
Image credit: NASA/Joel Kowsky

Liftoff Environments Overview

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NASA Marshall Space Flight Center
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Outline

- **Background**
- **Liftoff Environments**
  - Pre-Launch
    - Excess Hydrogen Pop
    - RS-25 Nozzle Flow Transient Acoustics
    - Core Stage Engine Overpressure
    - Hold-down Acoustics
  - Post-Launch
    - Booster Igniter Shock
    - Booster Ignition Overpressure & Duct Overpressure
    - Liftoff Acoustics
    - Infrasonic Acoustics
- **Select Data Assessments**
  - Time Correlations
  - Sensor Port Resonances

Image credit: NASA/Chris Coleman, Kevin Davis

Background

- **Artemis I launch on November 16th 2022**
  - First integrated flight test of Orion and SLS

- **Vehicle sea-level thrust at liftoff**
  - Space Shuttle – 6.5 million pounds
  - Saturn V – 7.6 million pounds
  - SLS – 8.8 million pounds

- **External vehicle pressure sensors and microphones**
  - Total of 331 sensors (sampling rate of 50 sps to 25,000 sps)
  - Total of 285 sensors applicable to launch environments (minimum of 100 sps)
  - Flight evaluation supporting flight objectives and verification of launch environment models

Image credit: NASA/Cory Huston

Liftoff Environments Overview

- **Liftoff Environments**
  - Liftoff environment – represents a source of loading during the hold-down or liftoff phase of a rocket launch.
  - A launch vehicle is subjected to transient and oscillatory pressure loading on its exterior surfaces induced by engines and boosters during vehicle hold-down and liftoff
    - A principal source of structural vibration which may result in the malfunction of vehicle components or the fatigue of exterior skin panels or component brackets (Loads)
    - External pressure loading gives rise to sound pressure within the vehicle which may impact components and other equipment (Vibroacoustics)
    - External pressure loading gives rise to sound pressure inside the crew cabin which may impact the crew's health, safety, or ability to communicate (Crew)
  - There are eight Liftoff Environments for SLS

8 Liftoff Environments

- **Acoustics**
  - Liftoff Acoustics
  - Hold-down Acoustics
  - RS-25 Nozzle Flow Transient Acoustics
  - Infrasonic Acoustics
- **Pressure Transients**
  - Booster Ignition Overpressure & Duct Overpressure
  - Excess Hydrogen Pop
  - Booster Igniter Shock
  - Core Stage Engine Overpressure

Liftoff Environments Team

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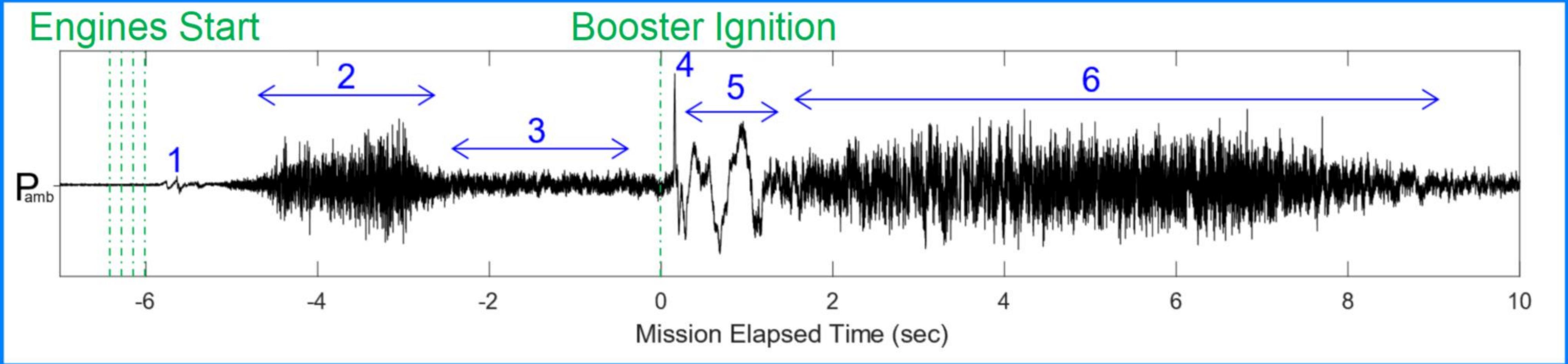
Pressure Measurement on SLS



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(6) Liftoff Acoustics and Infrasonic Acoustics

Excess Hydrogen Pop

- **Background**
  - Excess hydrogen accumulation
    - Results from ignition of excess hydrogen
    - RS-25 engines are hydrogen fuel lead: fuel valve command, fuel valve moves, flow initiated, ignition
    - Core Auxiliary Power Unit (CAPU) exhaust ducts emit hydrogen
  - Deflagration or detonation depends on how much H_2 accumulates and how well it mixes in air
  - Can result in damaging steep-fronted waves

Imagery showing HBOIs

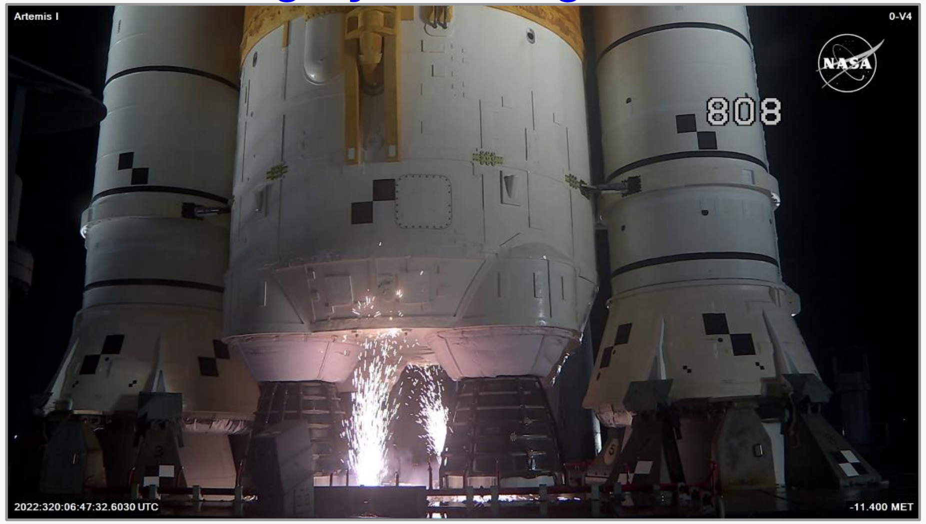
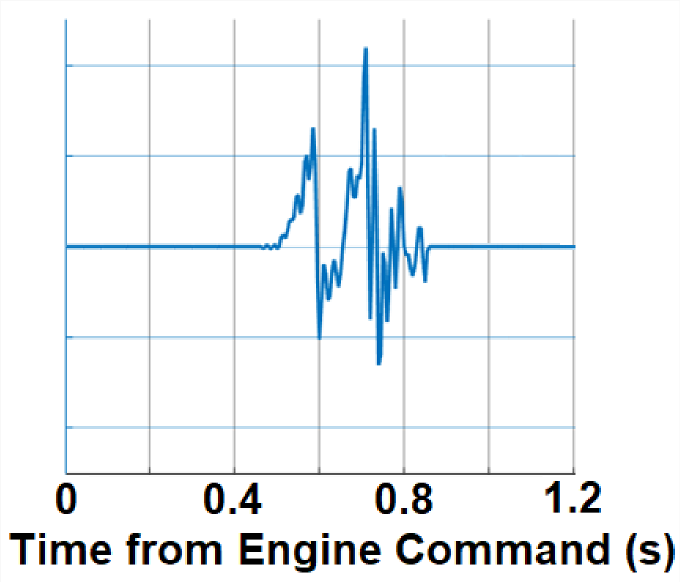


Image credit: NASA

- **Mitigation Approach**
  - Hydrogen Burn-off Igniters (HBOIs) - intended to burn off the hydrogen/air mixture before it accumulates
- **Modeling Approach**
  - Predictions based on reconstruction of heritage data including correlations from tests without HBOIs

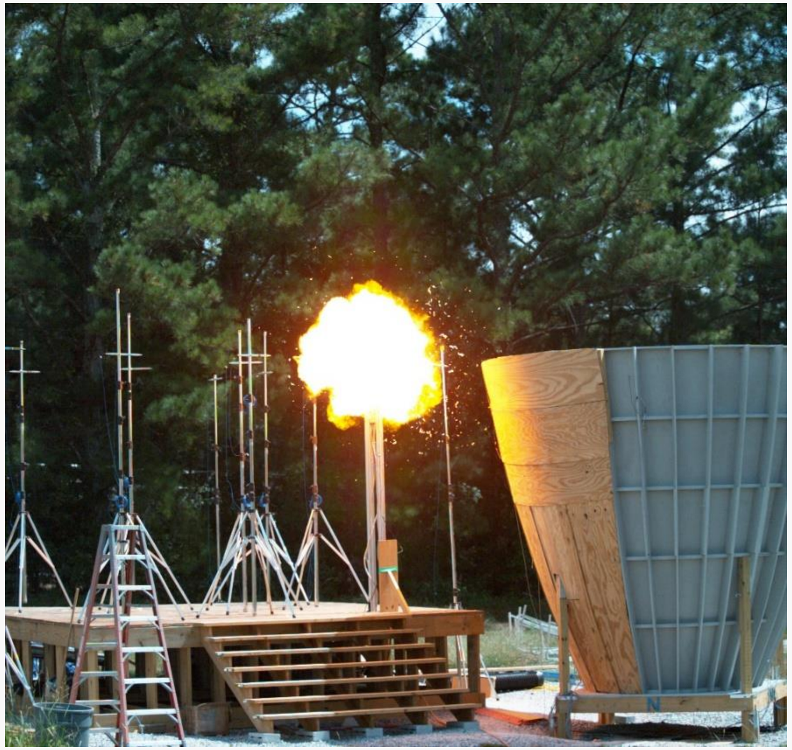
Core Heat Shield Excess H_2 Pop



H_2 Pop Test

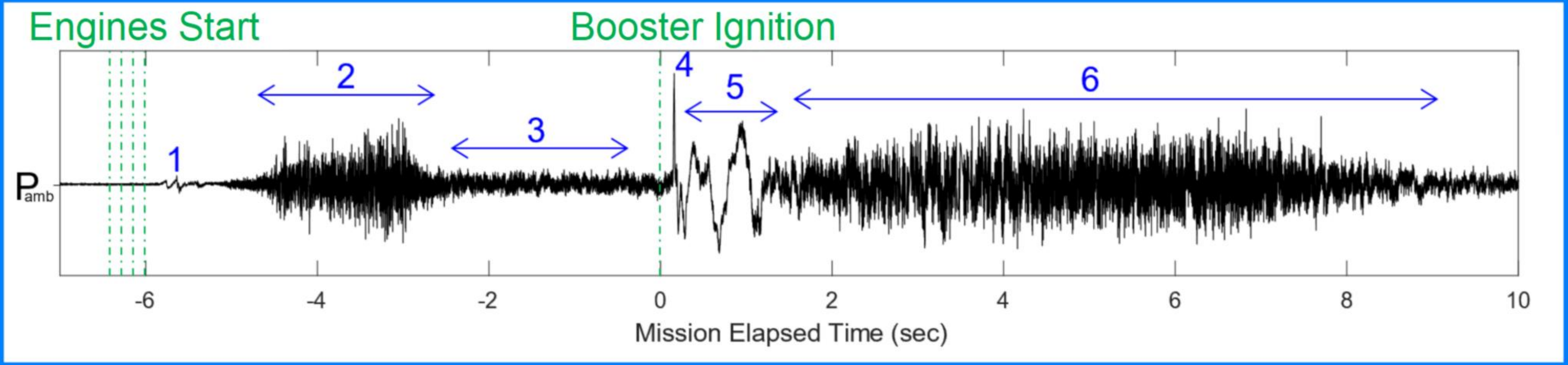
HUCTA Test Video

- **Hydrogen Uncontained Combustion Test Apparatus (HUCTA) Test**
  - Test to help understand environment at Booster nozzle throat plug
  - The bang is a simulated H_2 pop, tuned to the max environment on the platform (representing the SLS Core Heat Shield).
  - The plug environment is measured.



Simulated H_2 Pop

Pressure Measurement on SLS



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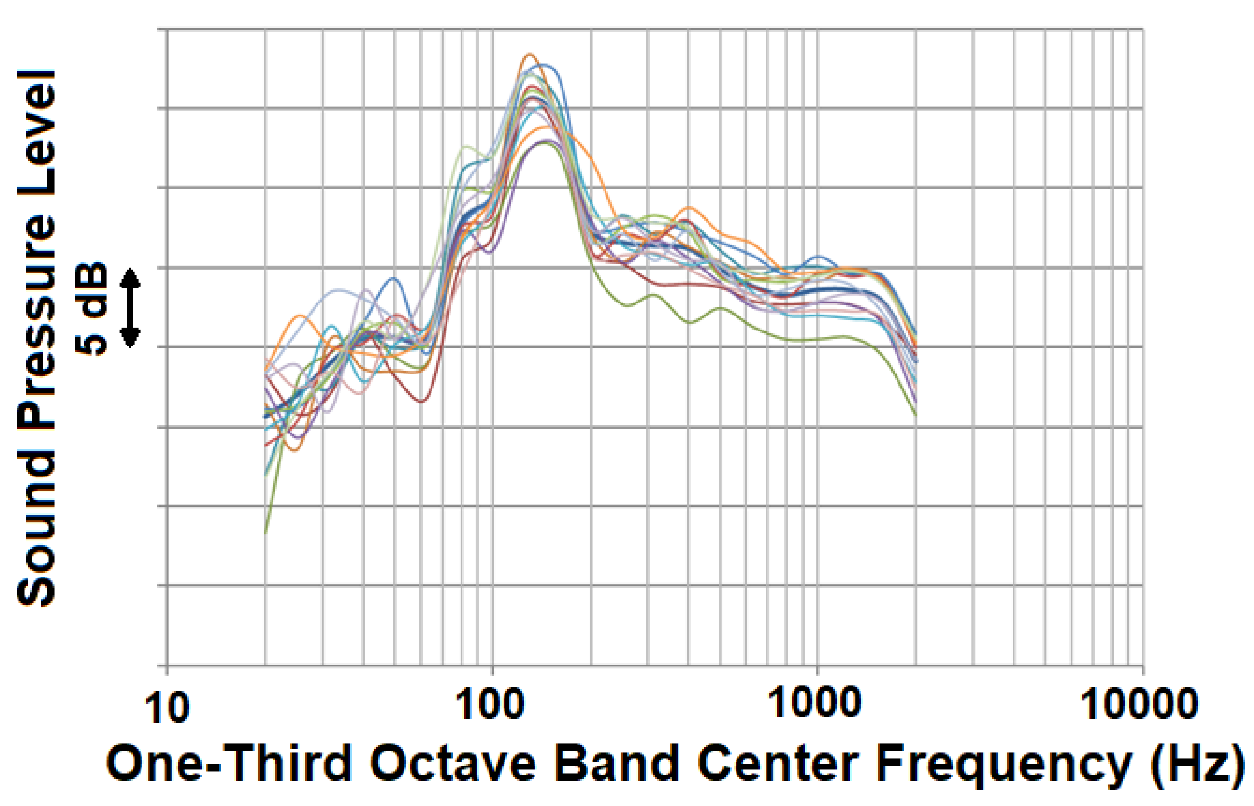
RS-25 Nozzle Flow Transient Acoustics

- **Background**
  - Produced by unsteady flow that develops in the RS-25 nozzle during its start and shutdown operations (during filling/emptying of nozzle)
  - Short duration 0.75 seconds during hold-down
  - Response generally peaks in the 125 Hz 1/3 octave band
  - Loudest liftoff event on Space Shuttle
  - Not always present on Shuttle – SLS had some low amplitude residual response in the 125 Hz octave band
- **Modeling Approach**
  - Predictions are based on reconstruction of heritage data and correlations from Space Shuttle launches
  - Applicable especially on Core Heat Shield
  - Peak is bounded due to expansive data history
- **Mitigation Approaches**
  - None - RS-25 start transient dependent; IOP/SS has some influence on the acoustics



Nozzle Flow Transient on Space Shuttle Orbiter Aft Heat Shield

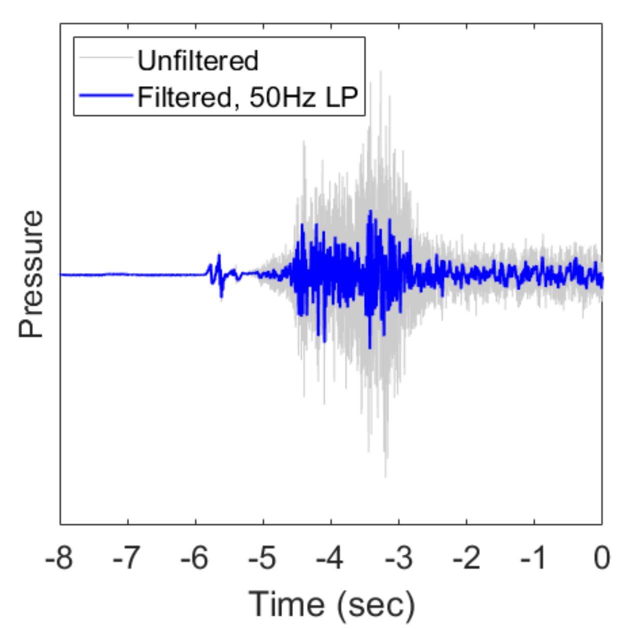
RS-25 Nozzle Flow Transient Acoustics

- **RS-25 NFT Acoustics Mechanism**
  - Flow fills nozzle during start transient as Pc increases.
  - When the location of flow separation reaches the end on nozzle, it becomes unstable.
    - The plume shock structure oscillates in and out of the nozzle: dynamic flow reattaching to the nozzle
  - Flow unsteadiness is the source of NFT Acoustics
    - The unsteadiness is also the source of sideloads leading to ovalization of nozzle (observed in video)

RS-25 Engine Test

Core Stage Engine Overpressure

- **Background**
  - CSE Overpressure Mechanism
    - Primarily the same as that of RS-25 NFT Acoustics
      - Unsteady flow during engine start
      - But also captures transient characteristics due to engine start
    - It is the time history definition in the low frequency range (below 50 Hz)
      - This definition is customer specific (loads)
    - Begins roughly at T-4.5 seconds and persists to T-2.5 seconds



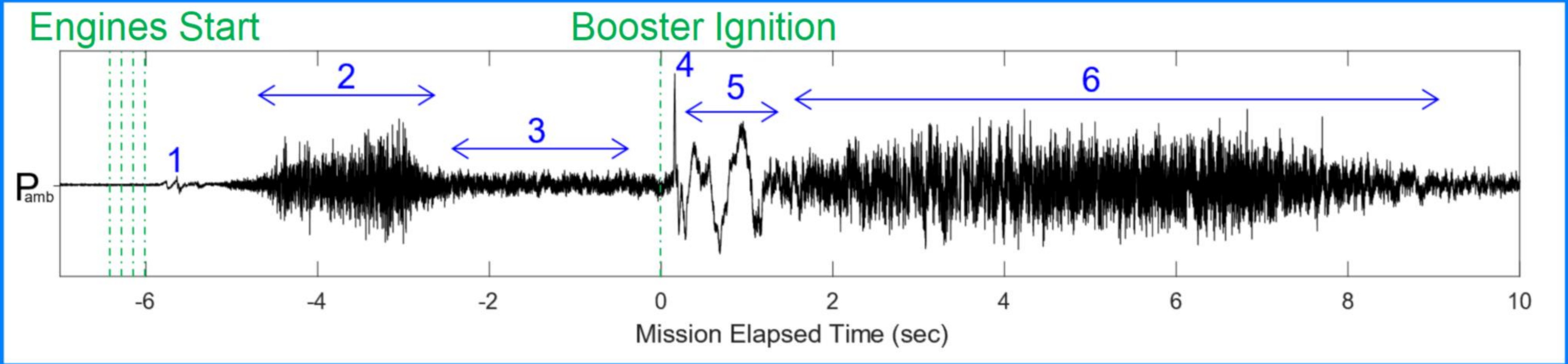
Core Stage Engine Overpressure
(Low on Vehicle)

Image credit: NASA

Artemis I during Hold-down Period

- **Modeling Approach**
  - Predictions are based on reconstruction of heritage data and correlations from Space Shuttle launches
- **Mitigation Approaches**
  - None - RS-25 start transient dependent; IOP/SS has an influence on acoustics

Pressure Measurement on SLS



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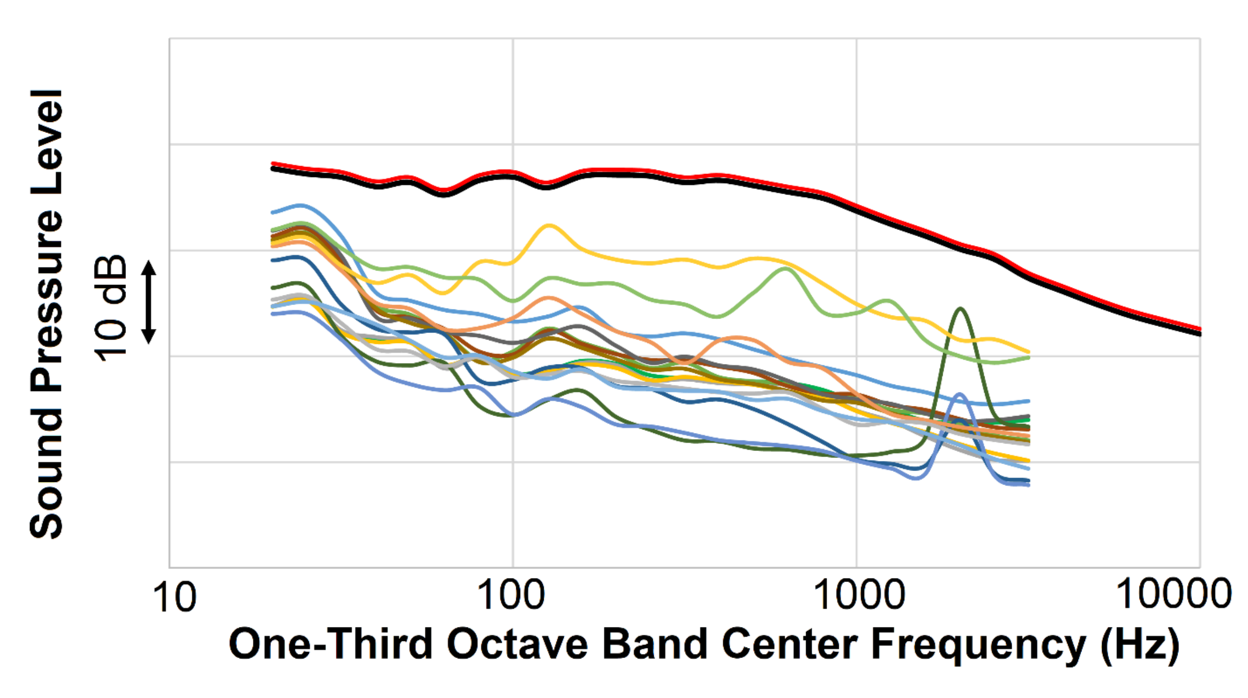
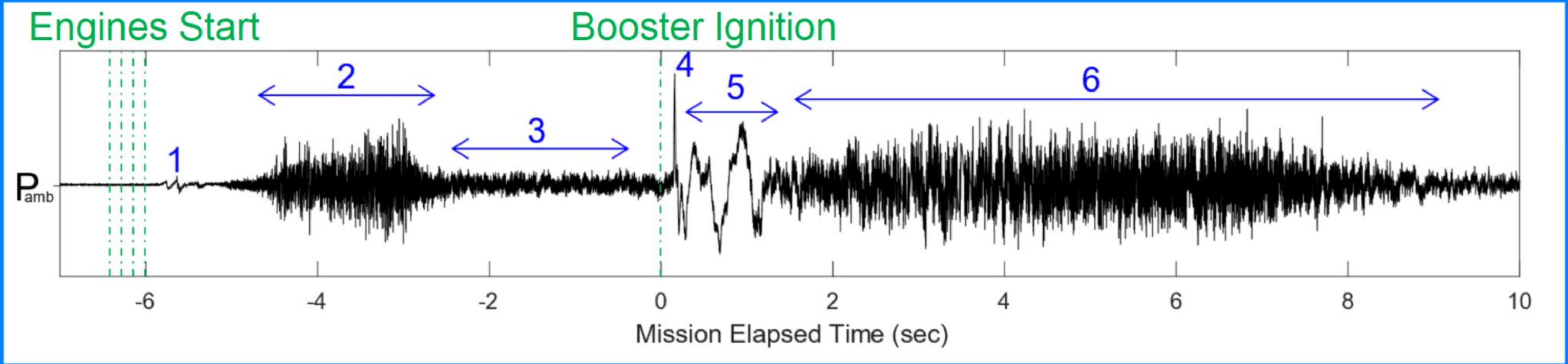
Hold-Down Acoustics

- **Background**
  - Noise generated during hold-down by the exhaust flow and its interactions with surrounding launch pad structures
  - Generally applicable prior to liftoff, however due to the timing of the retraction of umbilicals and other ground support equipment, also specified for a period after Booster ignition
  - HDA is generally the most benign
- **Modeling Approach**
  - SLS Subscale Model Acoustics Test
  - Reconstruction of heritage data and correlations
- **Mitigation Approach**
  - None; IOP/SS has an influence on acoustics



Hold-Down Acoustics (T-4 to T+1.5)
(High on Vehicle)

Pressure Measurement on SLS



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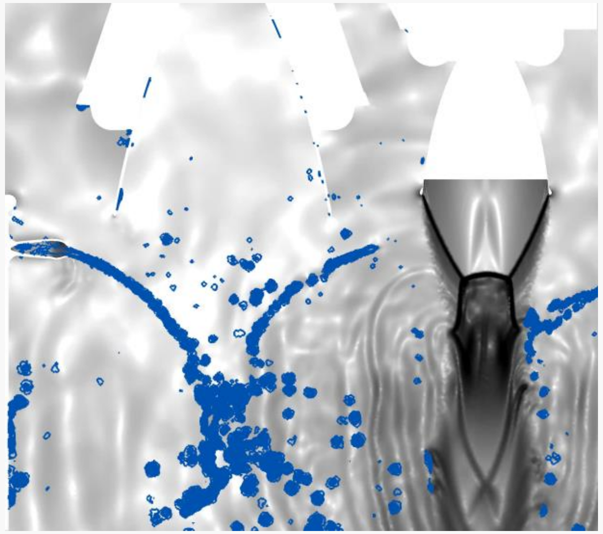
Booster Igniter Shock

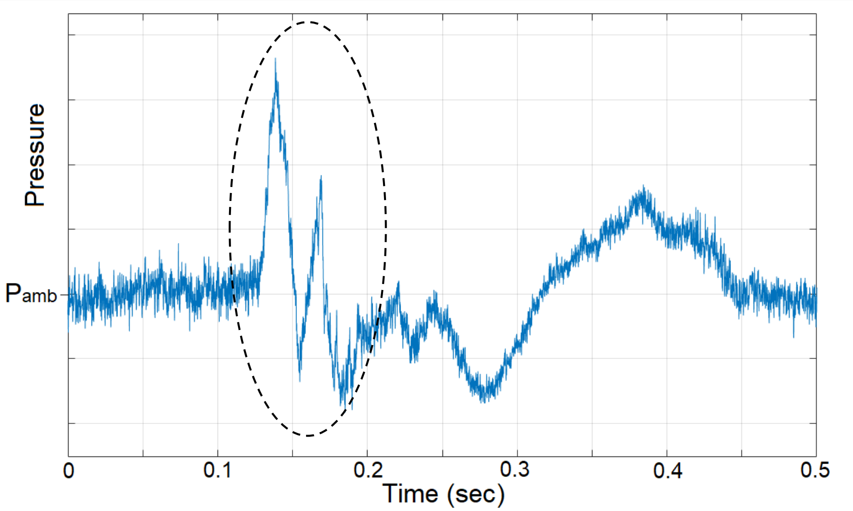
- **Background**
  - Due to the initial release of motor pressure coincident with the throat plug rupture
  - Pressure transient prior to IOP beginning approximately 0.1 seconds after Booster ignition
  - Similar physics as IOP; water sheet influences propagation and reflections



CFD Simulation, T. Rivord

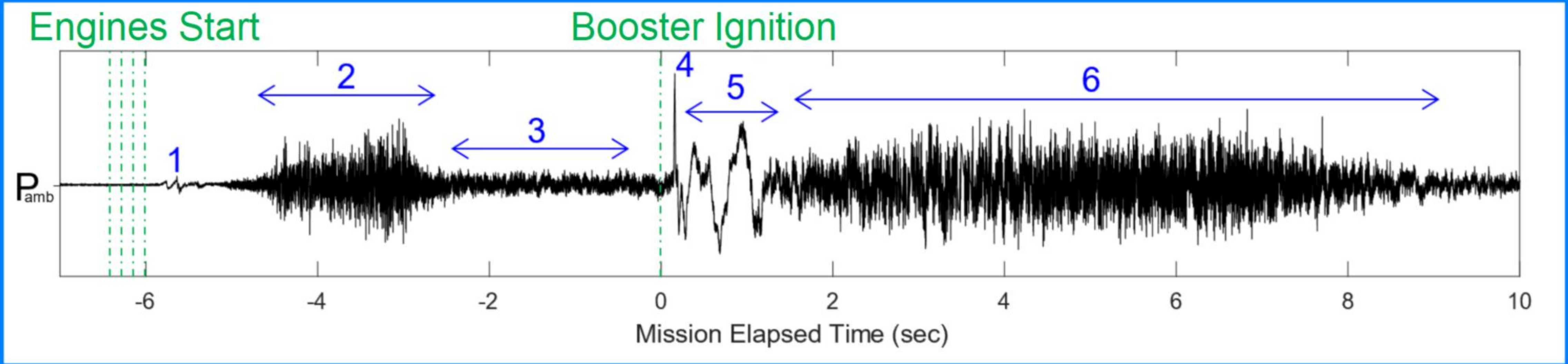
RSRMV QM-1 Ground Test Firing

- **Modeling Approach**
  - Heritage correlations
  - Computational acoustics
  - CFD
- **Mitigation Approach**
  - None, generally only characterized
  - Throat plug design can influence igniter shock



Igniter Shock on SLS

Pressure Measurement on SLS



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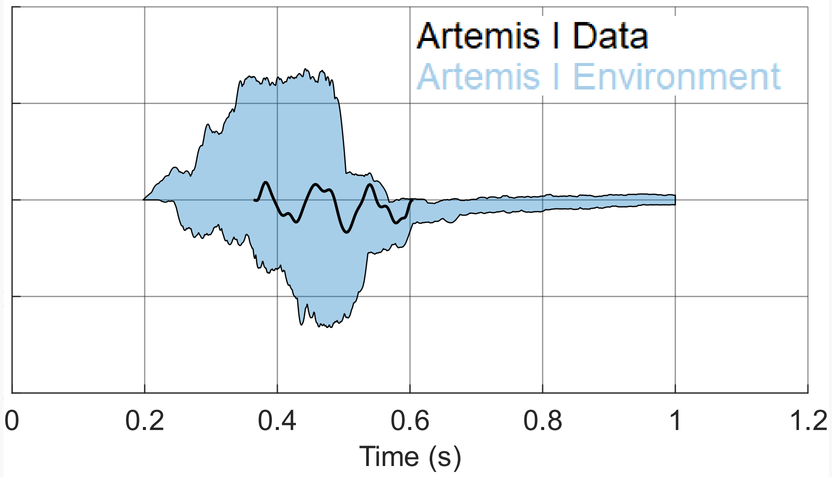
Booster Ignition Overpressure & Duct Overpressure

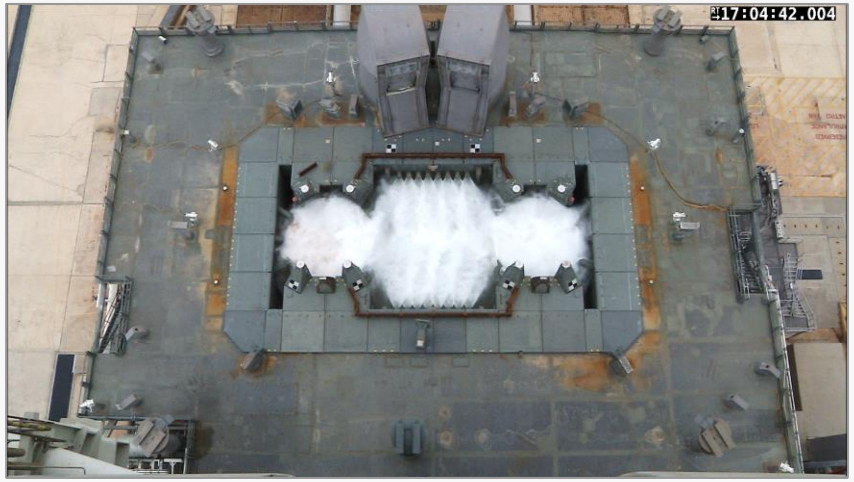
- **Background**
  - IOP & DOP are transient pressure events caused by the rapid pressure rise rate of the RSRMVs and subsequent compression of the accelerating exhaust flow
  - IOP exits upward out the exhaust hole and DOP exits the trench duct
  - Transients extracted from data using data characterization, spatial correlation, and propagation speed
  - Environment cloud envelope shown includes range of possible conditions



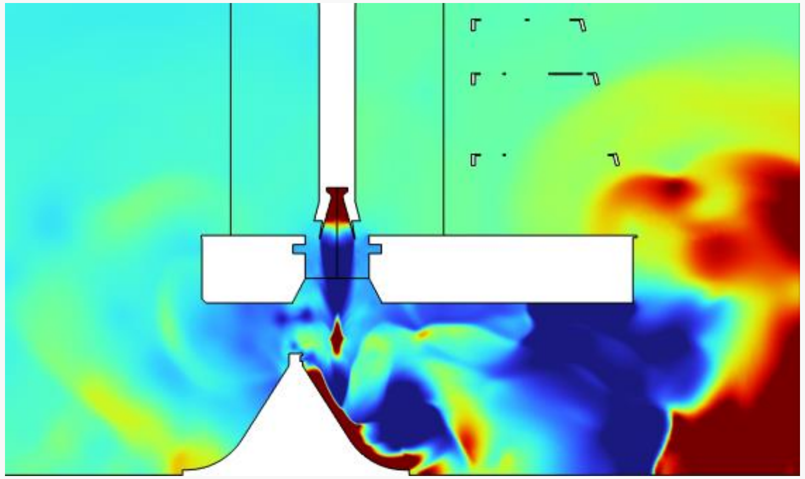
Artemis I Ignition Overpressure
(High on Vehicle)

- **Modeling Approach**
  - Heritage correlations
  - Physics-based engineering model
  - SLS Scale Model Acoustic Test
  - Computational Acoustics
  - CFD

- **Mitigation Approaches**
  - Ignition Overpressure Protection & Sound Suppression System



IOP/SS Water in Exhaust Holes



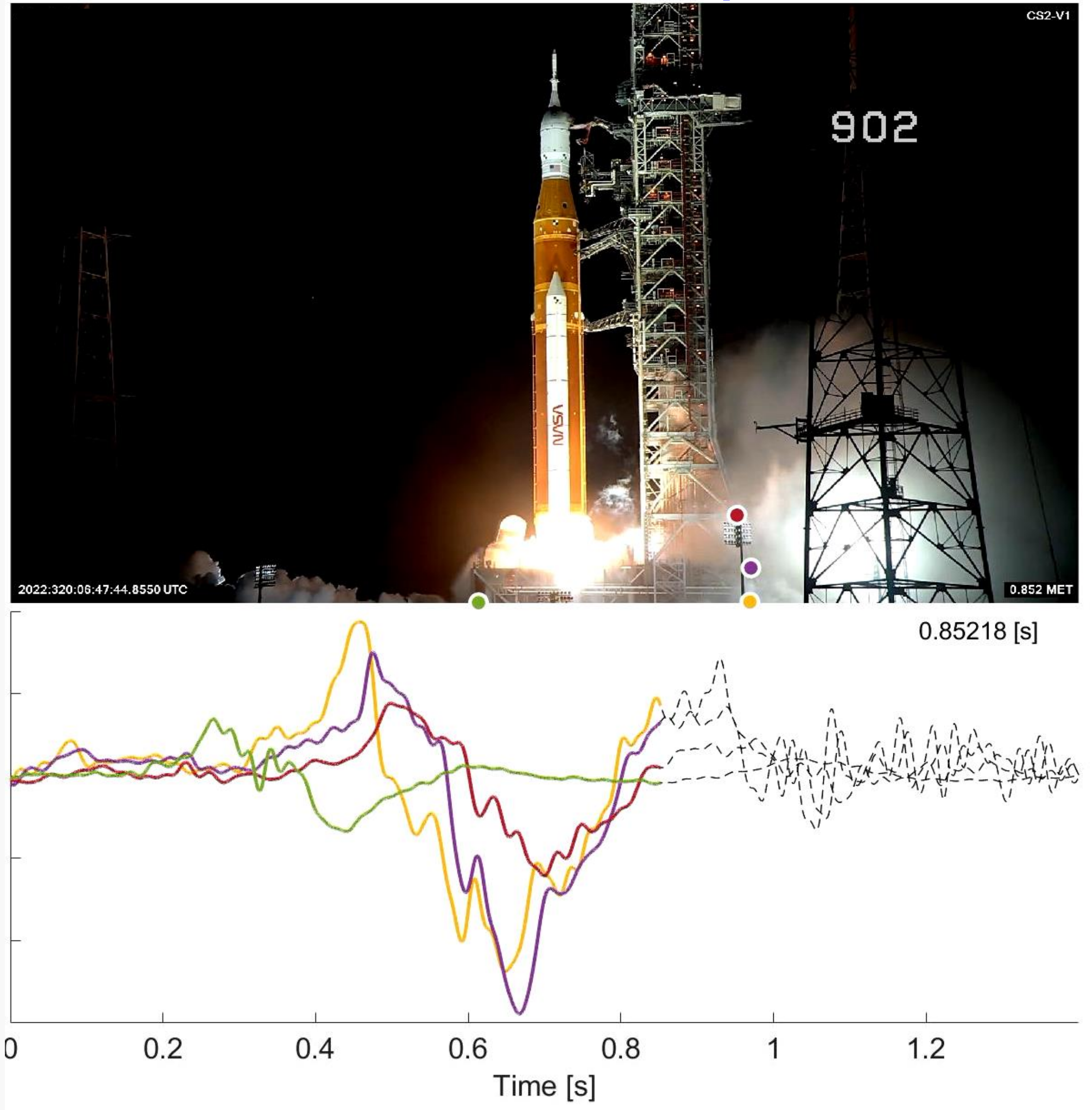
SMAT IOP/DOP Computational Acoustics

Duct Overpressure

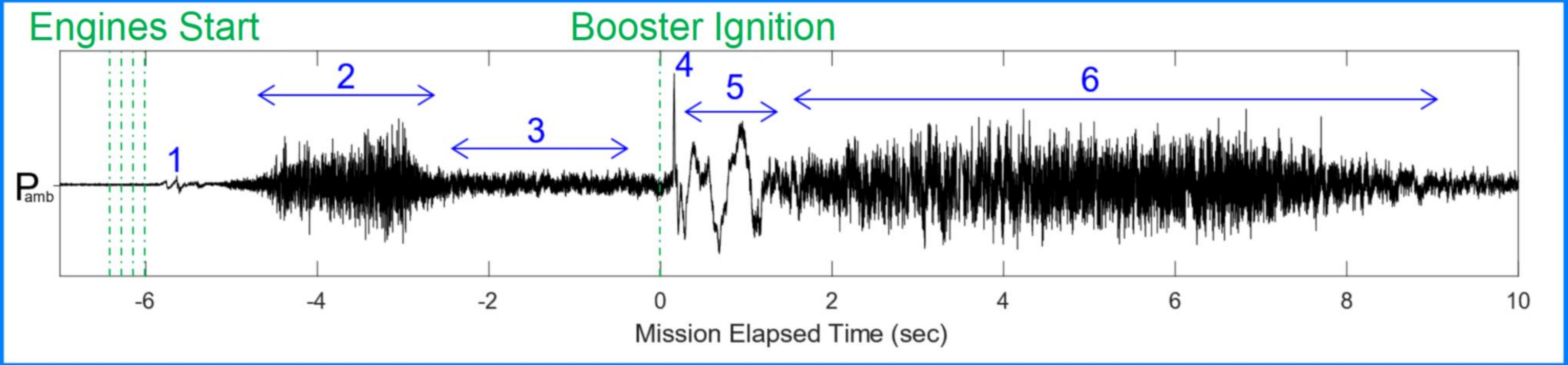
- **Duct Overpressure**
  - Continuation of the overpressure wave out of the trench exit
  - DOP has a two waveforms
  - Smaller south-side DOP also exists

- **Night launch and Ground data were central in identifying DOP and transients**
  - Imagery (dark background), Ground data, and ambient conditions (humid/dew point), helped identify events with data corroboration
  - DOP rarefaction accentuated by condensation clouds
  - Condensation cloud formation: pressure decrease (rarefaction) → temperature lowering → condensation forming

Artemis I Duct Overpressure



Pressure Measurement on SLS



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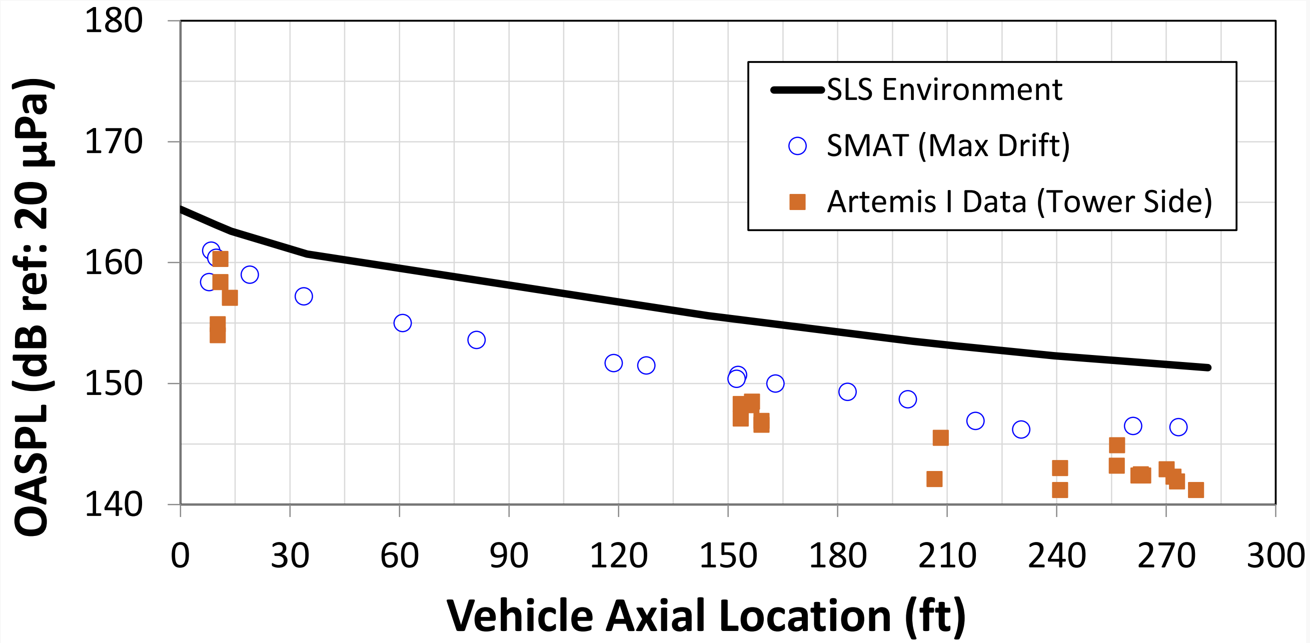
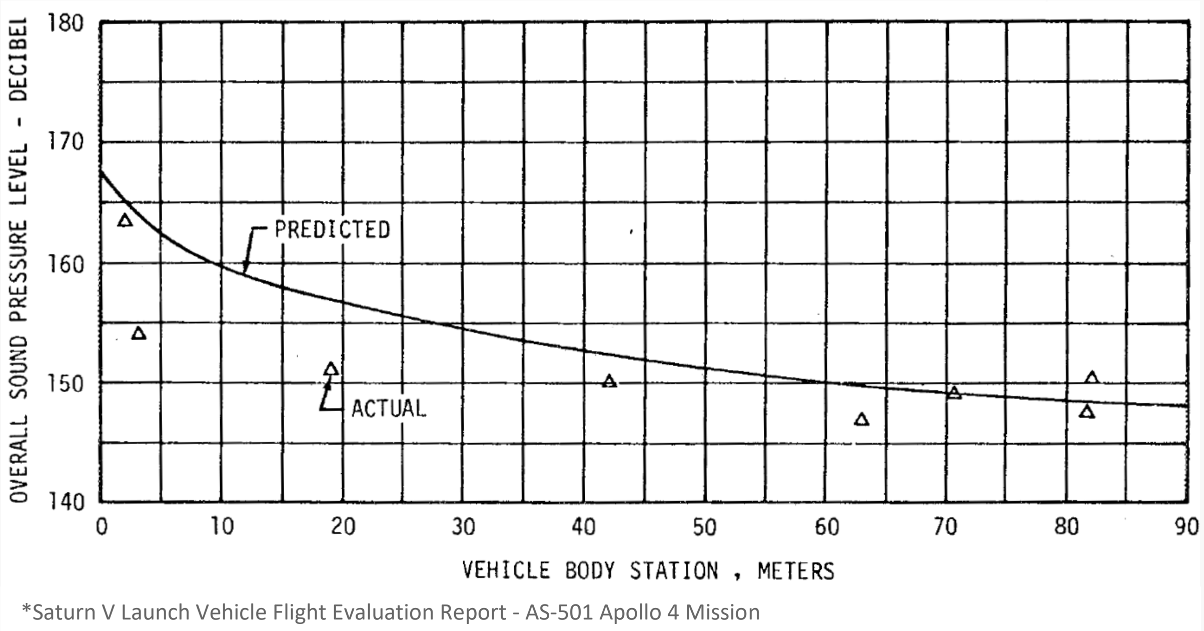
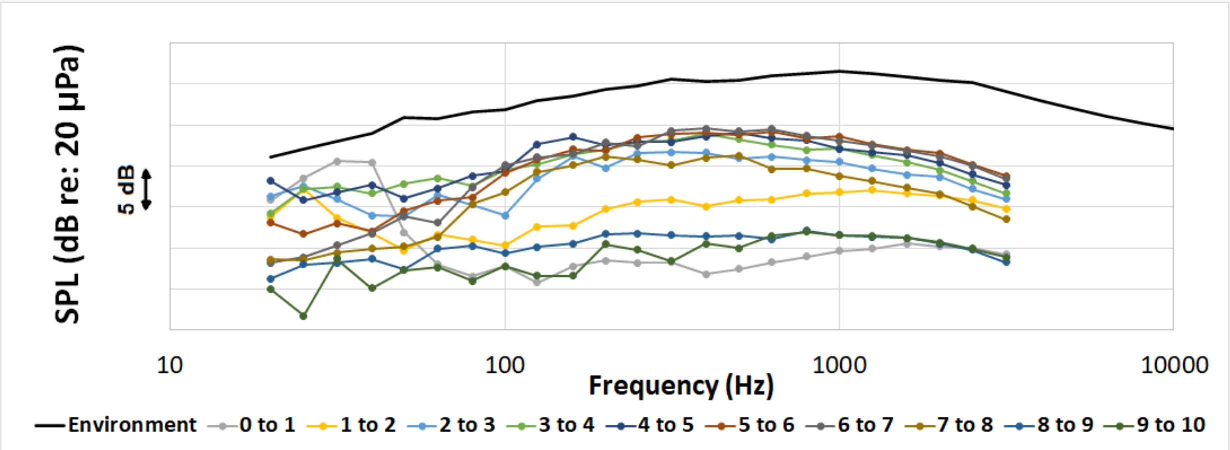
Liftoff Acoustics



Artemis I: Liftoff Acoustics *(1st Uncrewed Test Flight)*



Apollo 4: Liftoff Acoustics *(1st Uncrewed Test Flight)*

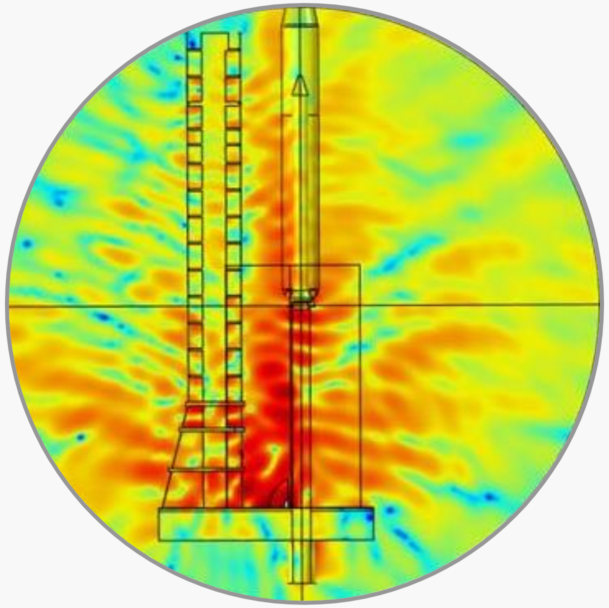


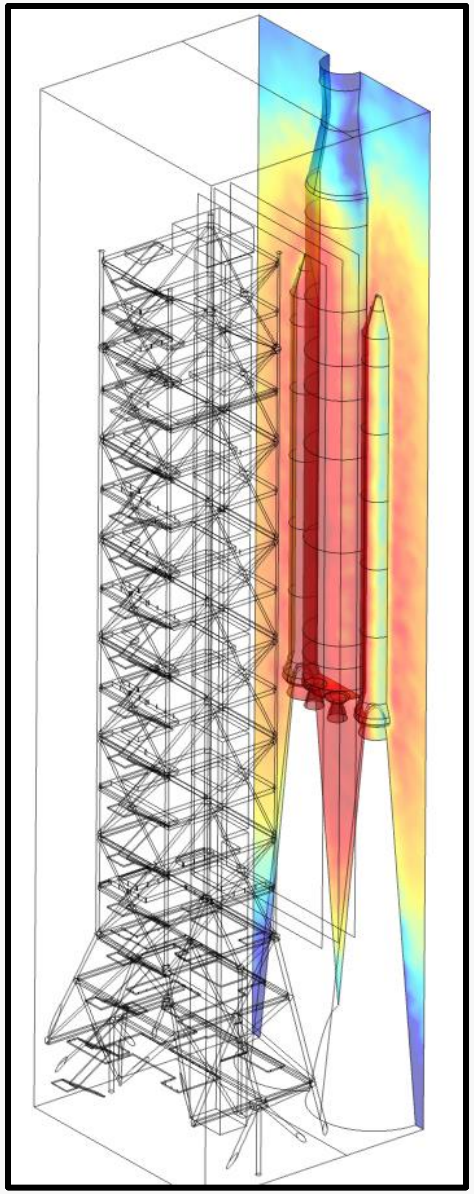
Artemis I: 1/3 Octave Band Spectrum (Low on Vehicle)

- **Background**
  - Noise generated during liftoff by the exhaust flow and its interactions with surrounding launch pad structures

Liftoff Acoustics

- **Modeling Approach**
  - Heritage correlations
  - Physics-based engineering model
  - SLS Scale Model Acoustic Test
  - Computational Acoustics
  - CFD
- **Mitigation Approaches**
  - Ignition Overpressure Protection & Sound Suppression System



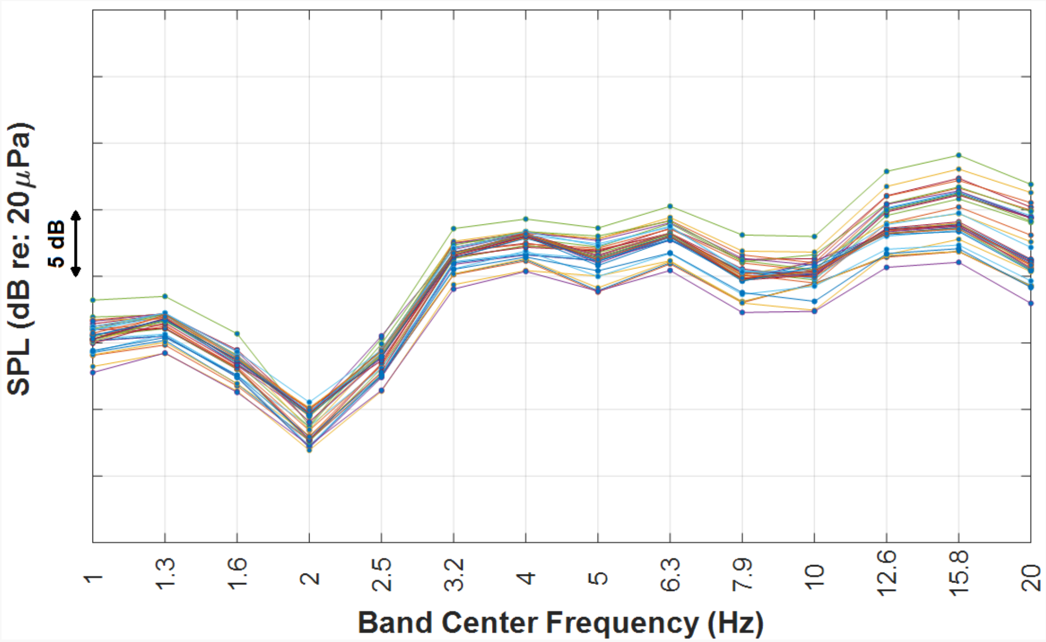


Infrasonic Acoustics

- **Background**
  - Noise generated during liftoff by the exhaust flow and its interactions with surrounding launch pad structures
  - An extension of Liftoff Acoustics into the low frequency range at 20 Hz and below
  - The low frequency acoustics create loads on the external vehicle surfaces which then transmit through the vehicle into the Crew cabin
  - Data analysis is challenging due to low frequency and short duration

- **Modeling Approach**
  - SLS Scale Model Acoustic Test

- **Mitigation Approaches**
  - None - influenced by IOP/SS

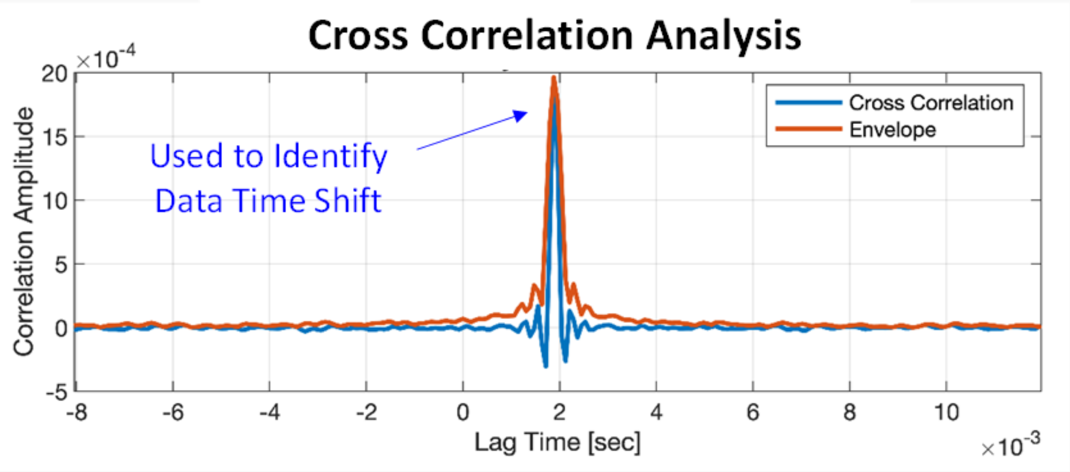


Artemis I Infrasonic Acoustics

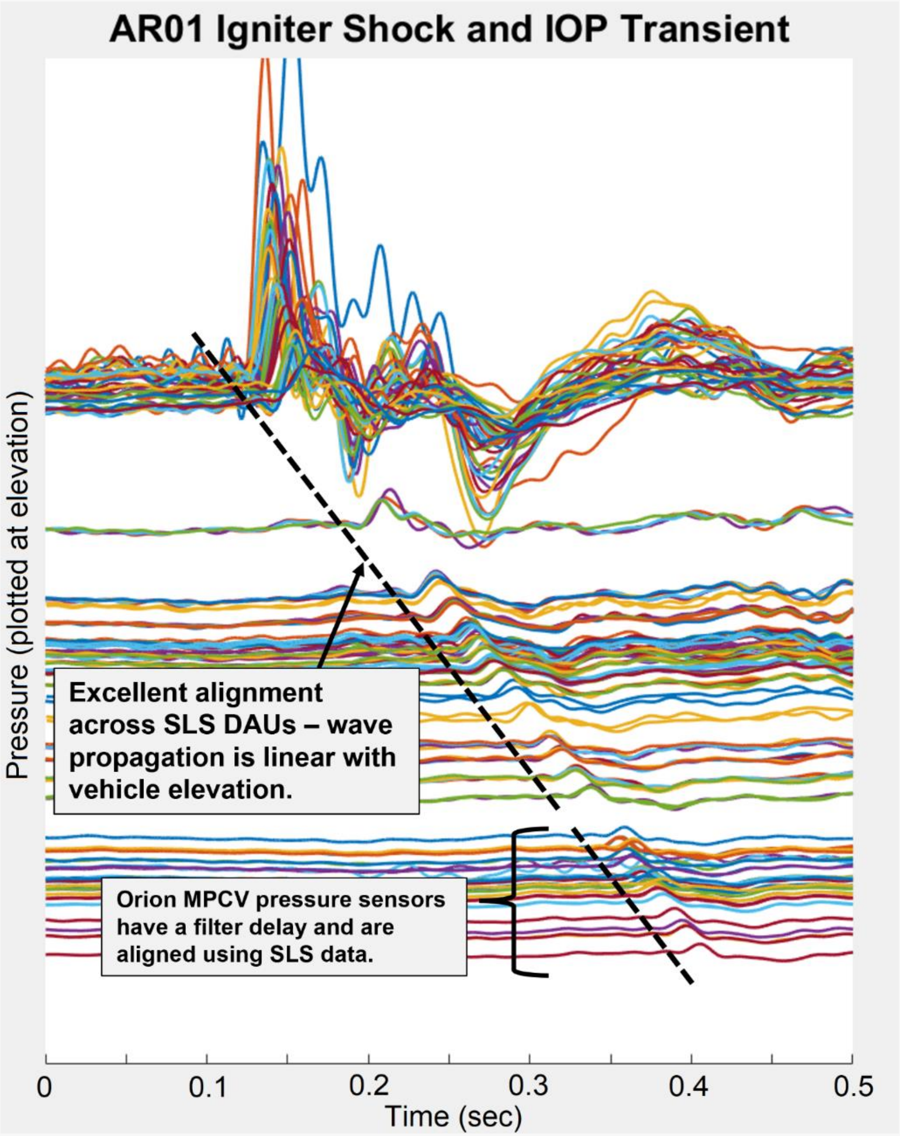
Data Assessments

Time Correlation Assessments

- **Time alignment issues of Ares I-X flight test in 2009**
  - Acoustics team identified Ares I-X timestamps were out of sync between the Ground system and Vehicle DFI data
- **Ares I-X helped justify the data acquisition verification tests**
  - Characterization needed to quantify the frequency response and time alignment
- **SIL DAU Characterization Test**
  - SLS System Integration Lab (SIL) – replica of SLS Data Acquisition Units (DAUs)
  - Evaluate the effect of each DAU and channels – considers filters, delays, and system effects
  - Record a truth signal and 'processed' signal
  - Cross correlation signal processing technique is a mathematically rigorous approach to compute a metric at the point in time where the signals are best aligned
  - *Eliminated* the time alignment issues by providing appropriate delay correction values to the avionics team



Analysis Technique used for Alignment Assessment

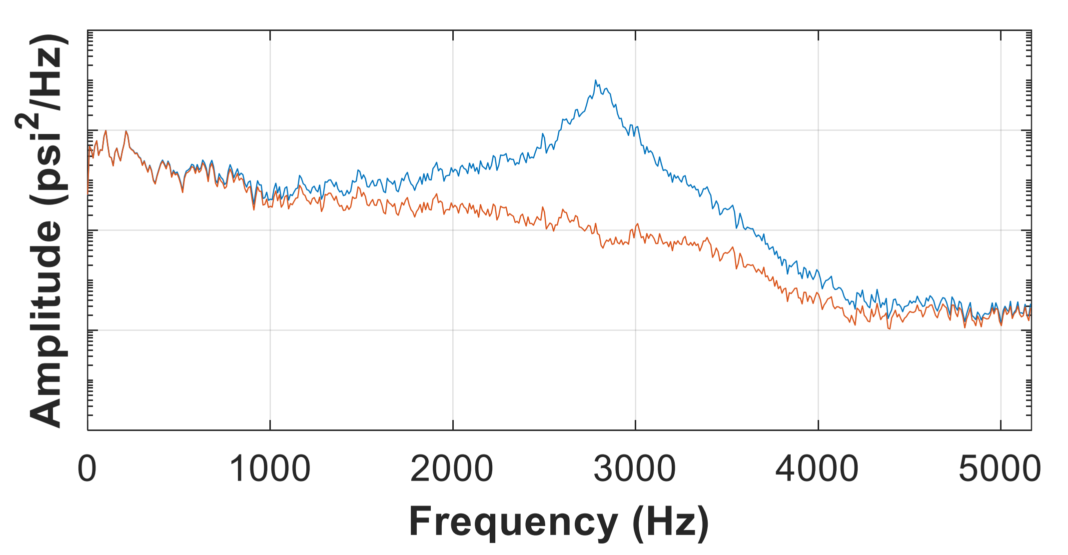


Excellent Alignment across all SLS DAUs

Sensor Port Response

- **Some sensors showed a significant influence due to the port response**
- **Removal is necessary to obtain accurate acoustics**
- **Methodology developed during Green Run Hotfire test to remove response**
  - Using approach described in Casiano, M. J., "Analytical and Numerical Modeling of Sensor Port Acoustics," NASA TP-2021-0000024, May 2021.
  - To remove the port resonance, data is 'filtered' using a sensor port response model. And therefore, time data can be reproduced for further analysis.

- **Reduction on some sensors over 10 dB OASPL and 20+ dB in specific bands**
- **Resonances impact Liftoff Acoustics, Engine NFT Acoustics, and Hold-down Acoustics**



Pressure Power Spectral Density

Summary

- **A Liftoff Environment, or Launch Environment, represents a source of loading during the hold-down or liftoff phase of a rocket launch.**
  - Transient and acoustic loading on vehicle exterior surfaces
  - 8 environments (Excess Hydrogen Pop, Core Stage Engine Overpressure, RS-25 Nozzle Flow Transient Acoustics, Hold-Down Acoustics, Booster Igniter Shock, Ignition Overpressure & Duct Overpressure, Liftoff Acoustics, and Infrasonic Acoustics)

- **Methods and Procedures in quantifying Launch Environments**
  - Computational Acoustics, Computational Fluid Dynamics, Scale Model Acoustic Testing, Reduced-order Modeling, Data Processing, and Signal Processing

- **The confidence in our Artemis I models and data ultimately help improve our confidence as we prepare for the first manned mission.**

Image credit: NASA/Kim Shiflett

Artemis II Crew: Jeremy Hansen, Victor Glover, Reid Wiseman, Christina Koch