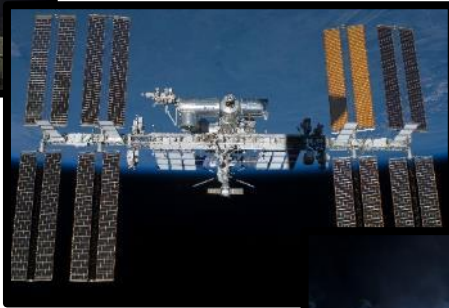
**An Introduction to the
NASA Engineering Safety Center (NESC)**



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***

- 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

We Are Going to the Moon

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

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.



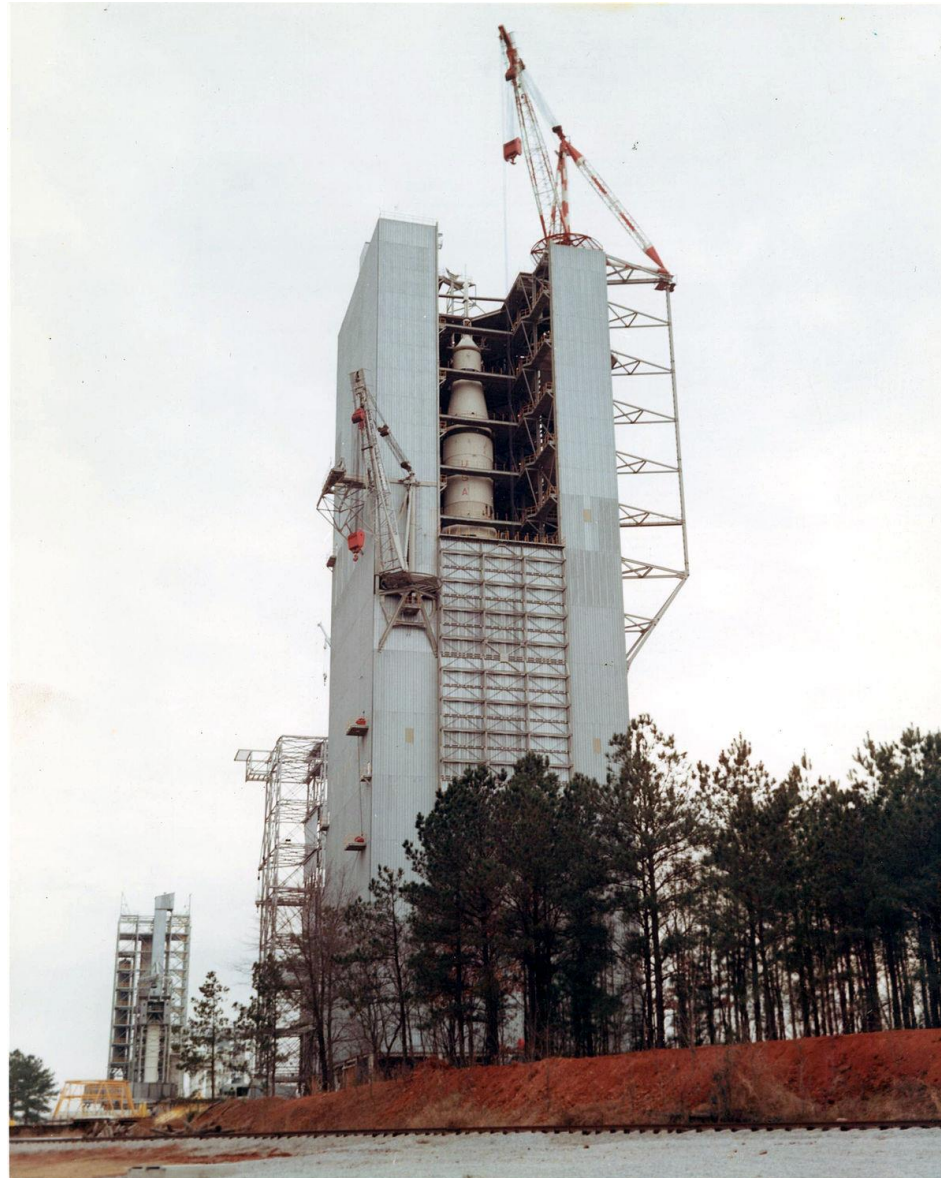
Challenge 1: Testing of Large Systems (Civil meets Aerospace Structures) ^[1]



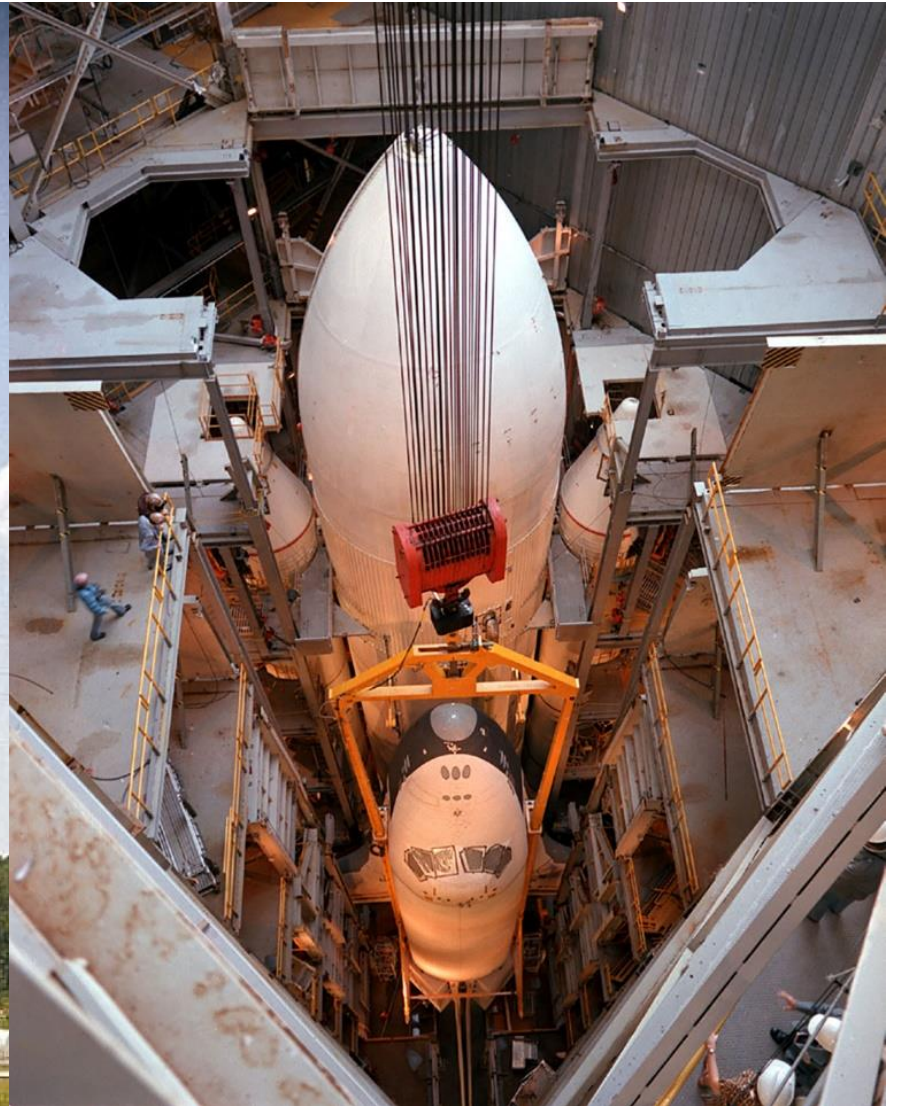
- **NASA is developing an expendable heavy lift launch vehicle capability, the Space Launch System (SLS), to support lunar and deep space exploration.**
- **The Mobile Launcher (ML) is a very large heavy beam/truss steel structure designed to support the Space Launch System during its buildup and integration in the Vehicle Assembly Building (VAB), transportation from the VAB out to the launch pad, and provides the launch platform at the launch pad.**
- **ML will serve as the IMT modal test fixture supporting the Artemis I integrated vehicle.**

[1] Excerpt from the International Modal Analysis Conference XXXVIII, "Space Launch System Mobile Launcher Modal Pretest Analysis," J.C. Akers–NASA Glenn Research Center; J.W. Sills–NASA Johnson Space Center

Challenge 1: MSFC Test Stand 4450 & Apollo SA-500D Installed (Past) ^[1]



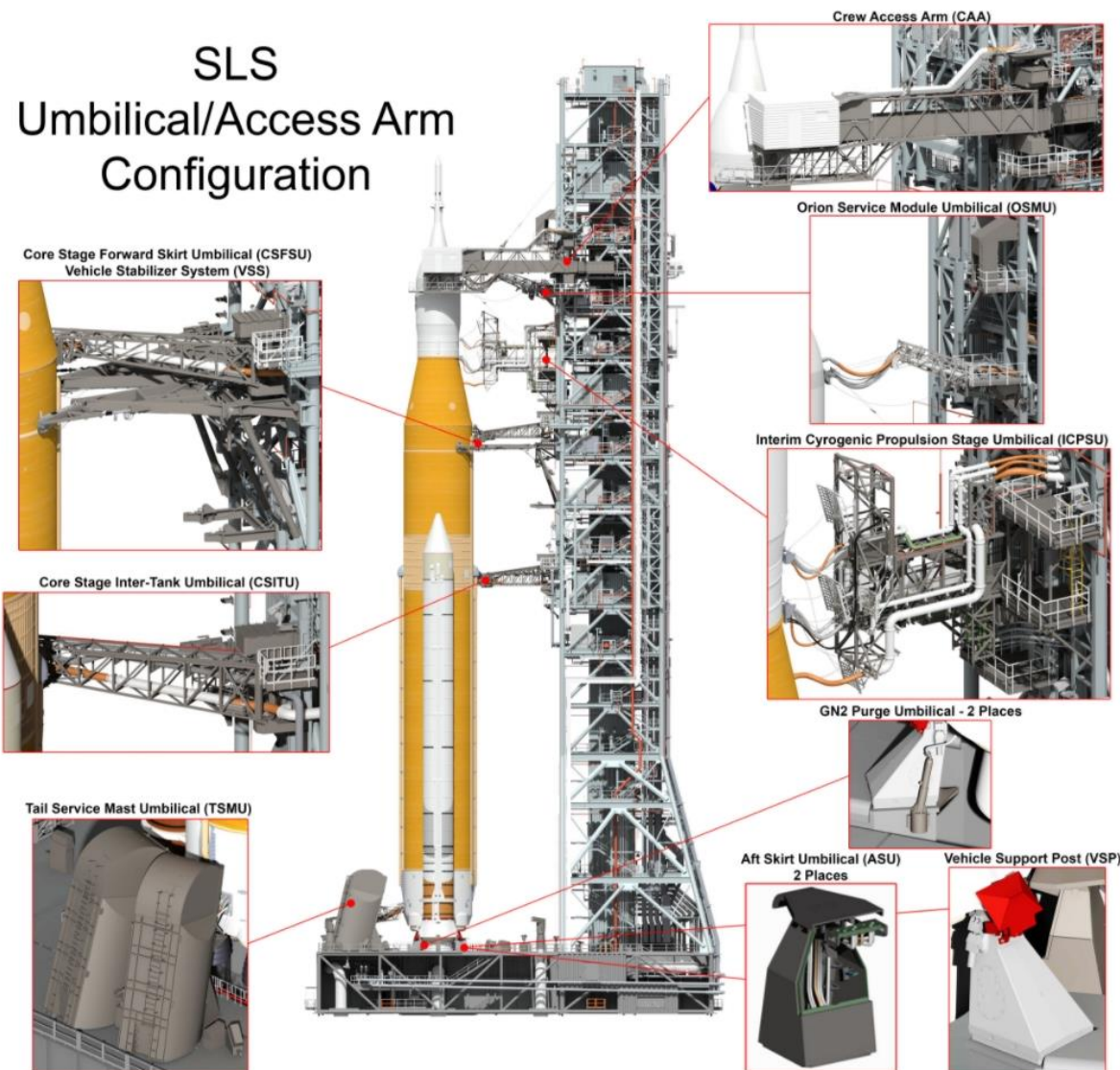
Challenge 1: MSFC Test Stand 4450 & Shuttle Orbiter Enterprise (Past) ^[1]



Challenge 1: Mobile Launcher (ML) (Present) ^[1]



SLS Umbilical/Access Arm Configuration



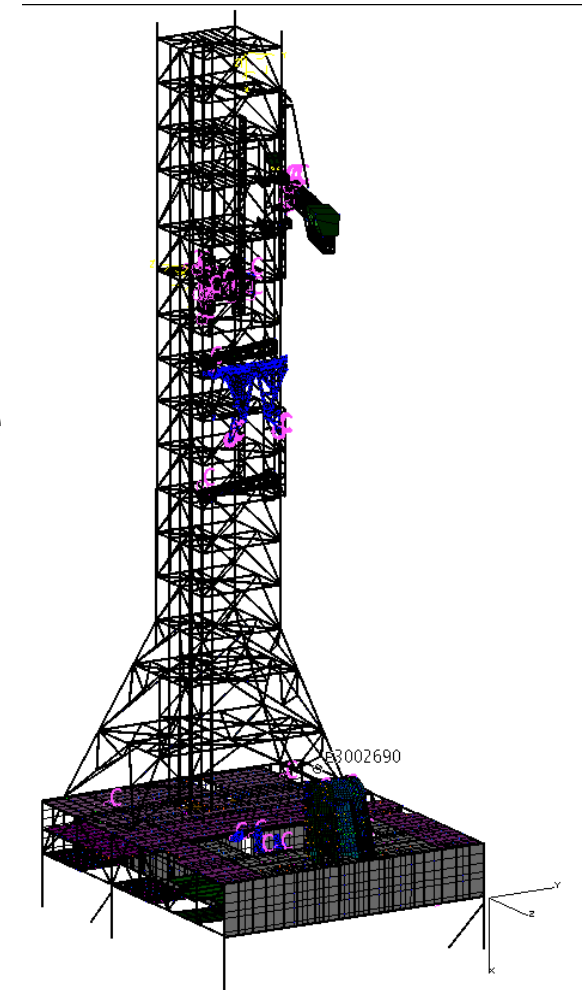
Challenge 1: Integrated Modal Test (IMT) Challenge ^[1]

- 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.

Challenge 1: ML Only Modal Test ^[1]



- **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**
- **Test performed June 2019**





Challenge 1: ML Only Modal Test Pretest Analysis ^[1]

- **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.**



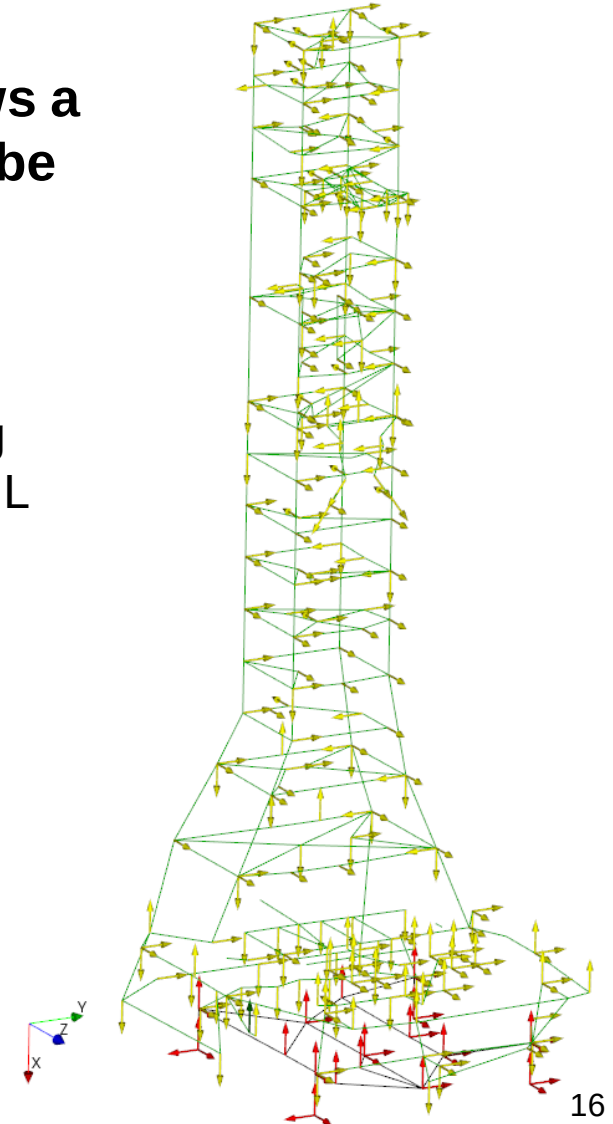
Challenge 1: Crawler Transporter (CT-2) – Rollout and OMA



Challenge 1: 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.

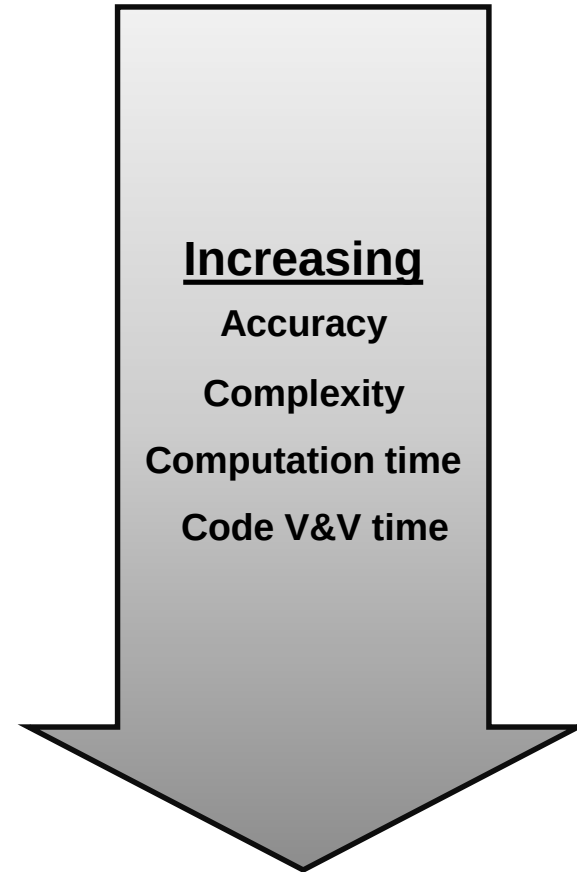


Challenge 2: Nonlinear (NL) Structures – What to do?



Multi-Fidelity Hierarchy of Computational Methods

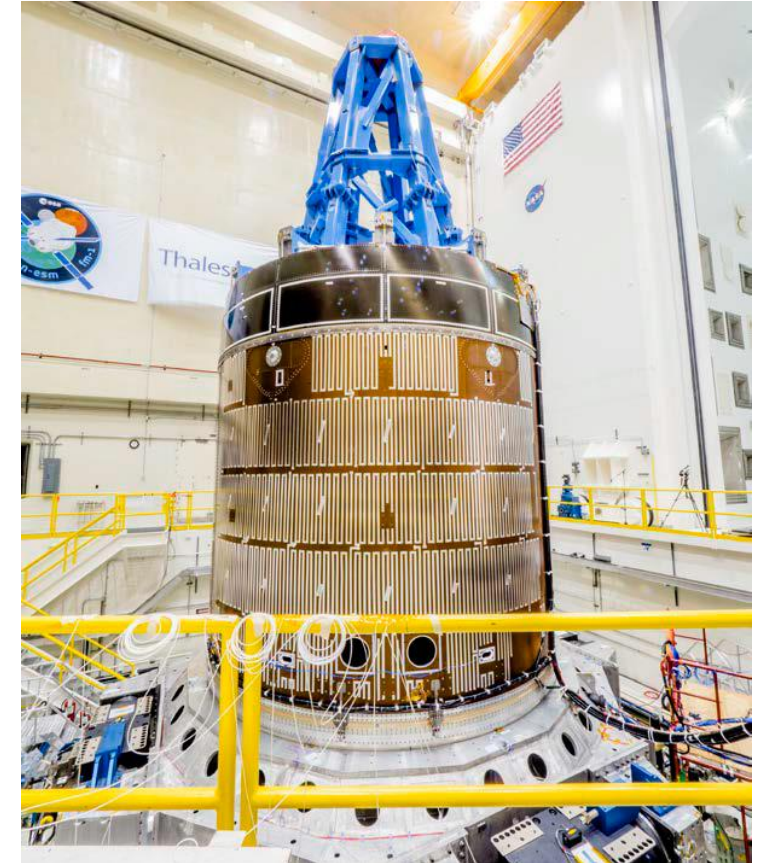
- Ignore it
- Linear modal model, calibrated to given load level
- Uncoupled modal models with nonlinear corrections (QSMA Approach)
- Linear component models with nonlinear interfaces
- Nonlinear, coupled modal models
- Fully nonlinear finite element analysis



Challenge 2: Nonlinear Structures [2]



- **Vibration testing performed on European Service Module (ESM) Structural Test Article (E-STA)**
 - Verify structural integrity of flight-like specimen of ESM near flight load levels
- **Large nonlinear behaviors observed in primary dynamic responses**
- **Independent E-STA model correlation performed**
 - 1) Linear model correlation
 - 2) Nonlinear model generation & correlation
 - 3) CLA response study and uncertainty assessment



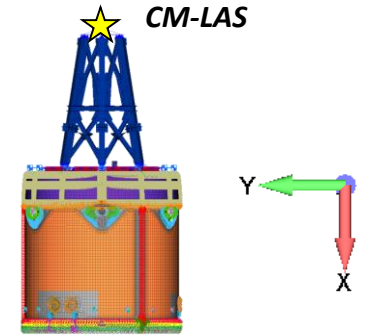
[2] Excerpt from the International Modal Analysis Conference XXXVIII, "Orion E-STA Nonlinear Dynamic Correlation and Coupled Loads Analysis," M. Griebel–Quartus Engineering Incorporated; A. Johnson–Quartus Engineering Incorporated; B. Erickson–Quartus Engineering Incorporated; A. Doan–Quartus Engineering Incorporated; C. Flanagan–Quartus Engineering Incorporated; J. Wilson–Quartus Engineering Incorporated; P. Bremner–AeroHydroPLUS; J. Sills–NASA Engineering and Safety Center; E. Bruno–Analytical Mechanics Associates, Inc.

Challenge 2: Linear Correlation Results – Acceleration [2]

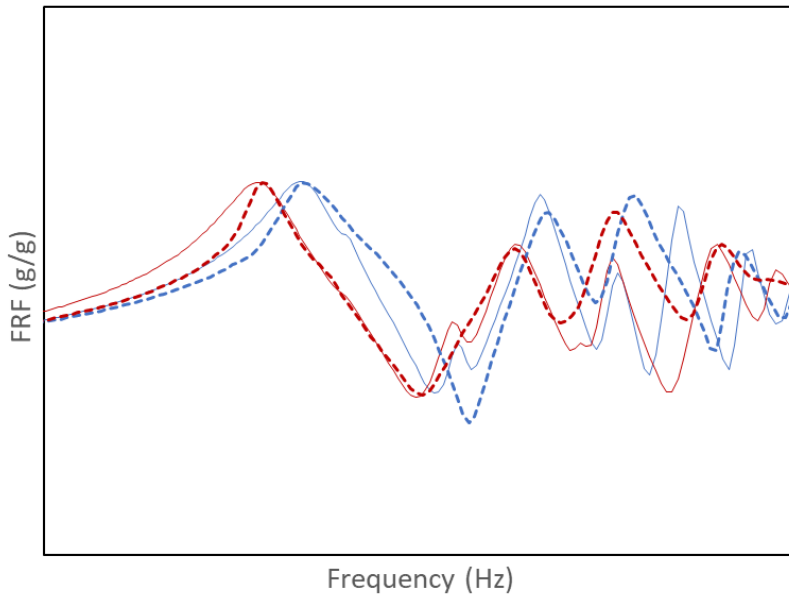


- **Representative location shown (CM-LAS)**

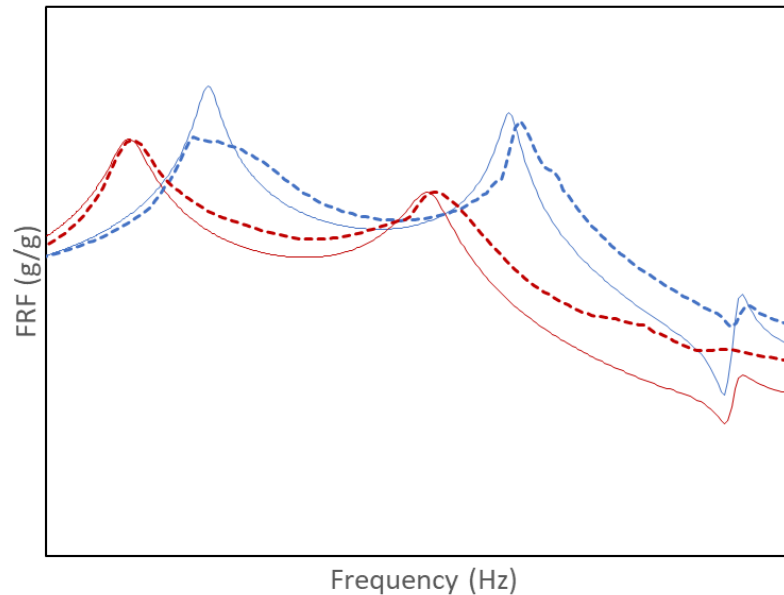
- Many more locations were examined/compared during the correlation process



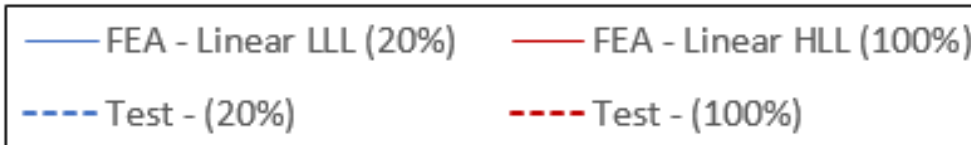
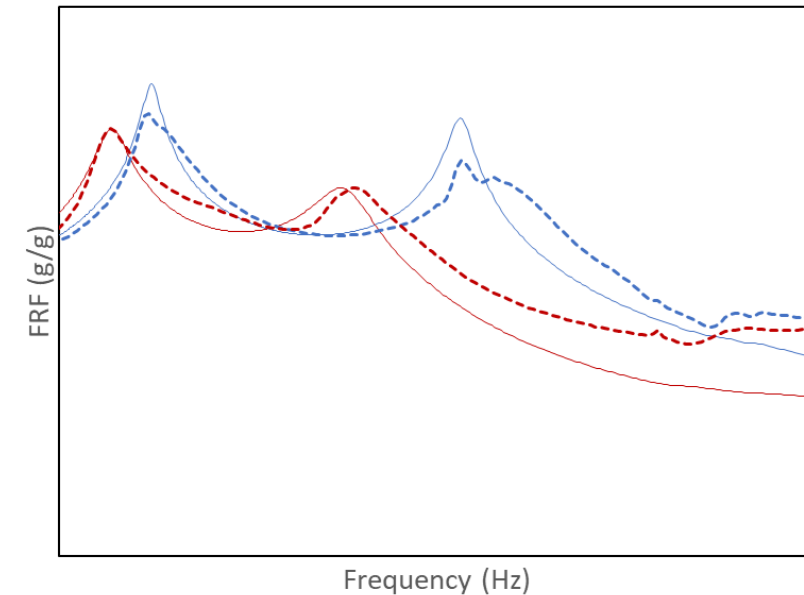
X-Drive - FRF - SAM00, CMLAS, Mass Sim-Z



Y-Drive - FRF - SAM00, CMLAS, Mass Sim-Y



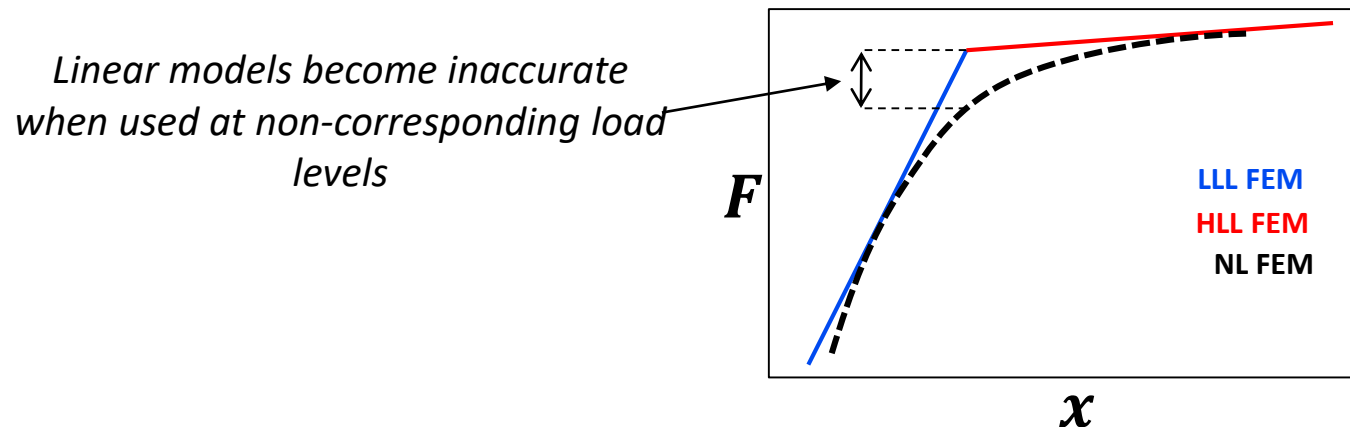
Z-Drive - FRF - SAM00, CMLAS, Mass Sim-X



Challenge 2: Nonlinear Correlation Motivation [2]

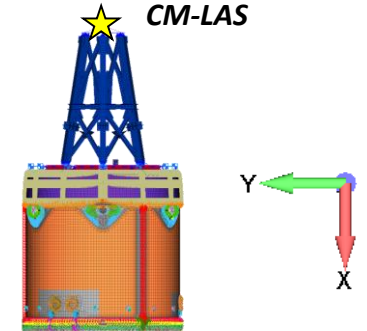
- Further elucidate the source and type of nonlinearity
- Capture nonlinear dynamics in a single model
- Inform the use of linear finite element model (FEM) in coupled loads analysis (CLA)
 - Can linearized models accurately predict flight responses?
 - What linear FEM should be used with each CLA load type (i.e. liftoff, transonic, etc...)?
 - Uncertainty introduced from using linearization of nonlinear system
 - Linear FEMs represent linearization about two different load levels (high load level (HLL) & low load level (LLL))

Linearization Uncertainty Illustration

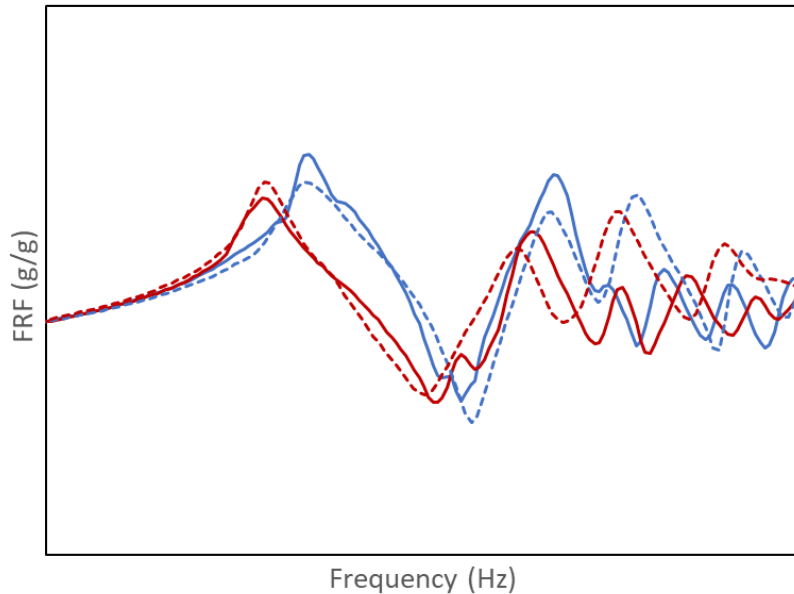


Challenge 2: Nonlinear FEM Correlation Results – Acceleration [2]

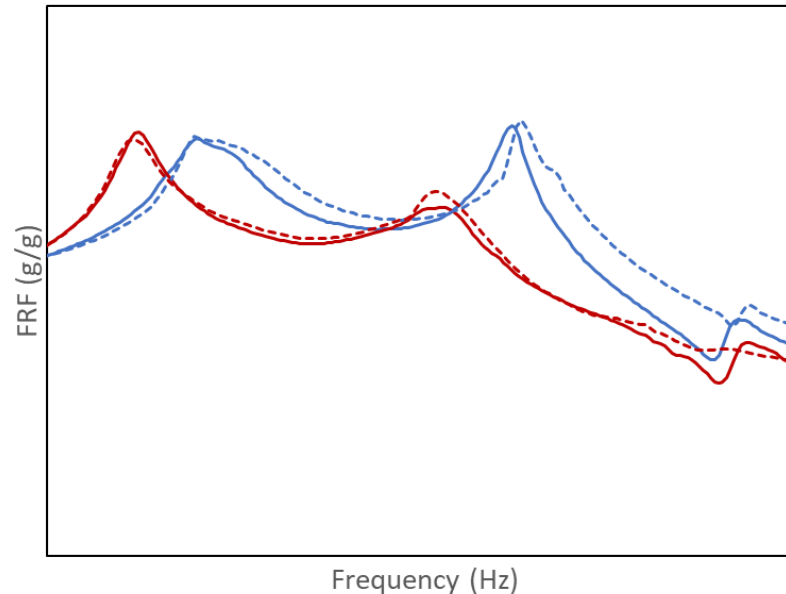
- **Representative location shown (CM-LAS)**
 - Many more locations were examined/compared during the correlation process



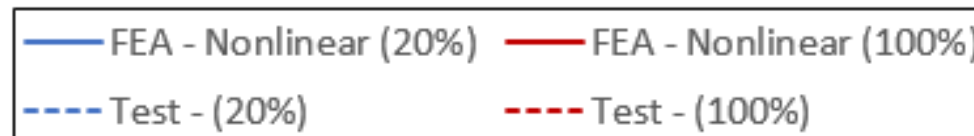
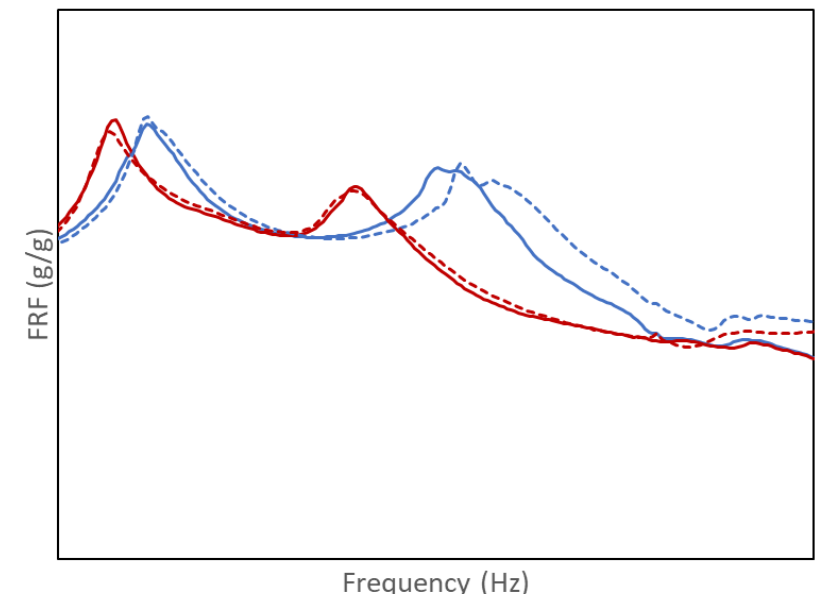
X-Drive - FRF - SAM00, CMLAS, Mass Sim-Z



Y-Drive - FRF - SAM00, CMLAS, Mass Sim-Y



Z-Drive - FRF - SAM00, CMLAS, Mass Sim-X



Challenge 2: Uncoupled, FEM-Derived Nonlinear Model Approach [3]



- **Examined application of Quasi-Static Modal Analysis (QSMA) to nonlinear model**
 - Nonlinear Abaqus model previously updated to match test data
- **Past applications of QSMA:**
 - Successfully applied to academic structures [4] but not to a structure as complex as the MPCV
 - Used for model updating procedures but not for time-domain simulations to an arbitrary input load
- **QSMA-based model developed for nonlinear, transient dynamic simulations**

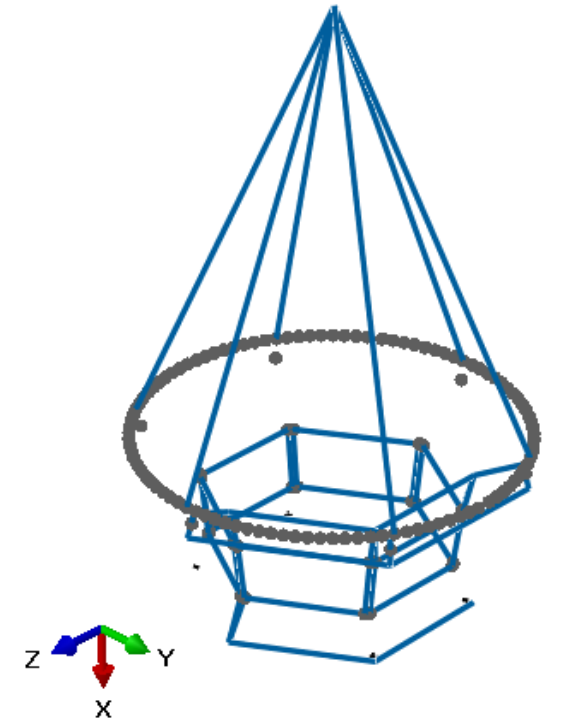
[3] Excerpt from the International Modal Analysis Conference XXXVIII, "Application of Quasi-Static Modal Analysis to an Orion Multi-Purpose Crew Vehicle Test Article," M.S. Allen—University of Wisconsin-Madison/ATA Engineering; J. Schoneman—ATA Engineering; W. Scott—ATA Engineering; J. Sills—NASA Johnson Space Center

[4] Lacayo & Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," MSSP, 2019

Challeng 2: Why is QSMA Useful? [3]



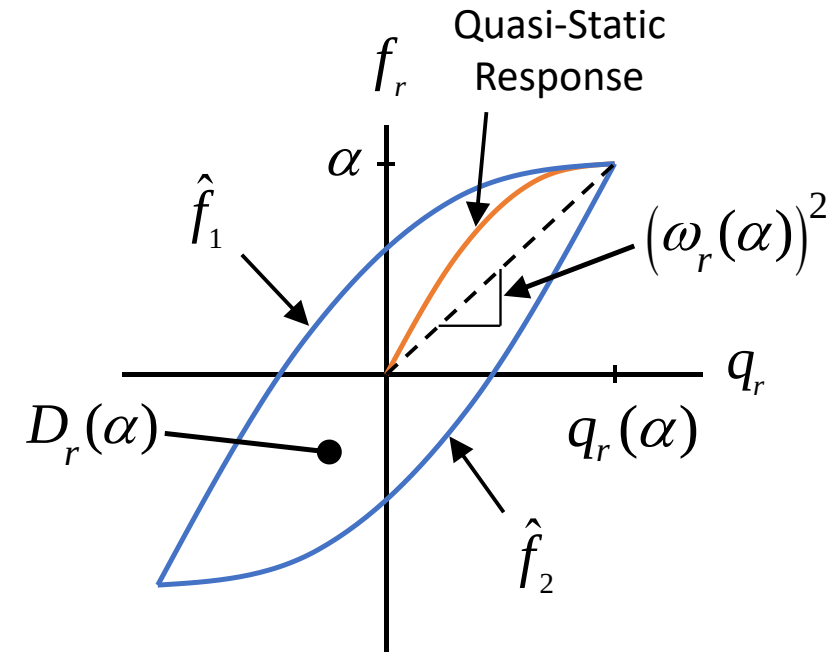
- **Suppose we have a nonlinear FEM**
 - FEM already updated to match test response
- **Dynamic response can be obtained via direct integration**
- **Commercial codes with robust NL capabilities take hours/days to integrate:**
 - Structural dynamic timescales
 - Meaningful time periods for CLA
 - Current commercial implementations of NL FEA do not scale well with CPU count
 - e.g. typical Abaqus speedup: 4x at 16 CPUs



Abaqus FEM representation
DMIG + NL Connector Elements

Challenge 2: How the QSMA model is derived [3]

- As an alternative to direct integration of a FEM, (QSMA) uses a nonlinear static analysis to characterize system dynamics
- Modal force/displacement curve obtained from a static analysis used to infer the nonlinear, hysteretic behavior of the structure
- Key assumption: Modal coupling can be neglected
 - Mode shapes at low displacements often vary only slightly at large displacements
 - Several studies have shown this can be an acceptable approximation in practice [5][6]
 - QSMA also provides a method to check this assumption



Schematic of QSMA Procedure [7]

[5] Roettgen & Allen, "Nonlinear characterization of a bolted, industrial structure using a modal framework," MSSP 2017

[6] Lacayo, Deaner, & Allen, "A Numerical Study on the Limitations of Modal Iwan Models for Impulsive Excitations," JSV 2017

[7] Allen, Lacayo, & Brake, "Quasi-static Modal Analysis based on Implicit Condensation for Structures with Nonlinear Joints," ISMA 2016

Challenge 2: Application of QSMA – Effective Frequency and Damping^[3]



- To study the r^{th} mode, apply a load proportional to a scale factor α :

$$\mathbf{f}_r(\alpha) = \mathbf{M}\boldsymbol{\phi}_r\alpha$$

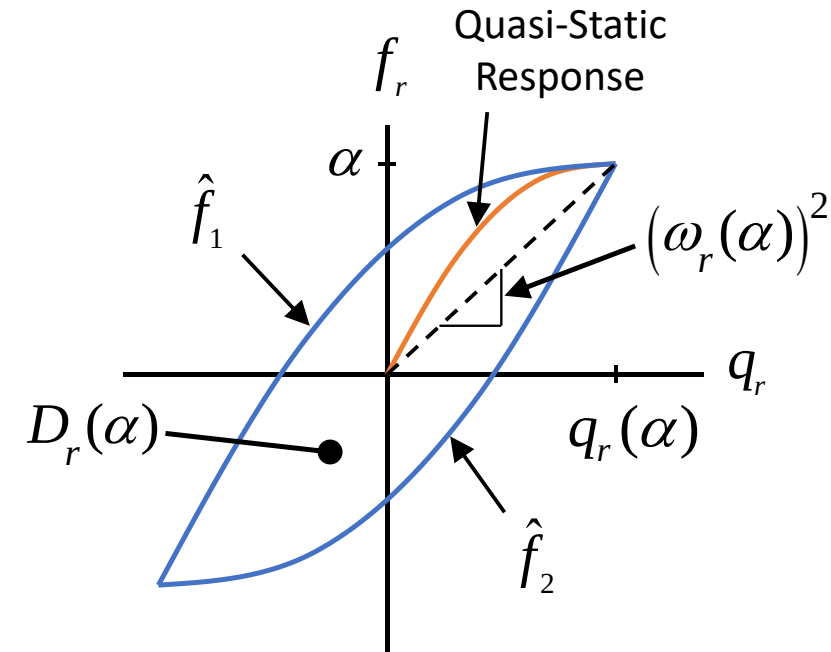
- α must be sufficiently large to exercise nonlinearity (key input)

- Obtain static response from NL FEM and map to modal space to obtain $q_r(\alpha)$

- Typically extract only the load-up response (red curve)

- Apply Masing rule to infer full hysteresis loop (blue curve)

- Energy dissipation per cycle $D_r(\alpha)$ can be used to compute effective damping $\zeta_r(\alpha)$ (adds to baseline viscous damping)
- Secant stiffness used to define effective frequency $\omega_r(\alpha)$



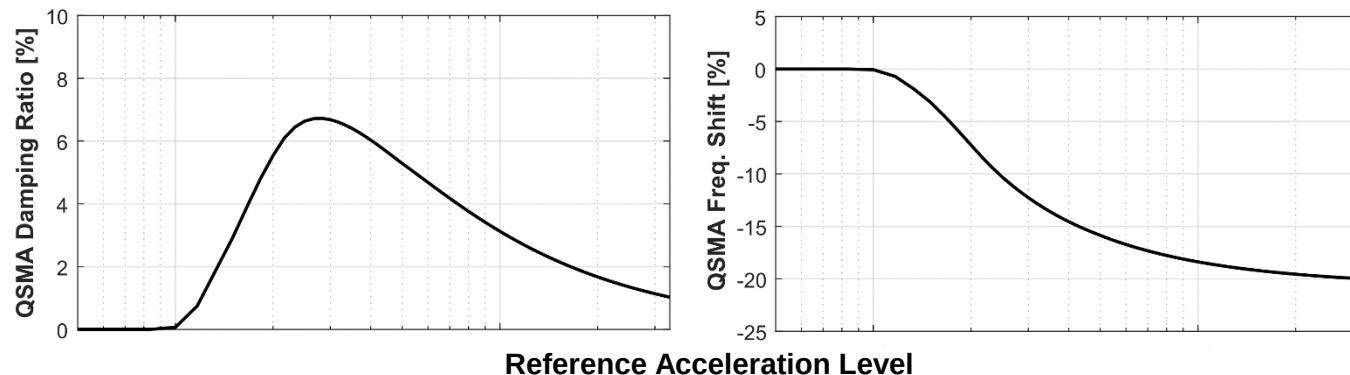
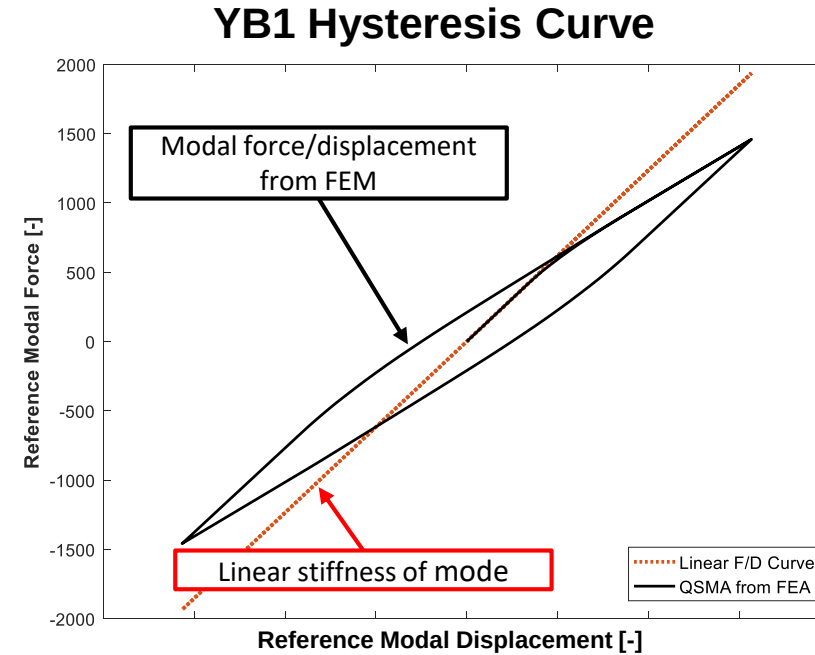
$$\omega_r(\alpha) \triangleq \sqrt{\frac{\alpha}{q_r(\alpha)}}$$

$$\zeta_r(\alpha) \triangleq \frac{D_r(\alpha)}{2\pi[q_r(\alpha)\omega_r(\alpha)]^2}$$

Challenge 2: Application to First Y-Bending Mode^[3]



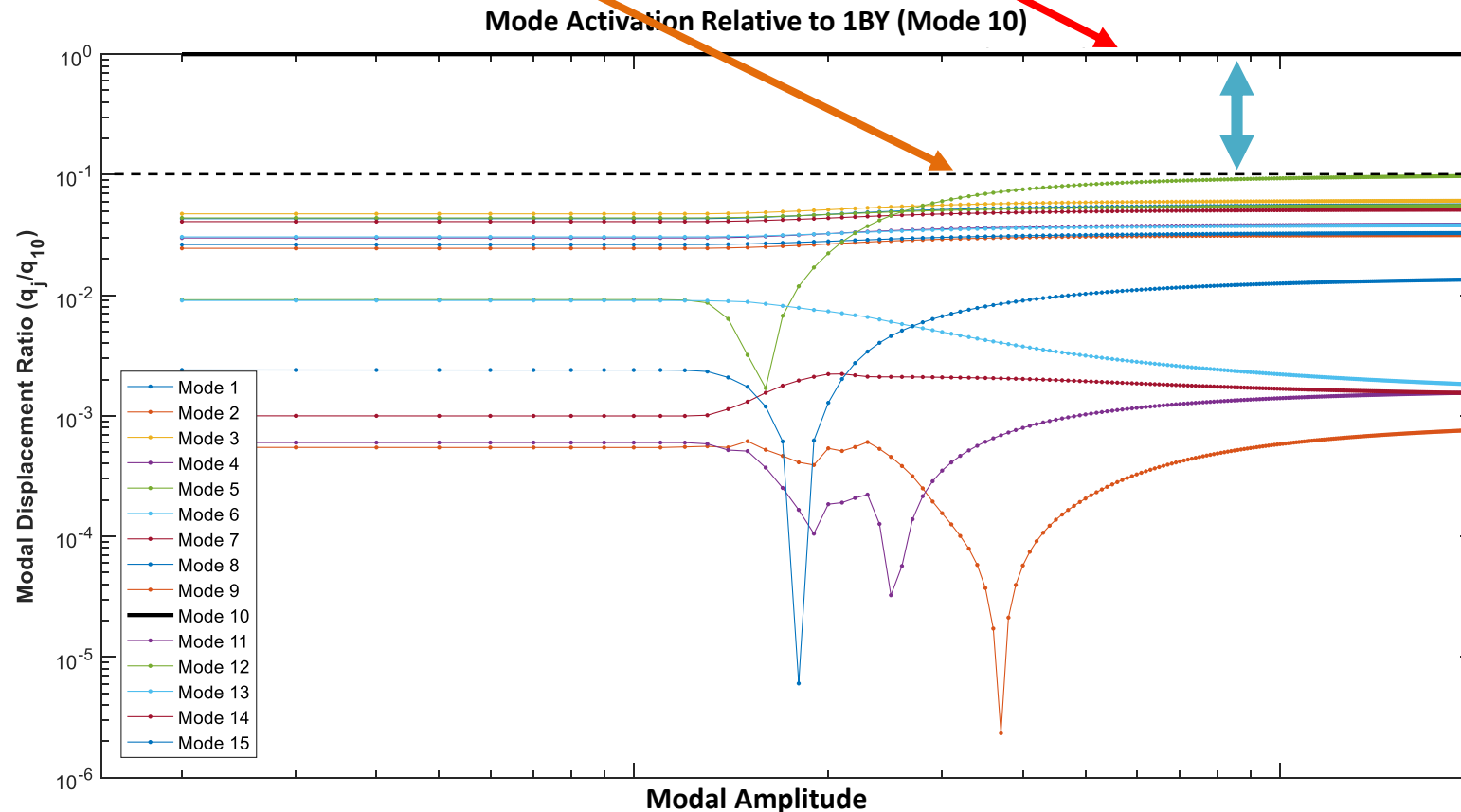
- Application of QSMA to primary Y-bending mode of FEM shows expected hysteretic behavior (right)
- Effective damping ratio and frequency shifts shown below
 - QSMA damping ratio is added to the standard modal viscous damping ratio



Challenge 2: Model shown to be modally uncoupled^[3]

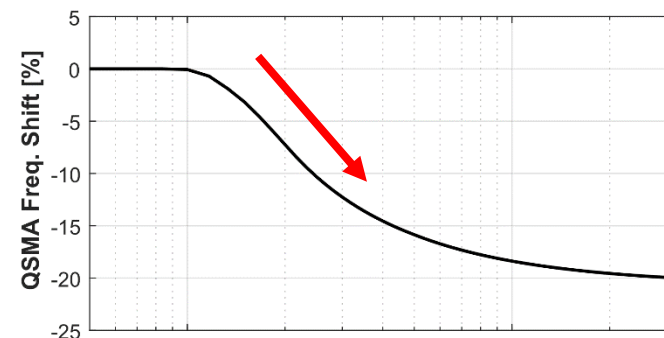
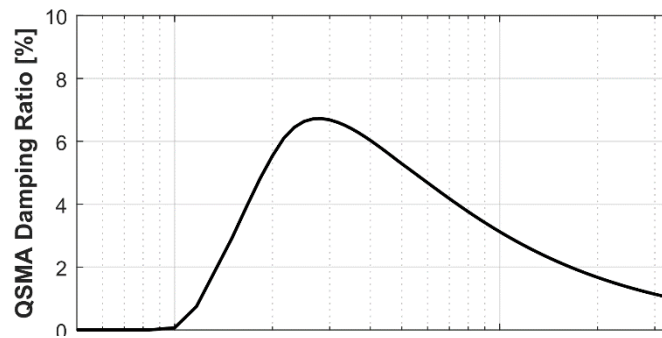
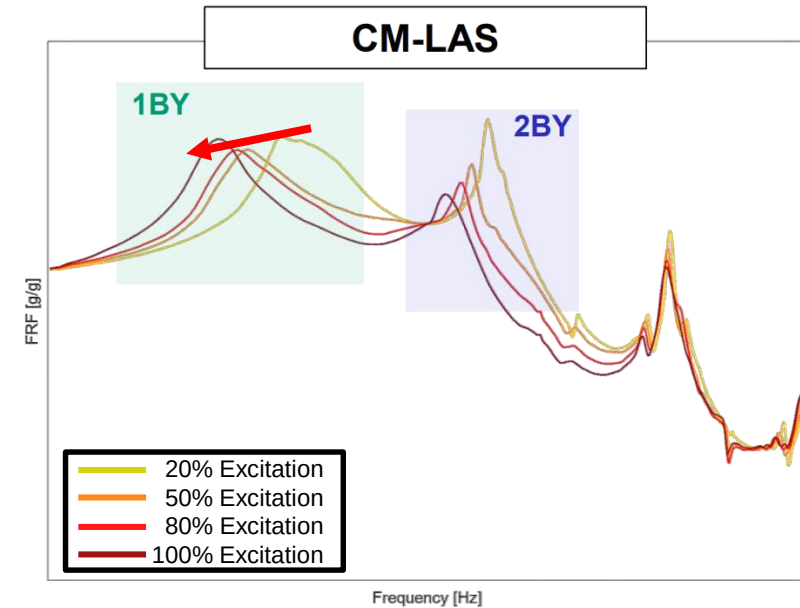


- Modal coupling can also be checked from static loading results
 - Reference mode at 1 for all amplitudes
 - In this case, 2nd bending mode (mode 12) reaches ~10% of 1st bending (mode 10) amplitude at peak loading



Challenge 2: Frequency and Damping in First Y-Bending Mode^[3]

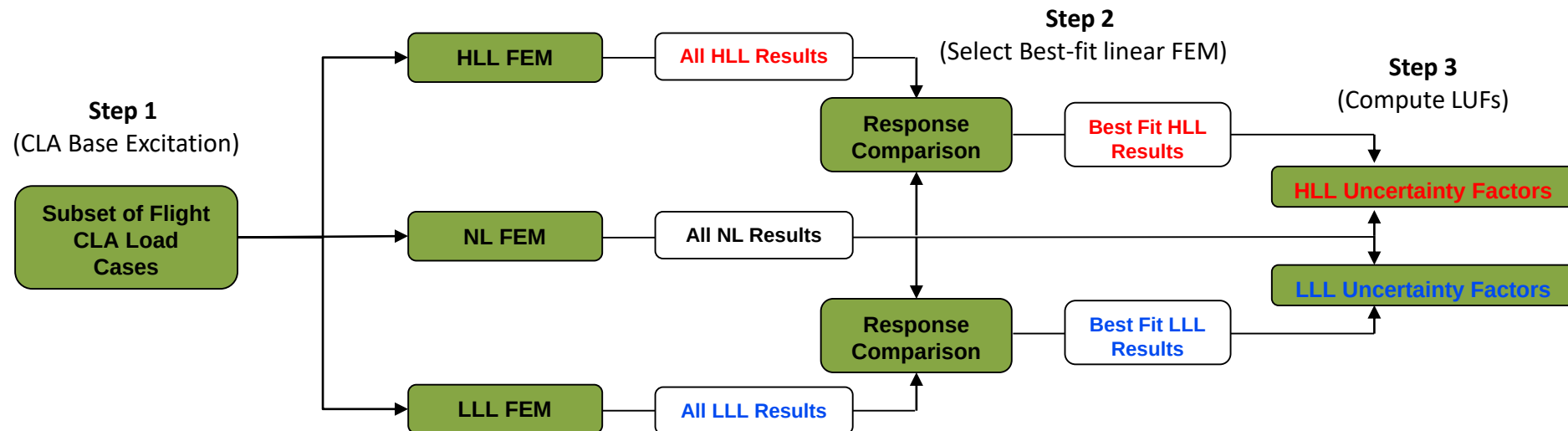
- Frequency drop is commensurate with observed softening from multi-level testing
- Comparisons of damping are more difficult by inspection
 - Extending QSMA model to the time-domain would allow direct comparison of test to the nonlinear model



Reference Acceleration Level

Challenge 2: Uncertainty Factor Derivation [2]

1. Apply subset of CLA load cases to NL FEM and linear FEMs
 - 5 X Liftoff
 - 6 X Transonic
 - 5 X Max Acceleration
2. Characterize best-fit linear FEM for each loading type
 - i.e. don't use LLL FEM for high-level load cases
3. Compute Linearization Uncertainty Factors (LUF) using best-fit models



Challenge 2: Response Comparison Methodology ^[2]



- **Utilized Pearson Correlation Coefficient**

- Provides top-level frequency and phase comparison between two signals
- Can help indicate which linear FEM best matches the true NL response

Note: Pearson correlation coefficient is a time-integrated (averaged) measure of the linear dependence of two variables and does not compare magnitudes between time histories

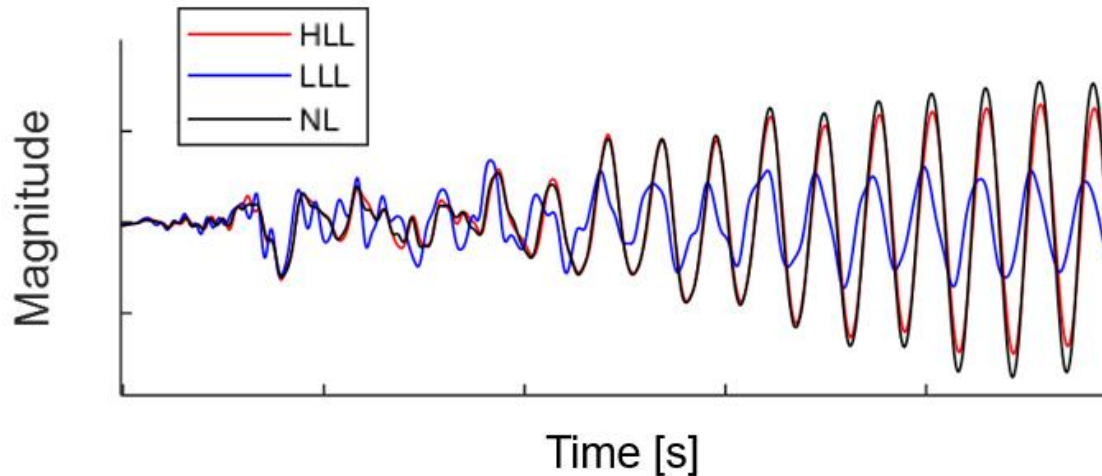
$$\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^N \left(\frac{A_i - u_A}{\sigma_A} \right) \left(\frac{B_i - u_B}{\sigma_B} \right)$$

Challenge 2: Response Comparison Example [2]

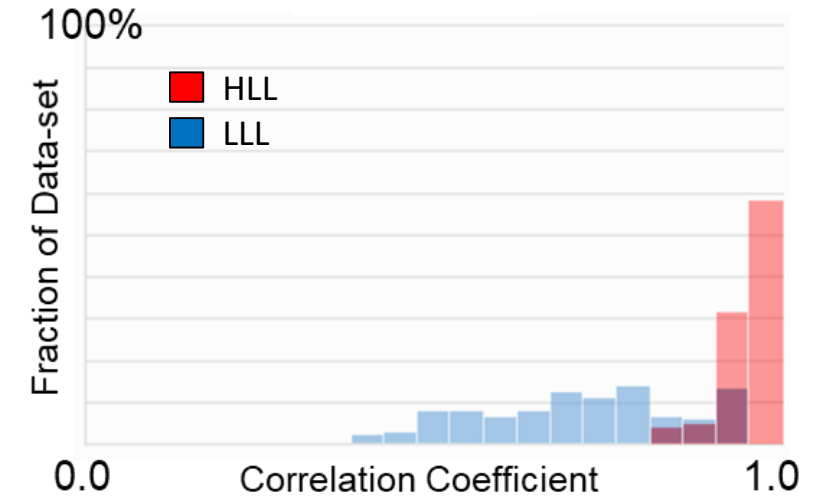


- **Correlation Coefficient evaluated at all response locations**
 - Evaluated separately for each loading type (i.e. Liftoff, Transonic, Max Acceleration)
- **Summarized Correlation Coefficients using histogram of all locations and load cases**

Sample Response Comparison at LAS (Z)



Liftoff Acceleration Response Comparison Summary

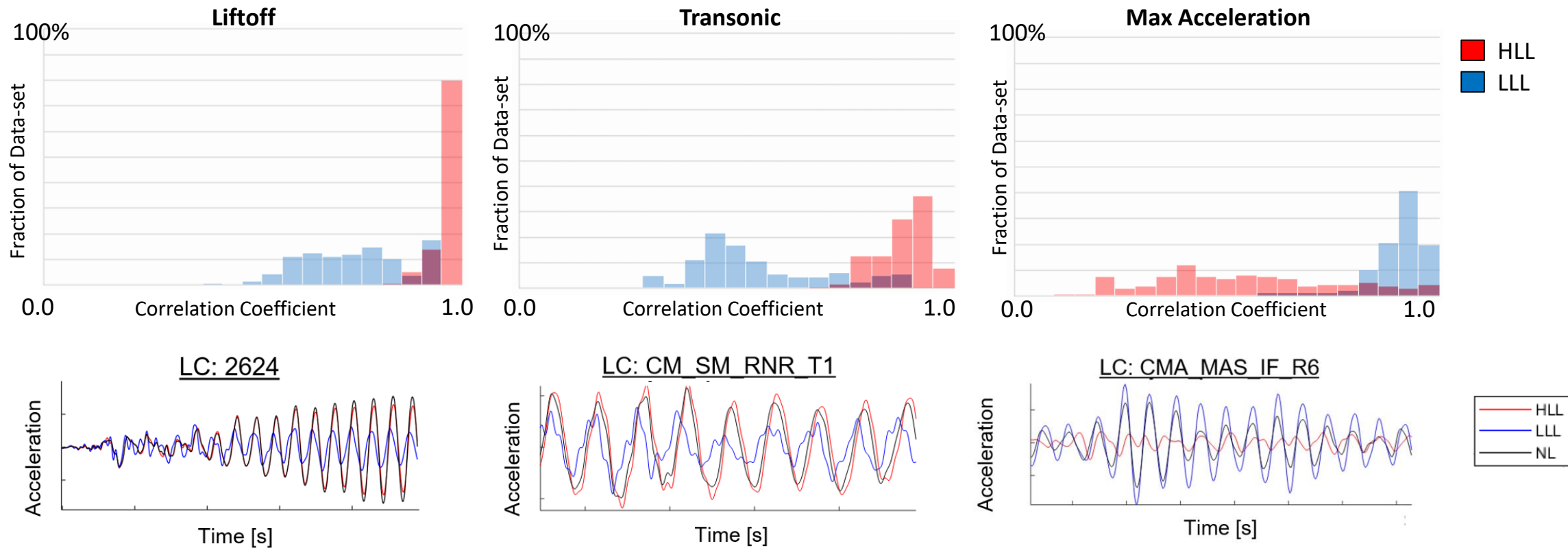


Challenge 2: Acceleration Response Comparison Summary ^[2]



- Liftoff and Transonic load cases best represented by HLL FEM
- Max Acceleration load cases best represented by LLL FEM

Correlation Coefficient Distribution By Load Type





Challenge 2: Uncertainty Factors [2]

- Max uncertainty factors were computed for each loading type using the appropriate linear model determined by correlation coefficients
- When appropriate correlated linear model is used, uncertainty factors are small (<1.25)

	Liftoff	Transonic	Max Acceleration
Max Uncertainty Factor	1.24	1.01	0.99
Selected Linear Model	High Load Level	High Load Level	Low Load Level
Probability	98%	98%	98%
Confidence	96%	98%	96%

Challenge 3: Operational Flight Measurements^[8]

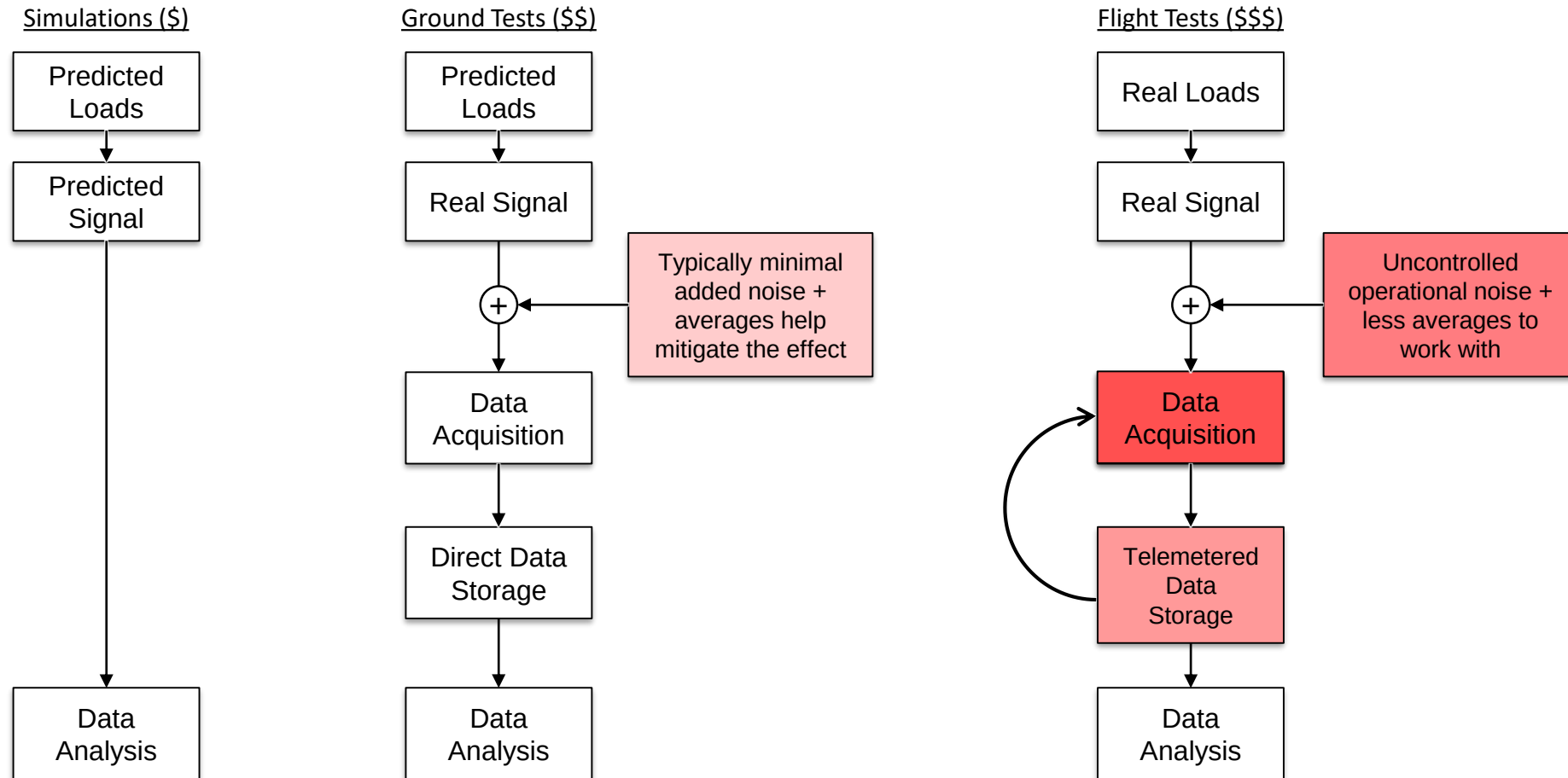


- **Flight data measurements offer greatest potential for system model characterization**
 - Accurate boundary conditions
 - Real loading
 - Accurate dynamic fuel conditions
 - Measure unpredicted events



[8] Excerpt from the International Modal Analysis Conference XXXVIII, "End-to-End Assessment of Artemis-1 Development Flight Instrumentation," A. Doan–Quartus Engineering Incorporated; A. Johnson–Quartus Engineering Incorporated; P. Bremner–AeroHydroPLUS; J. Sills–NASA Engineering Safety Center; T. Loogman–Quartus Engineering Incorporated

Challenge 3: Challenges with Flight Measurements^[8]



Challenge 3: Investigation Overview^[8]



- **Objectives:**

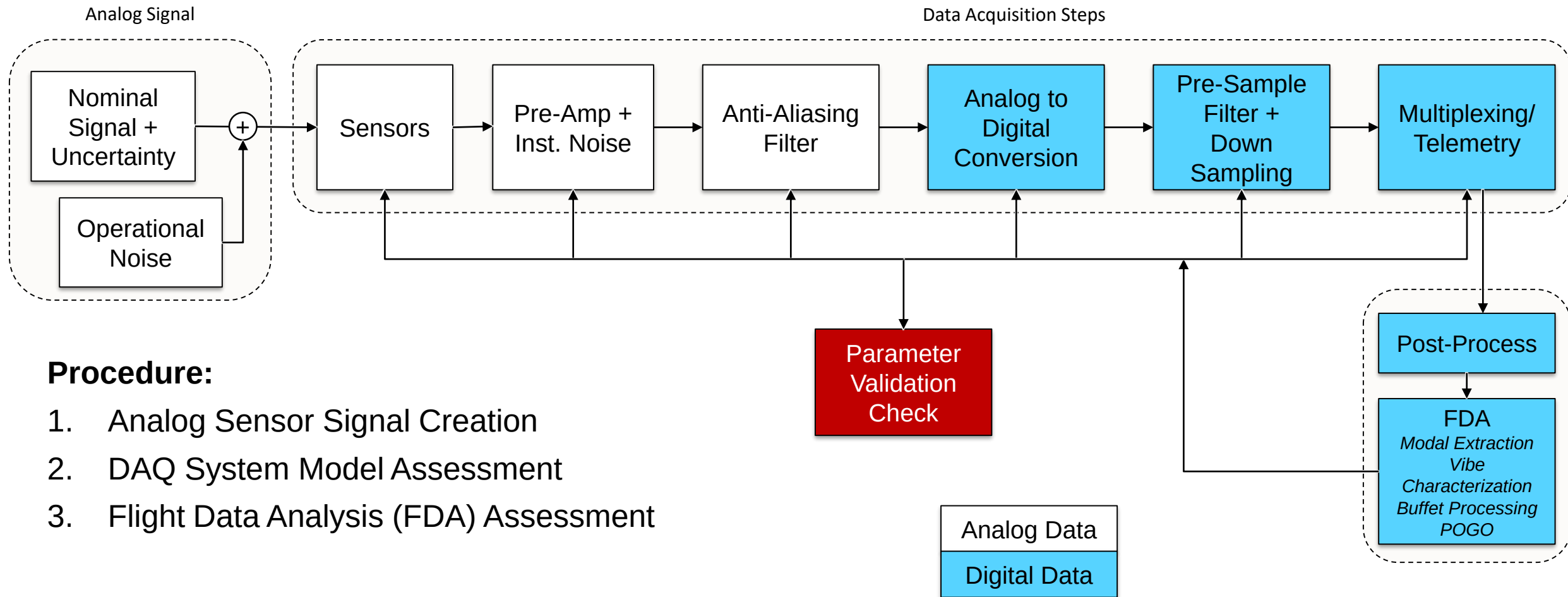
- Predict performance of Artemis-1 Development Flight Instrumentation (DFI) for Flight Test Objectives (FTO)
- Pinpoint problem areas and recommend fixes

- **Multiple FTOs investigated**

- Simulated data acquisition process
- Performed mock Flight Data Analysis (FDA)

FTO	Sensors				
	Low Freq Accels	High Freq Accels	Internal Pressure	External Pressure	External Mics
Modal Extraction	X				
Vibration Characterization		X			
POGO	X		X		
Aero/Buffer				X	X

Challenge 3: DFI Simulation Overview^[8]



Procedure:

1. Analog Sensor Signal Creation
2. DAQ System Model Assessment
3. Flight Data Analysis (FDA) Assessment

Challenge 3: Nominal Signal Predictions^[8]

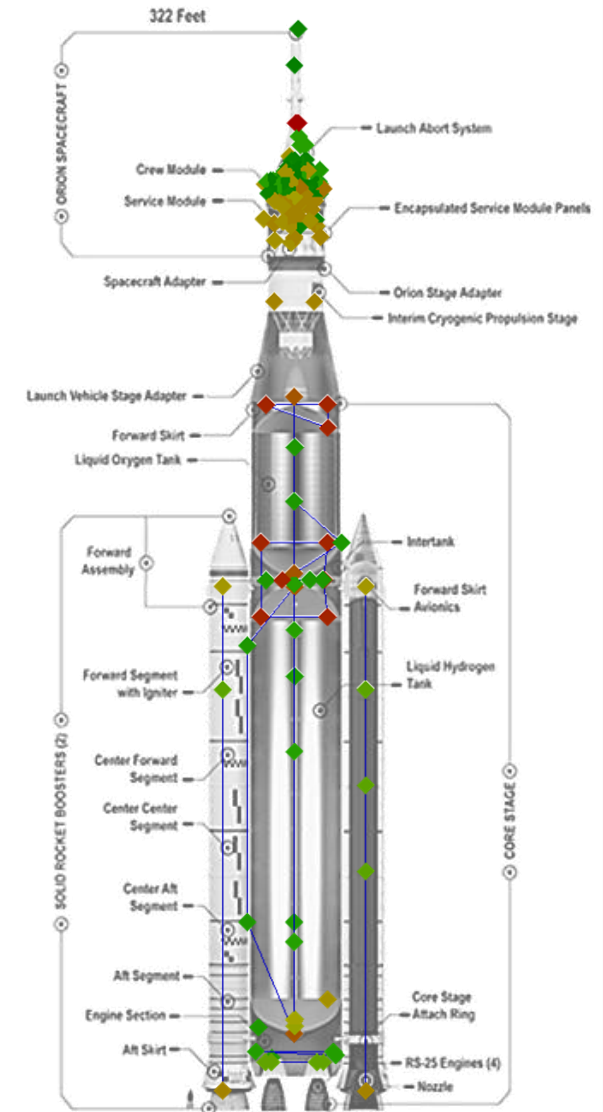
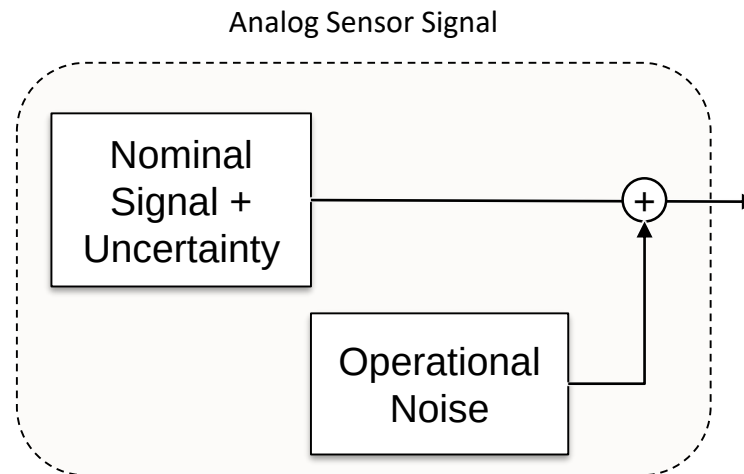


- **Nominal signals = portion of signal we want to measure**
- **Signal predictions unique based on FTO:**
 - Low frequency accelerometers: recovered signals from CLA transient analysis
 - High frequency accelerometers: predicted vibration environments
 - Buffet pressure sensors and aeroacoustic microphones: signals from full scale wind tunnel data
 - Pogo pressure and acceleration: derived from state-space matrices

Challenge 3: Operational Noise Estimation^[8]



- **Aero-acoustics assumed to be largest contributor to unwanted sensor noise**
 - Assessed max predicted environments (MPE) based on wind tunnel data and aeroacoustic models
 - MPEs defined as power spectral densities (PSDs) by zone and/or component throughout SLS
- **Mapped MPE levels to each individual sensor to approximate operational noise environments**
 - Synthesized transients from operational noise PSDs

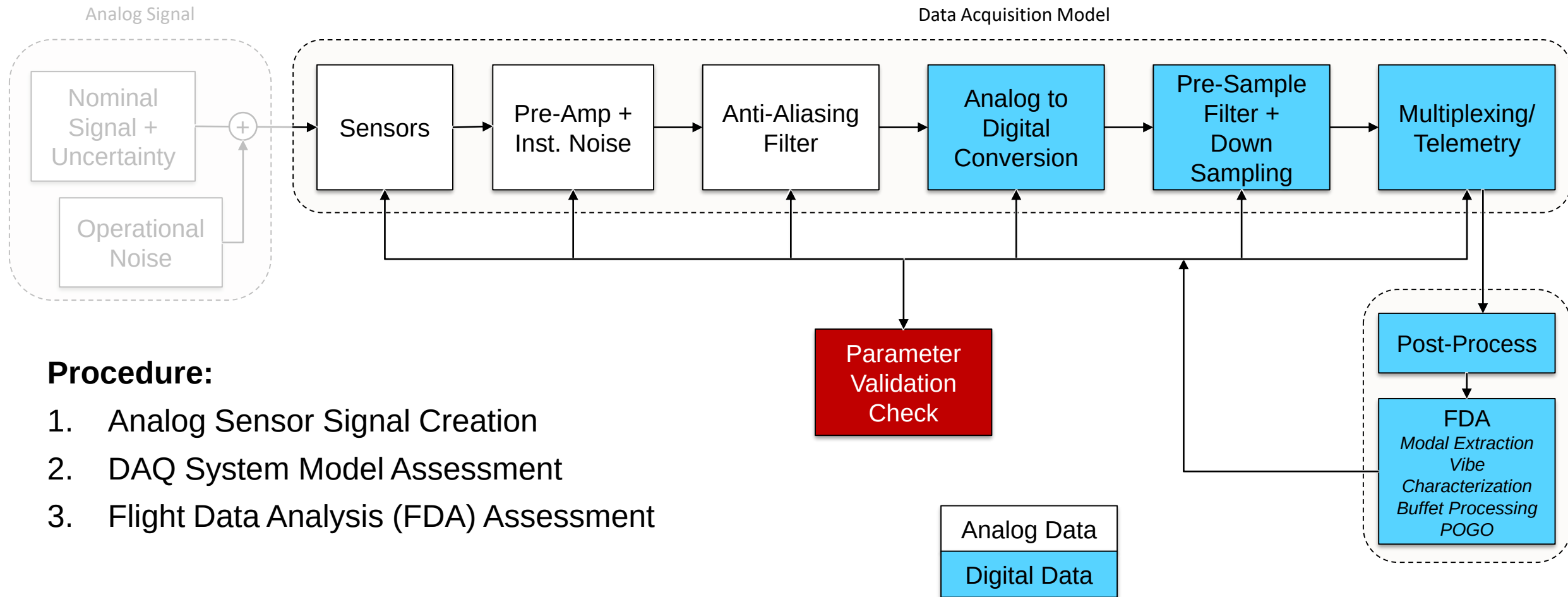


Challenge 3: Addition of Operational Noise^[8]



- **MPE operational noise environments added to nominal signal throughout ascent**
 - 0dB levels applied for liftoff, transonic, and Max Q
 - -12dB knock down applied for quiescent stages of ascent
 - SP-8050 Saturn I and STS flight data used to estimate knock down

Challenge 3: DFI Simulation Overview^[8]



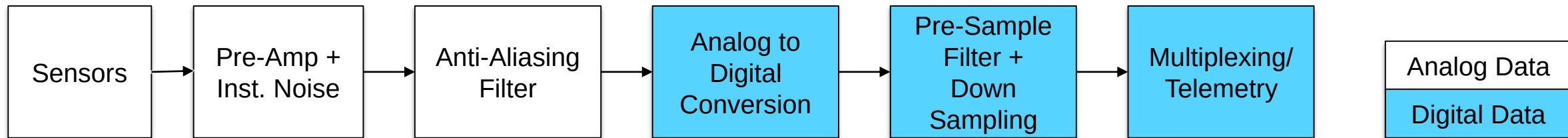
Procedure:

1. Analog Sensor Signal Creation
2. DAQ System Model Assessment
3. Flight Data Analysis (FDA) Assessment

Challenge 3: Consolidated Data Acquisition Settings^[8]



- **Data acquisition (DAQ) parameters consolidated for each sensor in DFI system**
 - Sensor settings
 - Sensor ranges, resolution, and coupling
 - Data acquisition cards
 - Filter settings, gains, word size, sampling frequency
 - Telemetry system
 - Time synchronization variation between acquisition systems
- **Computationally modeled each step in DAQ chain**



Challenge 3: Critical Parameters to Data Quality^[8]

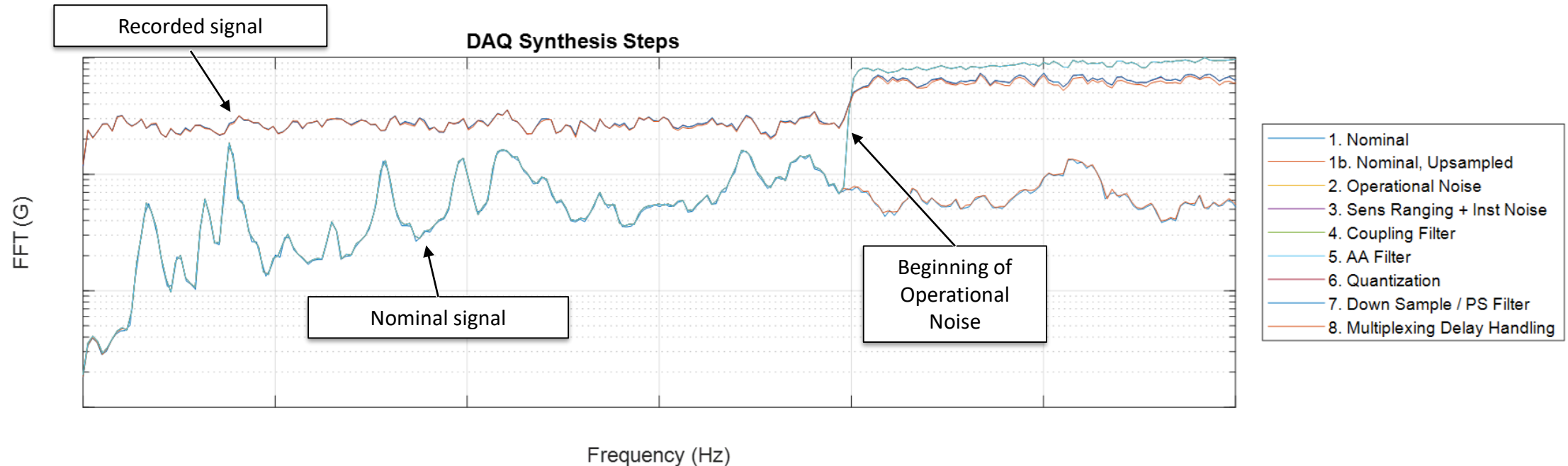


- **Multiple parameters deemed critical to signal quality throughout investigation**
 - Clipping: sensor range, anti-aliasing filter, and digital range (set by analog gain)
 - Resolution: gain, word size (dynamic range/bit resolution)
 - Phase distortion: pre-sample filter settings
- **How do you fix the data acquisition parameters if signal is compromised?**
 - Recommended fixes depend on source of corruption and FTO

Challenge 3: Effect of Signal Clipping^[8]



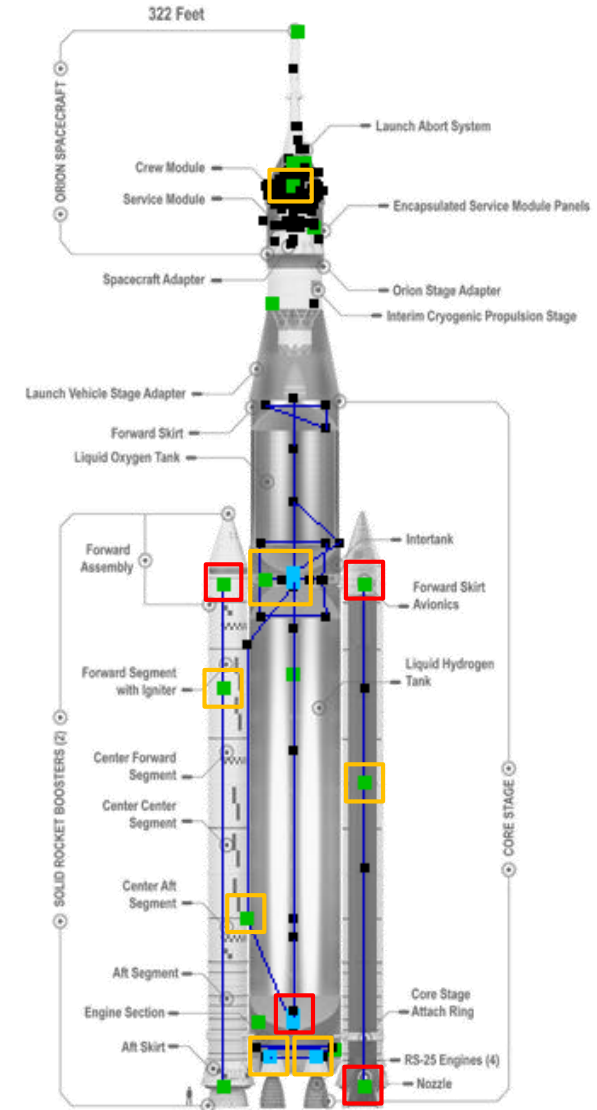
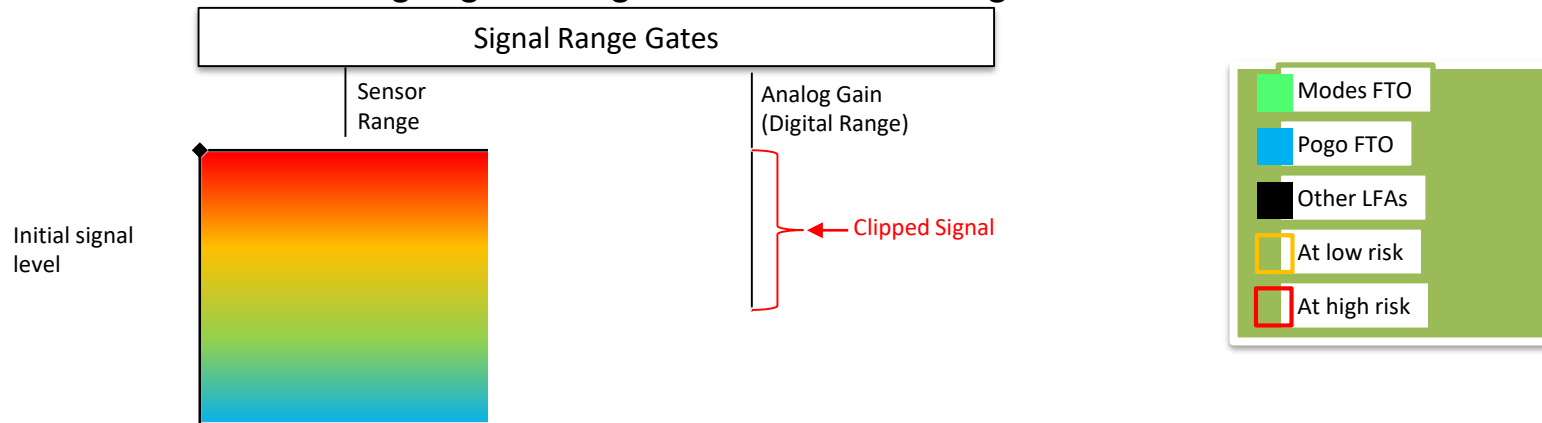
- Clipping leads to loss in spectral fidelity
- Clipping prediction requires complete understanding of:
 - All operational environments
 - All range and filter settings



Challenge 3: SLS Clipping Check^[8]



- **Clipping of sensors assessed for each FTO**
 - Used 3σ of stochastic MPE levels
 - Compared peak to each sensor and digital range
- **At risk sensors require unique solutions**
 - Multiple options for fixing the problem
 - Best solution depends on the intended use of the data
 - Better to sacrifice resolution or bandwidth?
 - Increasing digital range -> decrease in digital resolution

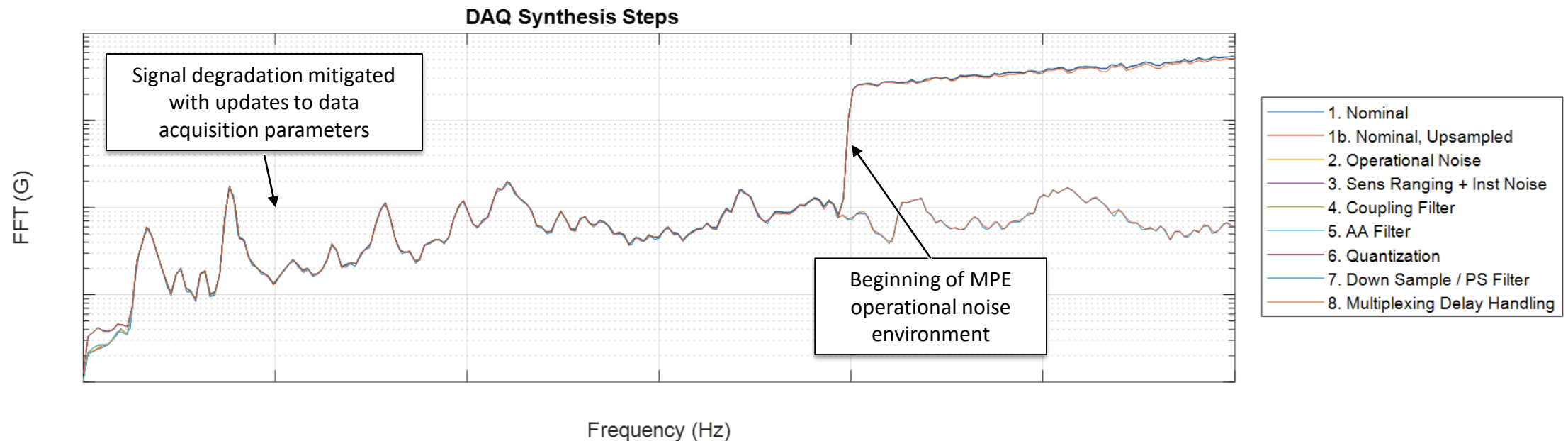
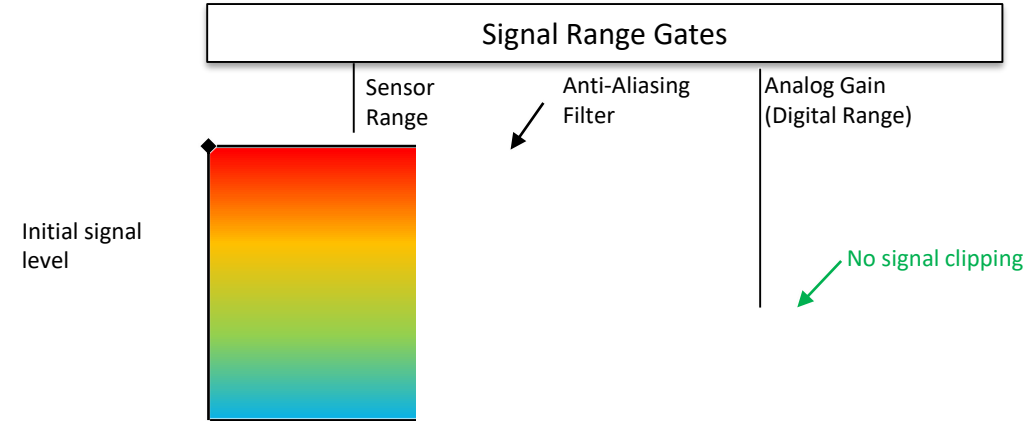


Challenge 3: System Performance Improvement^[8]



- **Updates to anti-aliasing filter could rectify data corruption**

- FTO success relies on high resolution at low frequencies
- Can sacrifice high frequency content without affecting FTO



Challenge 3: Summation^[8]



- **Flight measurements on launch vehicles:**
 - Have many advantages over ground based tests
 - Also come with unique challenges
 - Typically only get one opportunity to get the desired data
 - Unavoidable operational noise
 - Less robust storage which limits fidelity of data acquired
- **End-to-end assessment is important tool to guide data acquisition design and mitigate data corruption risks**
 - Necessary to find solutions that both mitigate data pollution while still accomplishing the test objective
 - If done before design of DAQ system, can save lots of headache down the road

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