



Developmental Flight Instrumentation:

Review of Space Shuttle, Ares I-X, and Artemis I

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Image Credit: NASA/Joel Kowsky



Introduction

- Ascent vehicles are instrumented with three types of sensors:
 - Operational Flight Instrumentation (OFI) – monitor the operation of vehicle
 - Engineering Flight Instrumentation (EFI) – monitor the engineering conditions of the vehicle needed for continuous evaluation of environments
 - **Developmental Flight Instrumentation (DFI)** – measure the environments used in the development of the vehicle
- DFI consists of the data acquisition system, which is separate OFI and EFI
 - Generally, are sampled at higher sample rates
 - Temporary subsystem in the avionics architecture

NASA Vehicles with DFI

- Artemis I test flight
 - Launched Nov 16, 2022, at 06:47:44.003265 UTC
 - Duration: 25 days, 10 hours, 53 minutes
 - KSC 39B
- Ares I-X test flight
 - Launched Oct 28, 2009, at 12:30:00.217
 - Duration: about 2 minutes
 - KSC 39B
- STS-1 Columbia first flight
 - Launched April 12, 1981, at 12:00:03.907
 - Duration: 2 days, 6 hours, 20 minutes, and 53 seconds
 - KSC 39A
- STS-2, 3, 4 – Columbia
- STS-7 – Challenger
- Other STS early missions



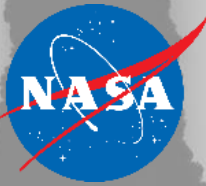
Photo Credit: NASA/Keegan Barber



Photo Credit: NASA



Photo Credit: NASA/Bill Ingalls

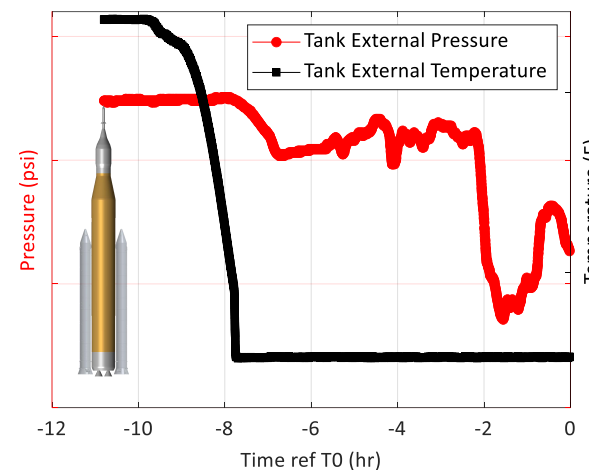


Motivation

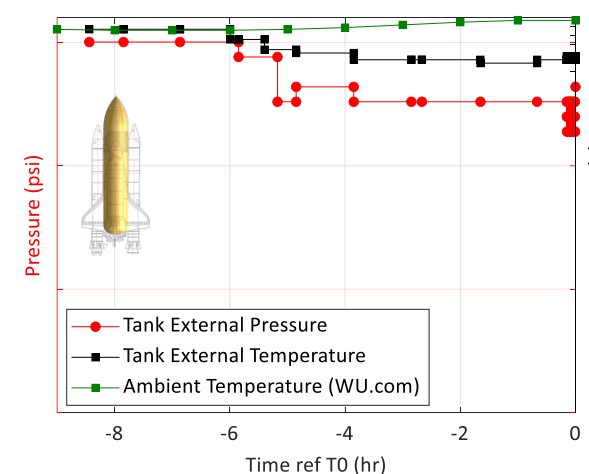
- Design similarities provide an appeal to compare the behavior captured by the DFI on the three vehicles
- For example, ice formation
 - Artemis I Core Stage experienced ice formation, which blocked some pressure sensors resulting in unexpected measurements
 - Further examination showed a potential ice formation on Shuttle, although not as severe
- Dr. Manish Mehta comparing the base heating environments on the Shuttle and the SLS¹

[1] Manish Mehta, Christopher I. Morris, Brandon L. Mobley and Terry L. Prickett. "Space Launch System Core Stage Green Run Base Heating: Anomaly, Mitigation and Flight Redesign," AIAA 2023-0644. AIAA SCITECH 2023 Forum. January 2023.

SLS External Pressure and Temperature

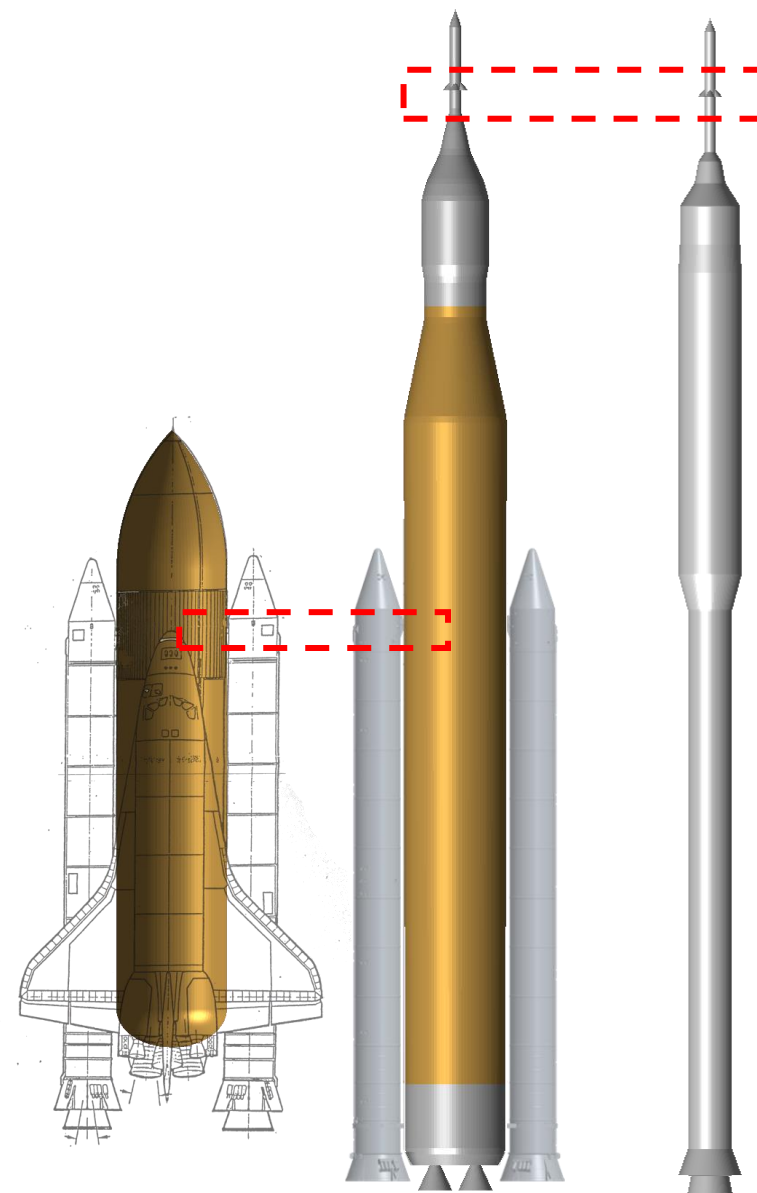


STS-4 External Pressure and Temperature



Objective

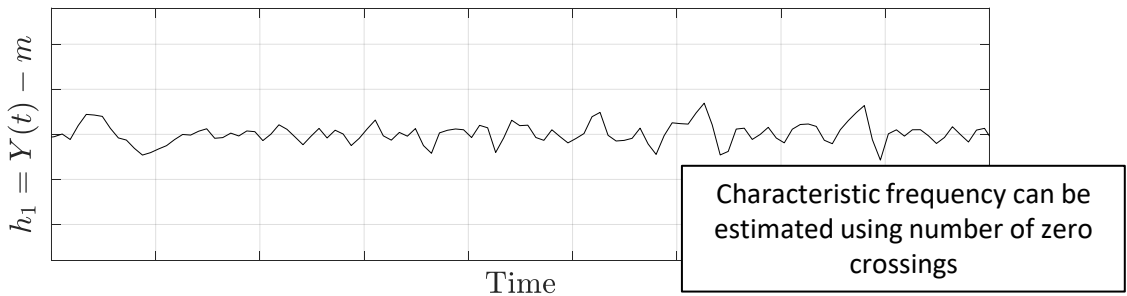
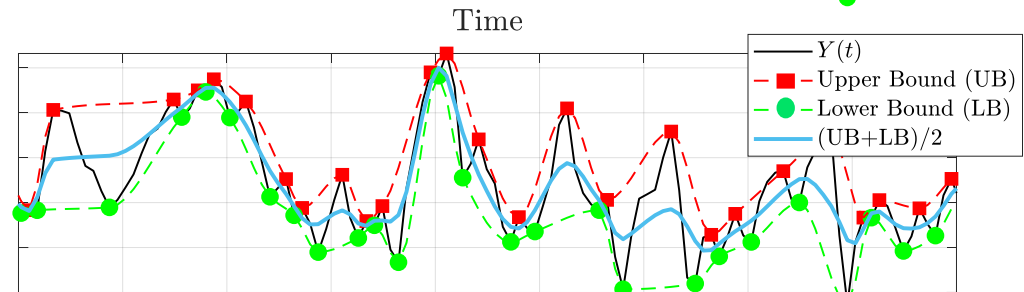
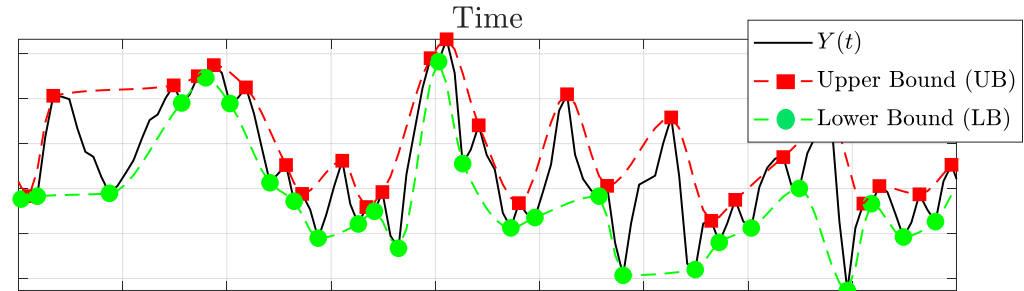
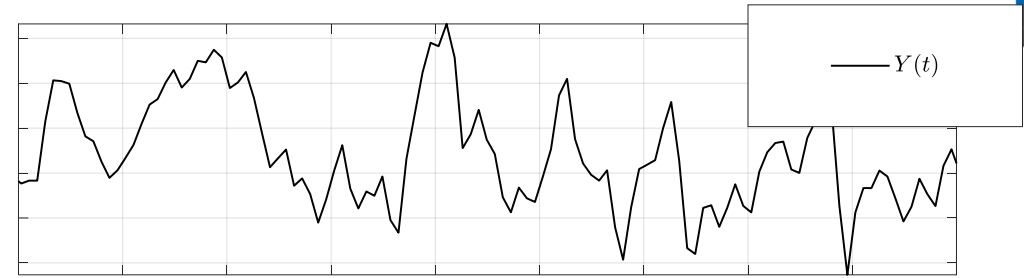
- Compare the DFI unsteady aerodynamics
- (Spoiler Alert) Comprehensive unsteady analysis between all three was difficult due to sparse sensor density and low sample rates on Shuttle External Tank (ET)
- Regions of similarity were selected to focus on
 - STS and Artemis I: Solid Rocket Booster Forward Attach Hardware (SRB FAH)
 - Artemis and Ares I-X: Launch Abort System (LAS) motor nozzles
 - Some other regions with interesting aerodynamics flow
- Use Intrinsic Mode Functions (IMF) based on Empirical Mode Decomposition (EMD) to analyze data





Introduction to EMD

- Primarily used in analyzing periodic signals. For example², pulsatile flow in cardiac system³
- Flight data may not be classified as periodic, so special attention is needed
- Process demonstrated following Huang et al.²
 - Local maxima are connected by a spline
 - Local minima are connected by a spline
 - Mean curve of the maxima and minima curves is computed
 - Mean is subtracted from the signal, revealing first IMF
 - Sifting process to improve the mean is described in the manuscript



[2] Huang, Norden E., et al. "The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-Stationary Time Series Analysis." *Proceedings: Mathematical, Physical and Engineering Sciences*, vol. 454, no. 1971, 1998, pp. 903–95. JSTOR, <http://www.jstor.org/stable/53161>. Accessed 13 Dec. 2023.

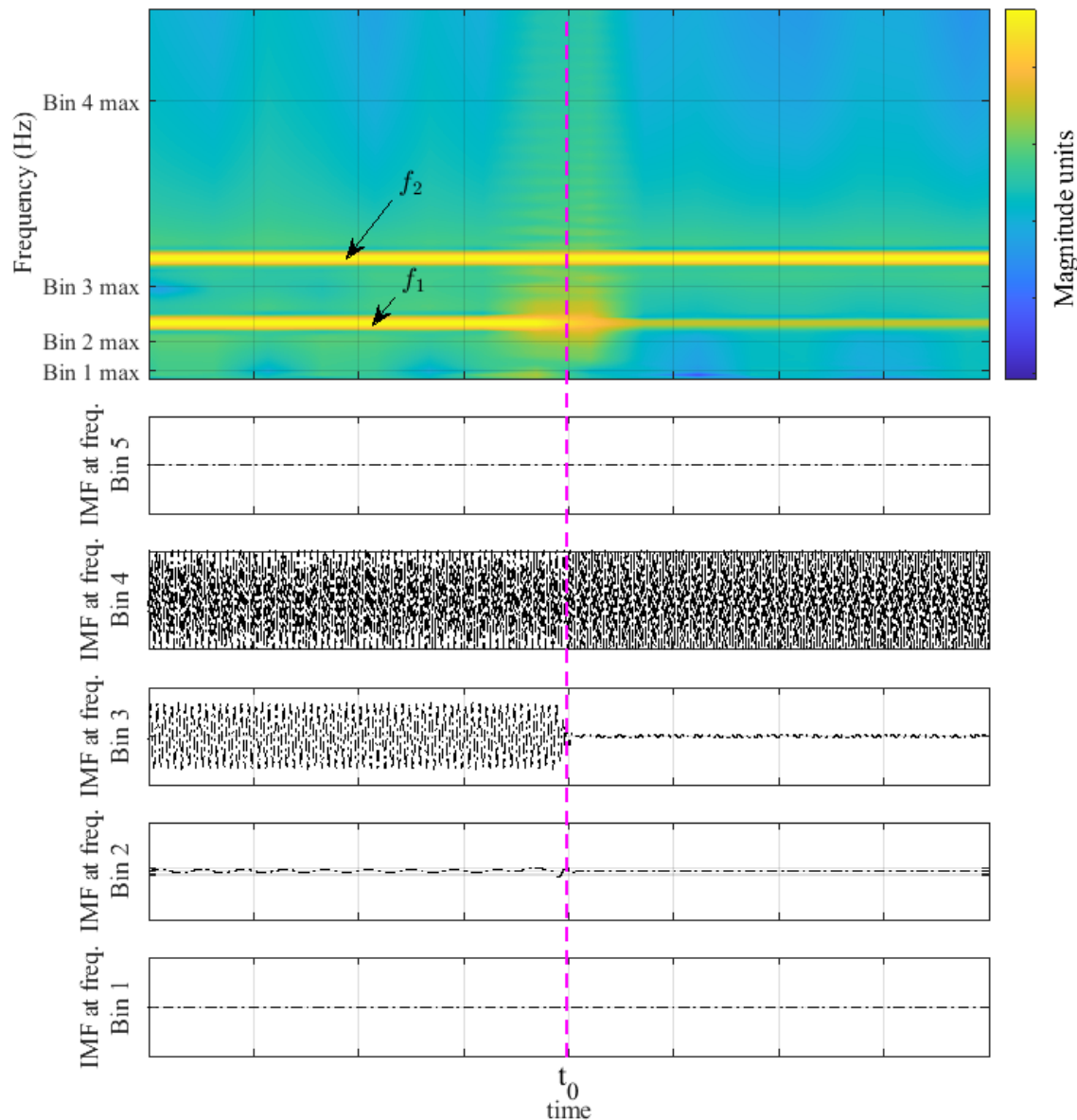
[3] Gomez J, Yu H, Andreopoulos Y. Role of flow reversals in transition to turbulence and relaminarization of pulsatile flows. *Journal of Fluid Mechanics*. 2021;917:A27. doi:10.1017/jfm.2021.269

IMF Example

- Sample calculation using the artificial signal:

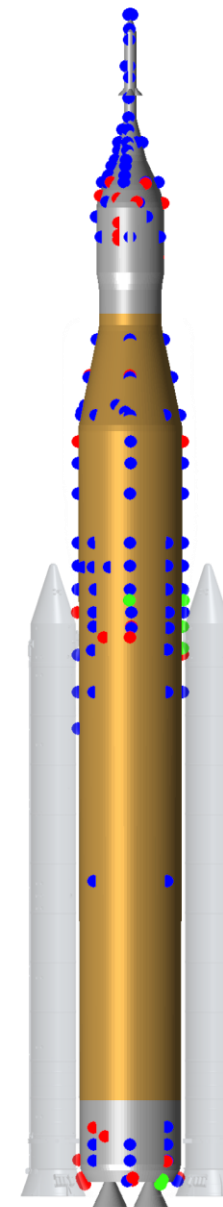
$$Y(t) = \begin{cases} \sin(2\pi f_1 t) + \sin(2\pi f_2 t) & \text{if } t \leq t_0 \\ 0.05 \sin(2\pi f_1 t) + \sin(2\pi f_2 t) & \text{if } t > t_0 \end{cases}$$

- Classical spectrogram is shown
- Characteristic frequency of each IMF is calculated based on the number of zero crossings
- IMFs are then grouped into five pre-defined Bins
 - Bin 1 – lowest frequency
 - Bin 5 – highest frequency



SLS – Artemis I DFI

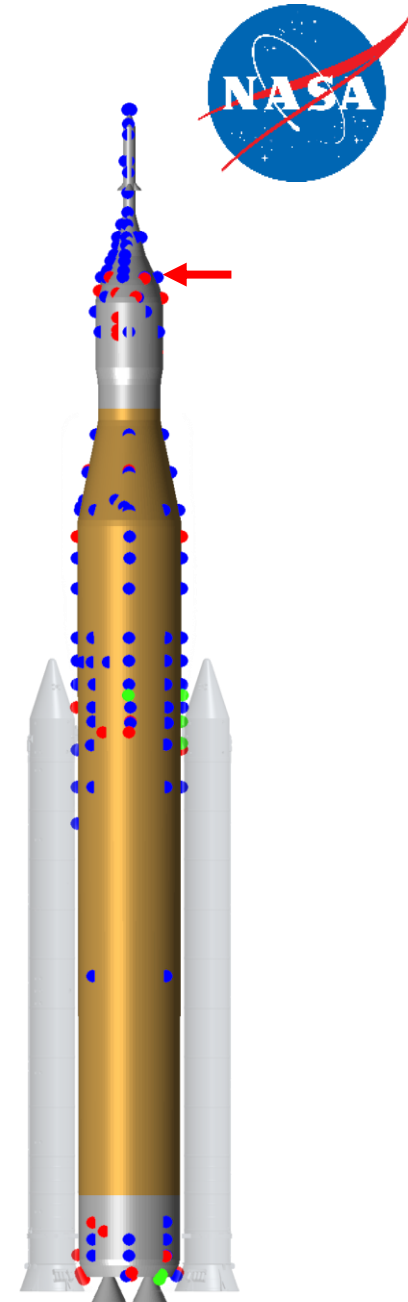
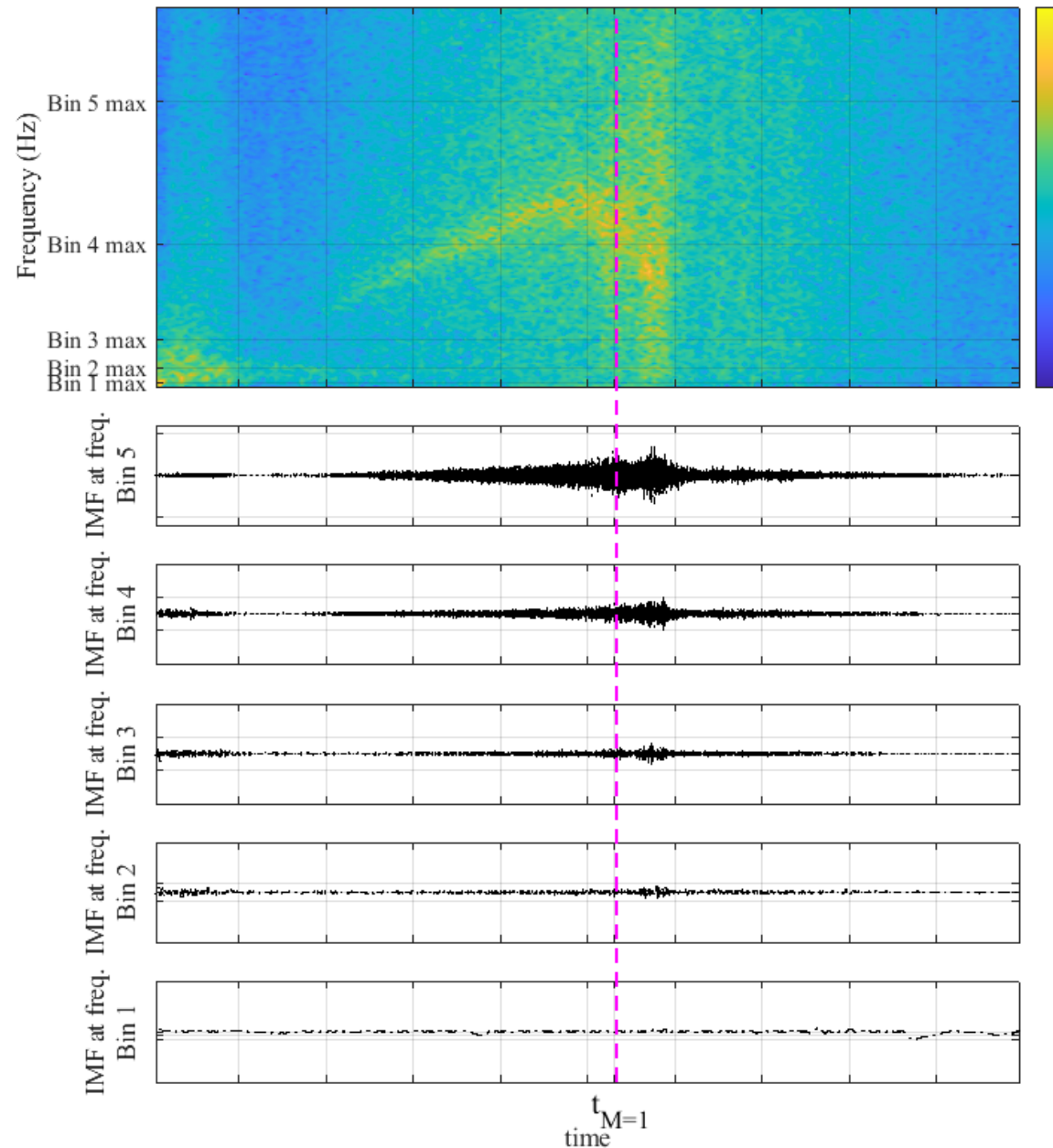
- Significant portion of Artemis DFI architecture was inherited from Constellation program⁴
- ICPS was derived from the Delta IV Cryogenic Second Stage
- 289 total DFI sensors on the entire stack dedicated to aerodynamics
- Core + Orion (without boosters) include some EFI
 - 20 sensors <100Hz (green)
 - 152 sensors <5k Hz (blue)
 - 84 sensors >5k Hz (red)



[4] Tim Atkins, David M. Gillespie, Todd Honeycutt, Matthew J. Casiano, Oleg Goushcha, Patrick S. Heaney, James M. Ramey, David J. Piatak, Martin K. Sekula, and Francesco Soranna. "Artemis I Flight Instrumentation Data Quality Assessment and Processing," AIAA Paper 2024, AIAA SCITECH Forum, Orlando, FL, 2024

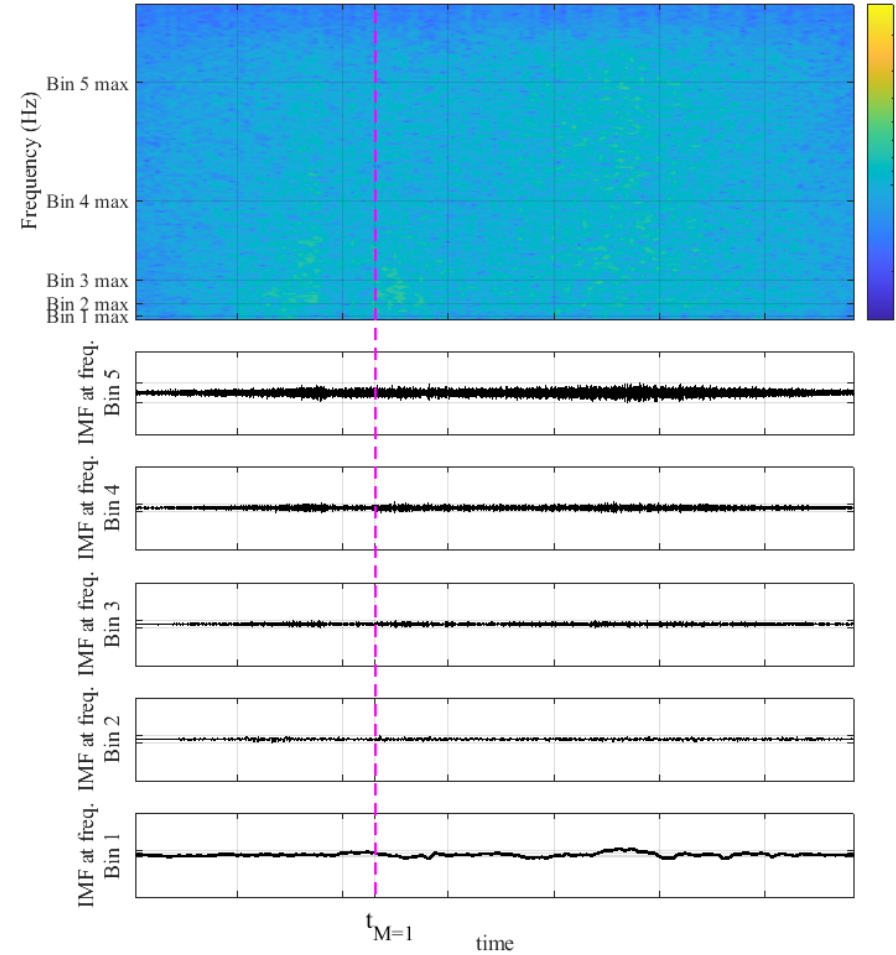
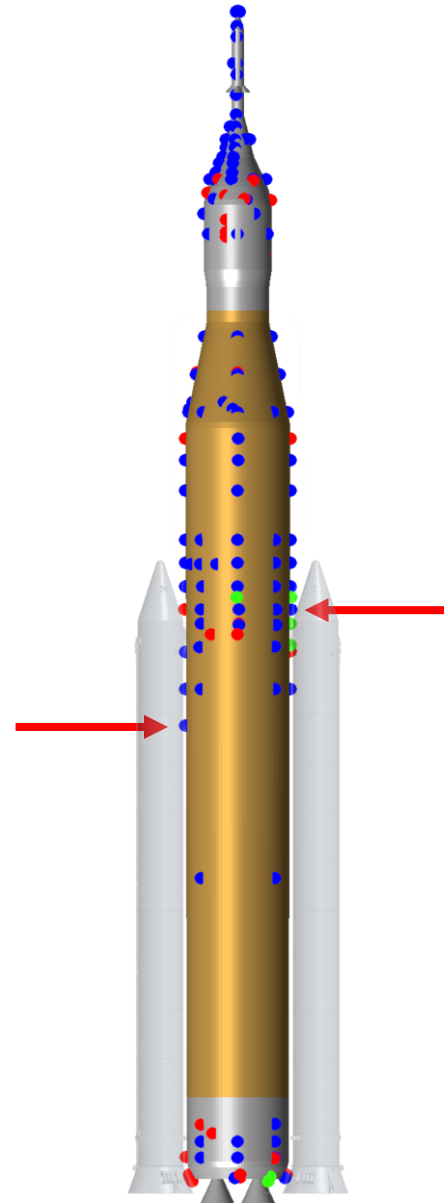
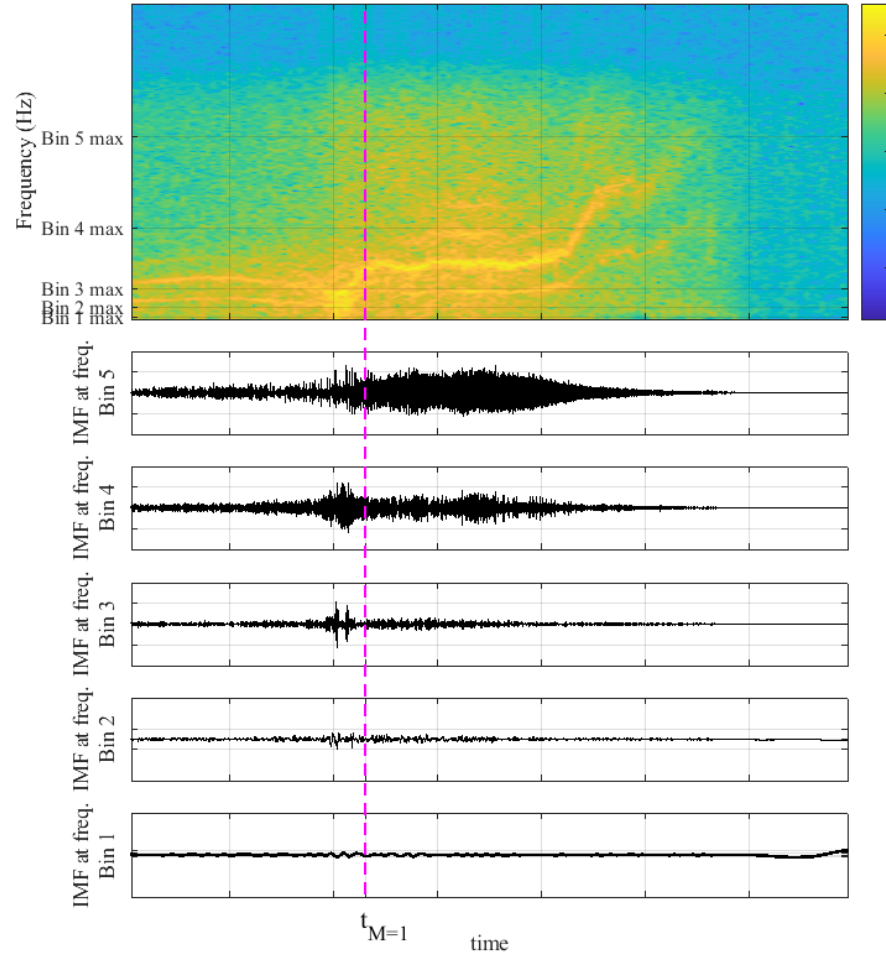
SLS – Artemis I

- LAS motor nozzle vortex shedding
- IMFs associated with Bin 4 and Bin 5 are active in capturing the phenomena, consistent with the spectrogram



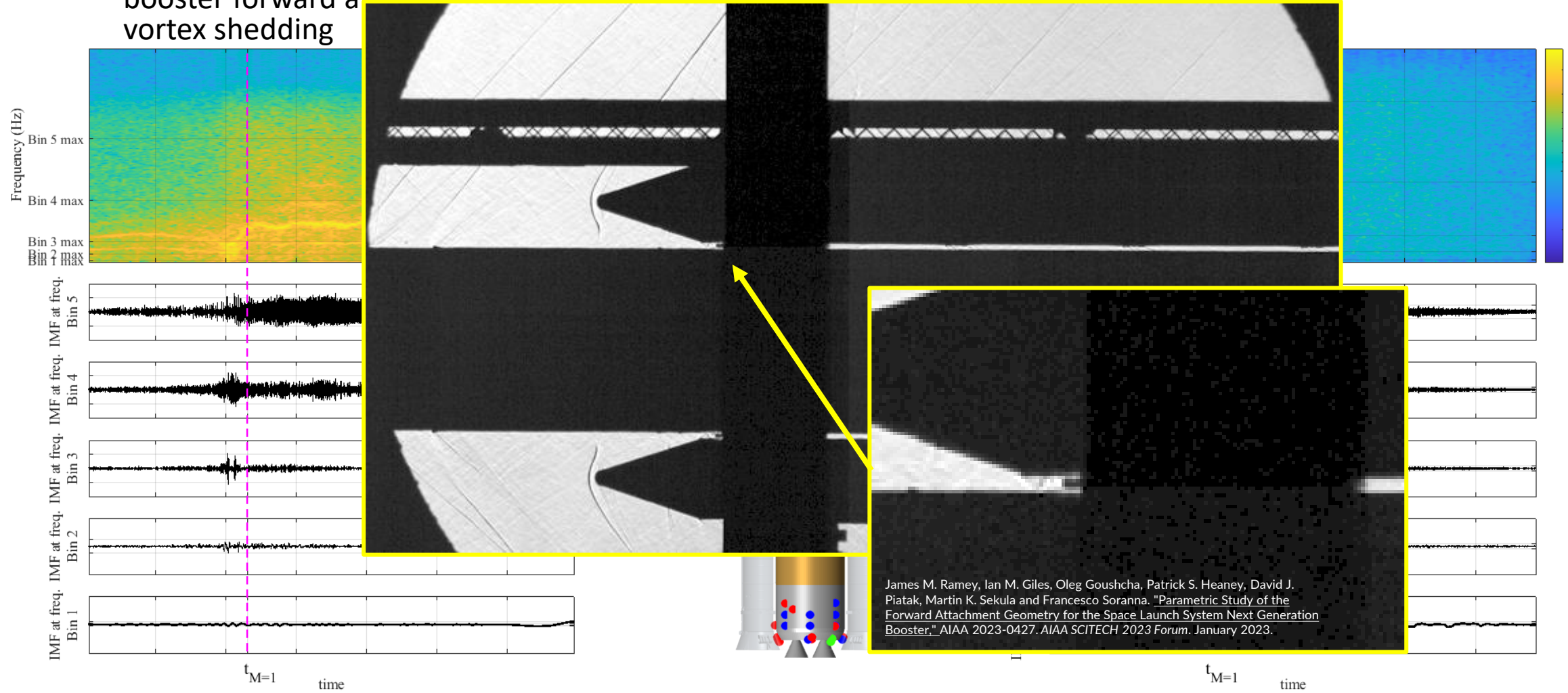
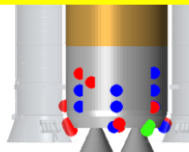
SLS – Artemis I

- Tones associated with the solid rocket booster forward attach hardware vortex shedding



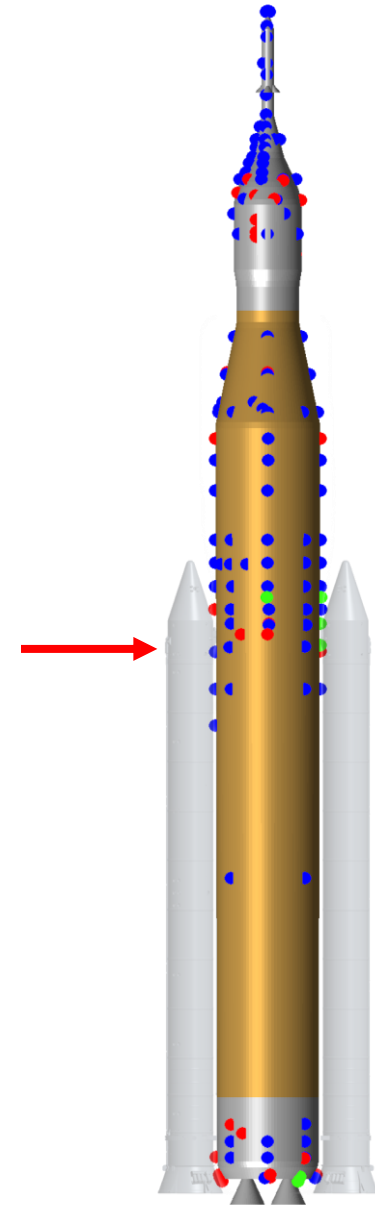
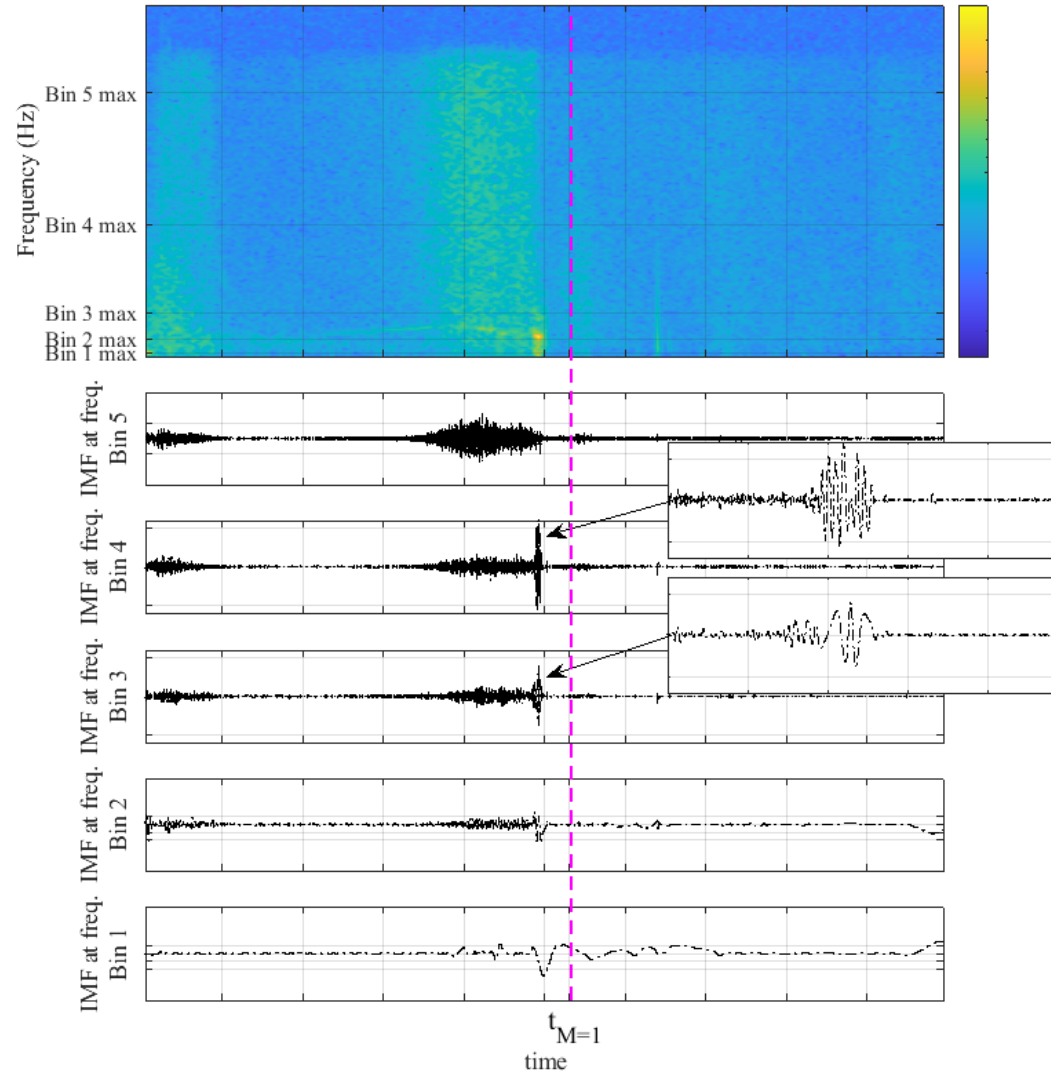
SLS – Artemis I

- Tones associated with the solid rocket booster forward attach hardware vortex shedding



SLS – Artemis I

- Alternating flow behavior is observed on the booster sensor
- IMF clearly indicate the oscillating flow behavior





Ares I-X

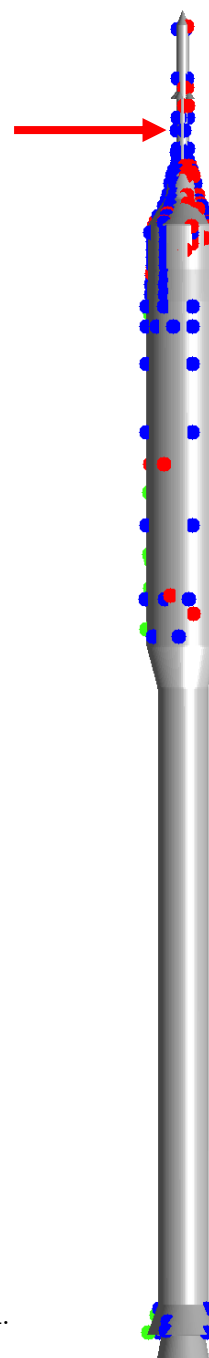
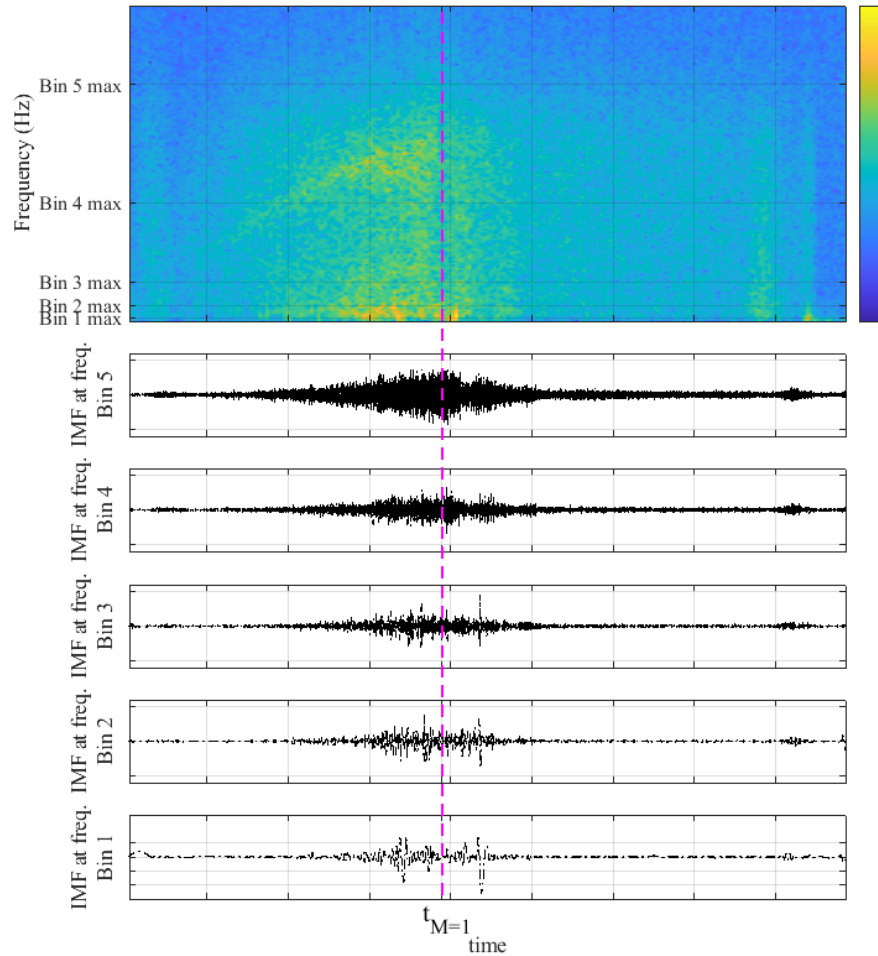
- DFI instrumentation:
 - 21 sensors Static Pressure (**green**)
 - 153 sensors - Unsteady Pressure LF sampled at 651Hz (**blue**)
 - 84 sensors - Unsteady Pressure HF sampled at 5.2k or 10.4kHz (**red**)
- Unique dataset as data were recorded during ascent and descent
- Descent cannot be considered a ballistic flight due to large angles of attack during that flight portion



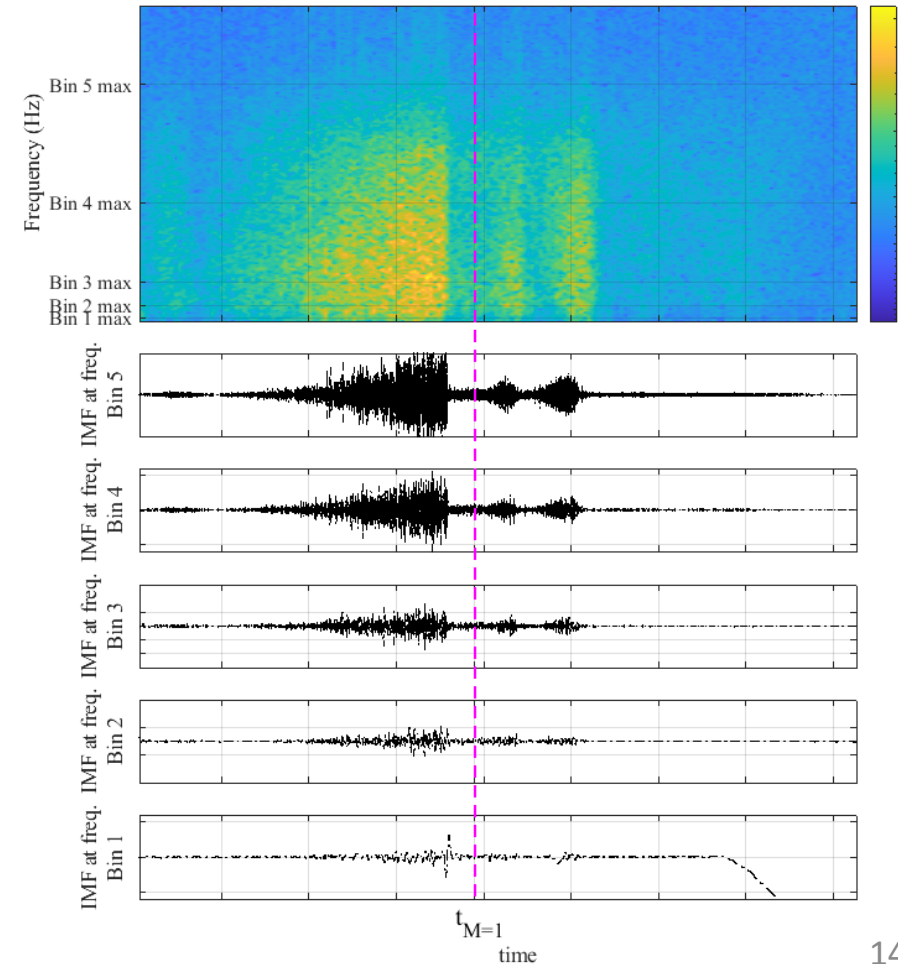
Ares I-X



- LAS motor nozzle vortex shedding



- Terminal shock followed by bursts of RoCS (Roll Control System)⁵



[5] David Piatak, Martin Sekula and Russ Rausch. "Comparison of Ares I-X Wind-Tunnel Derived Buffet Environment with Flight Data," AIAA 2011-3013. 29th AIAA Applied Aerodynamics Conference. June 2011.

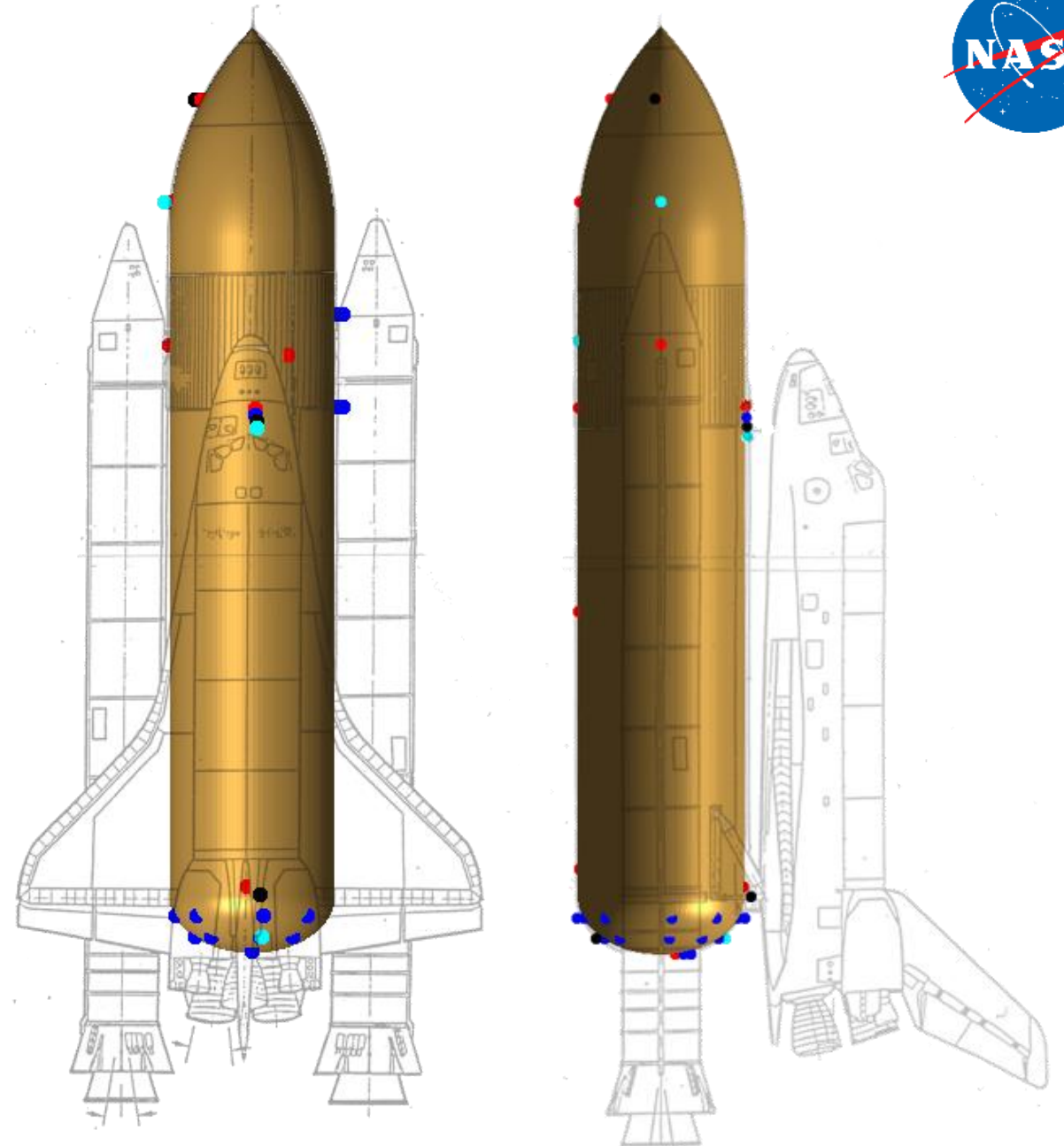
Shuttle



- Shuttle data have benefit of multiple launches. Several missions were examined in the current effort:

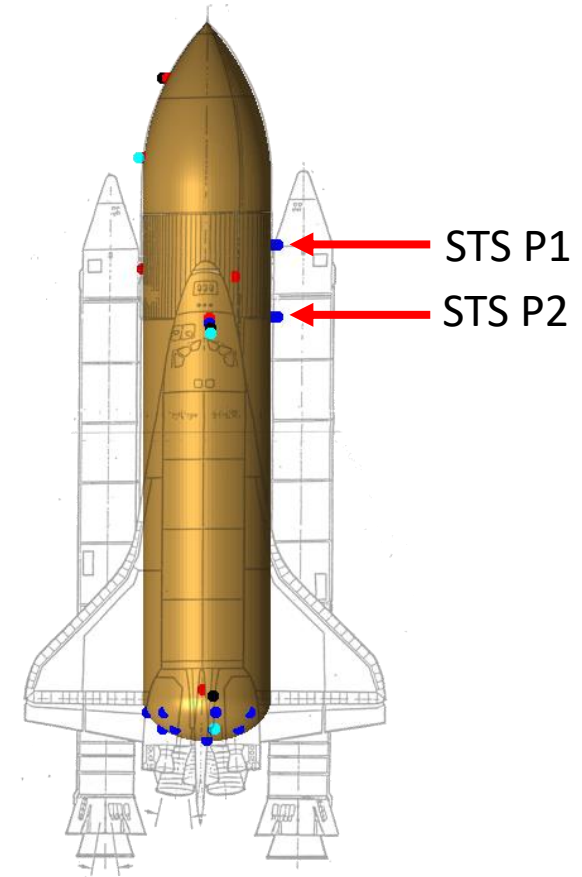
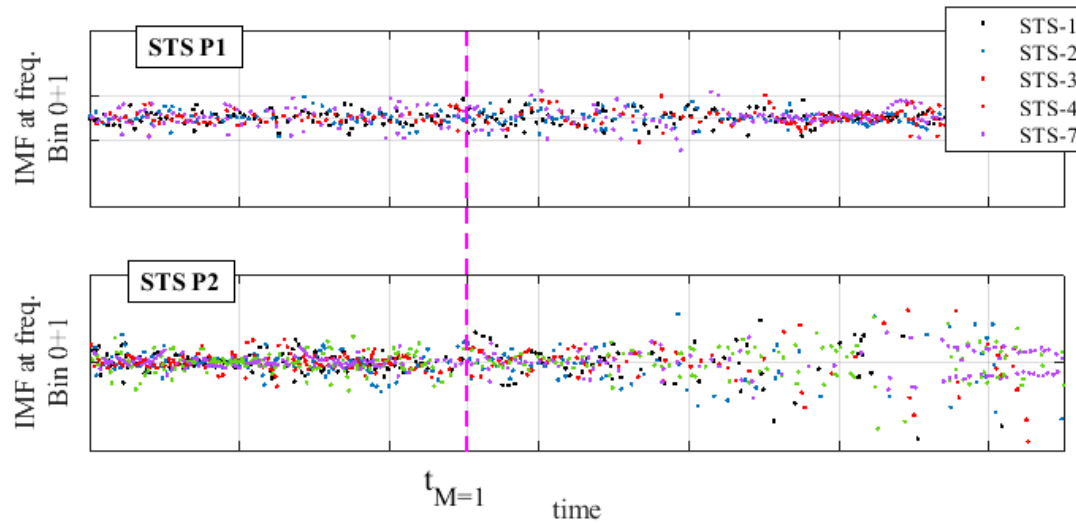
Mission	Launch Date
STS-1	April 12, 1981
STS-2	November 12, 1981
STS-3	March 22, 1982
STS-4	November 27, 1982
STS-7	June 18, 1983

- DFI instrumentation:
 - Temperature (black)
 - Low frequency pressure sampled at 1Hz (red)
 - “High” frequency pressure sampled at 10Hz (blue)
 - Microphones sampled at 50kHz (aqua)
- Nearly half of external tank instrumentation is on the base



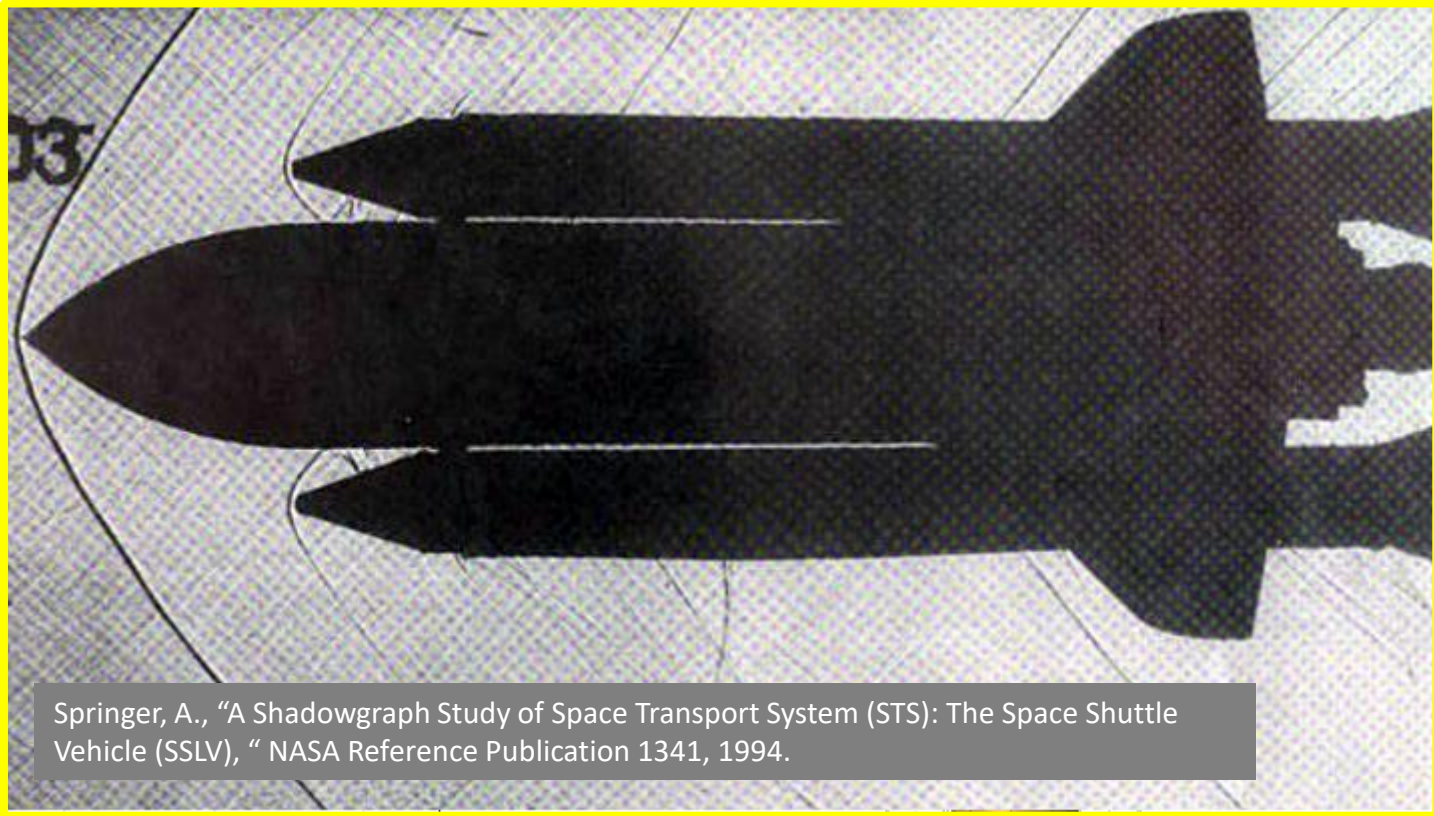
Shuttle

- Pressure measurements upstream of the booster FAH exhibit relatively constant fluctuation levels
- Pressure downstream of FAH show increased fluctuations visualized by plotting the signal from several STS missions together
- Similar behavior was observed in Artemis I data

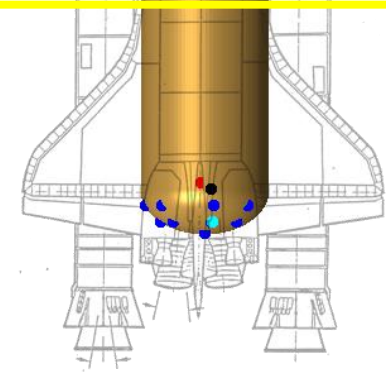
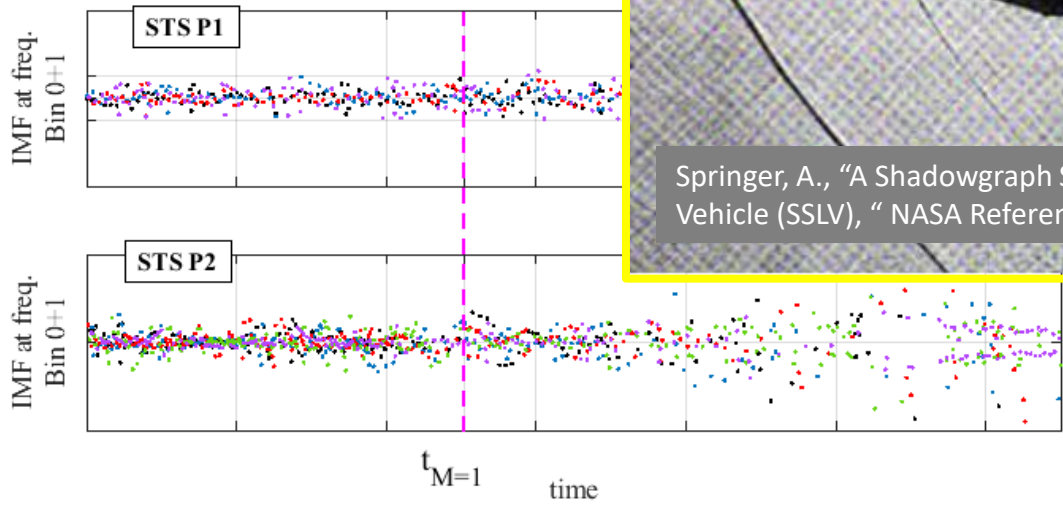


Shuttle

- Pressure measurements upstream of hardware (FAH) exhibit relatively constant behavior
- Pressure downstream of FAH show irregular behavior. In this plot, the signal from several STS missions is shown
- Similar behavior was observed in Art

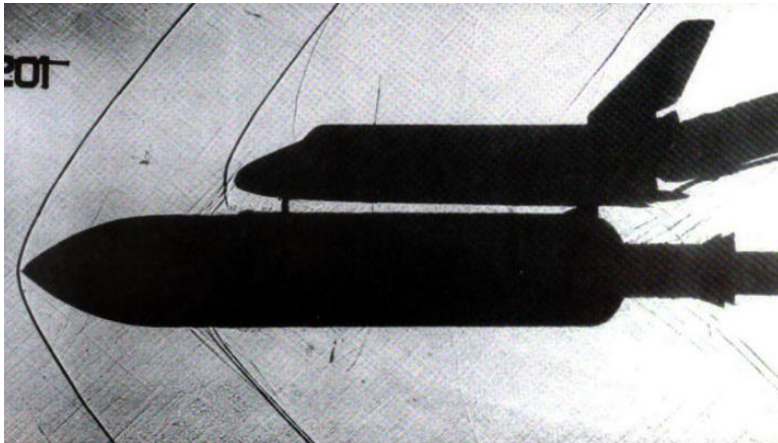


Springer, A., "A Shadowgraph Study of Space Transport System (STS): The Space Shuttle Vehicle (SSLV)," NASA Reference Publication 1341, 1994.

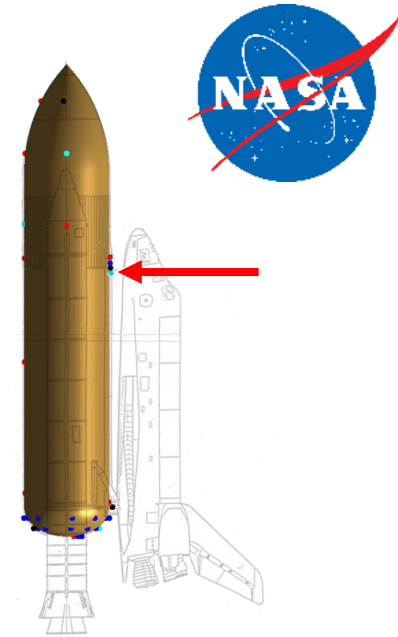
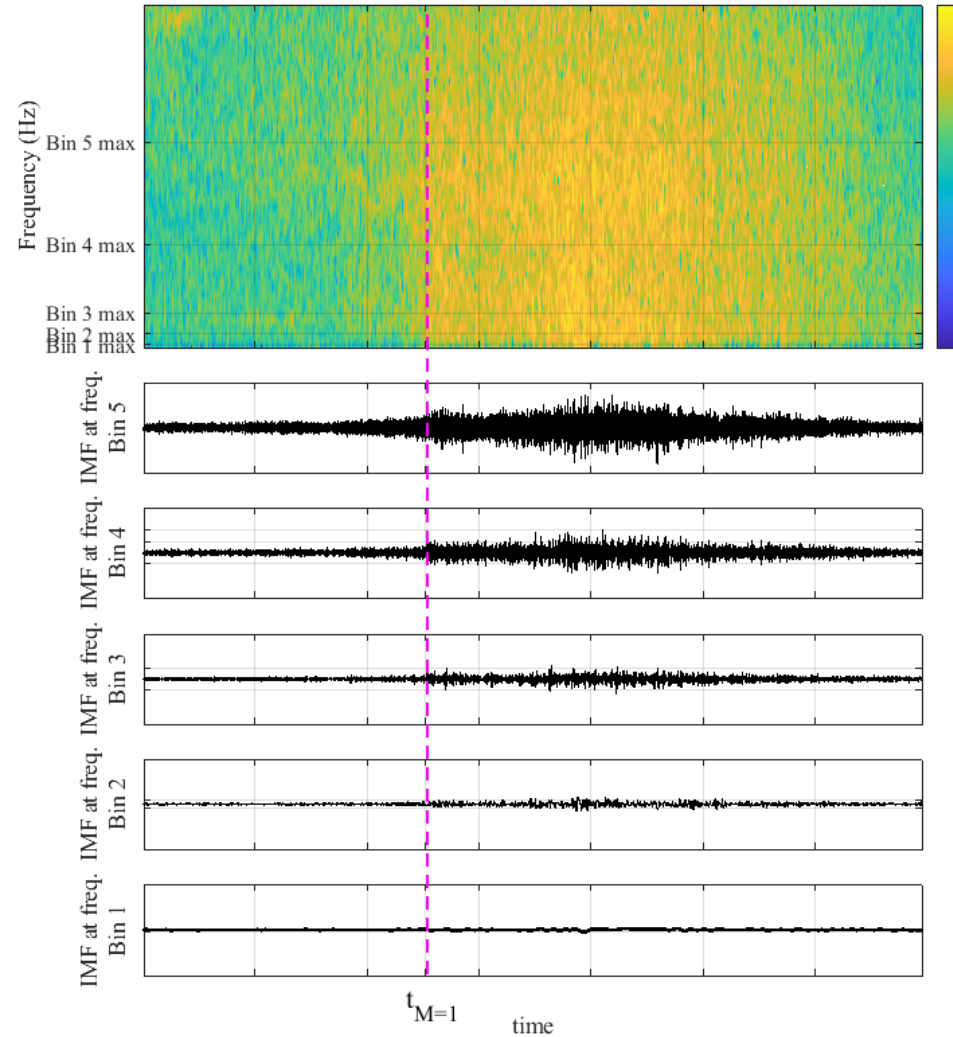


Shuttle

- Similar behavior as in the booster core gap was also observed in the orbiter-ET gap
- High frequency fluctuations increase in the supersonic flight downstream of the bow shock formed around the orbiter nose

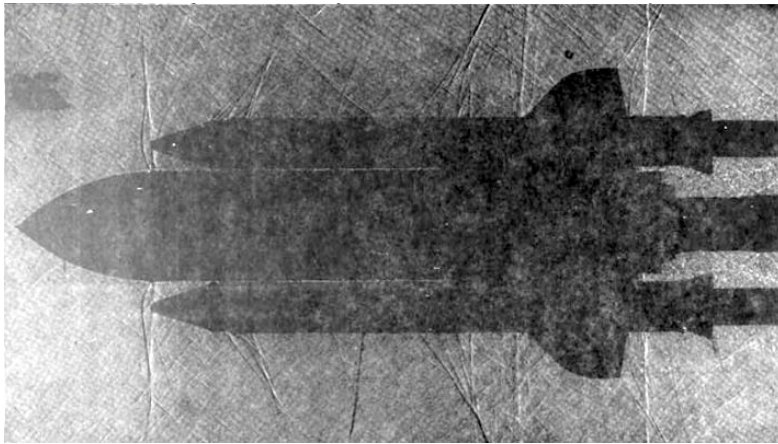


Springer, A., "A Shadowgraph Study of Space Transport System (STS): The Space Shuttle Vehicle (SSLV)," NASA Reference Publication 1341, 1994.

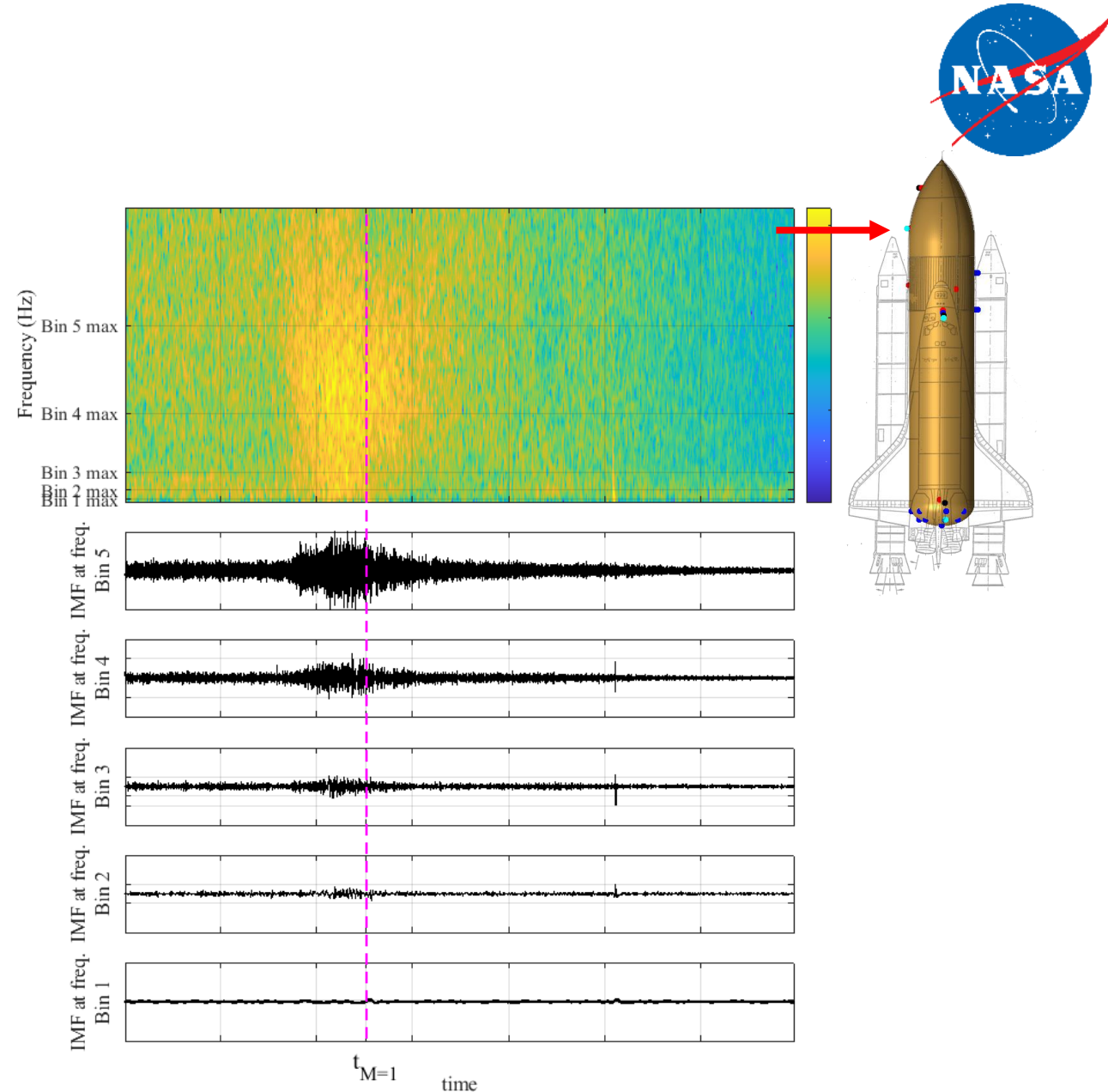


Shuttle

- Fluctuations on the ogive were observed near $M=1$
- Although unlike in the SLS and Ares I-X, no signature of the terminal shock was evident in the pressure signal



Springer, A., "A Shadowgraph Study of Space Transport System (STS): The Space Shuttle Vehicle (SSLV), " NASA Reference Publication 1341, 1994.



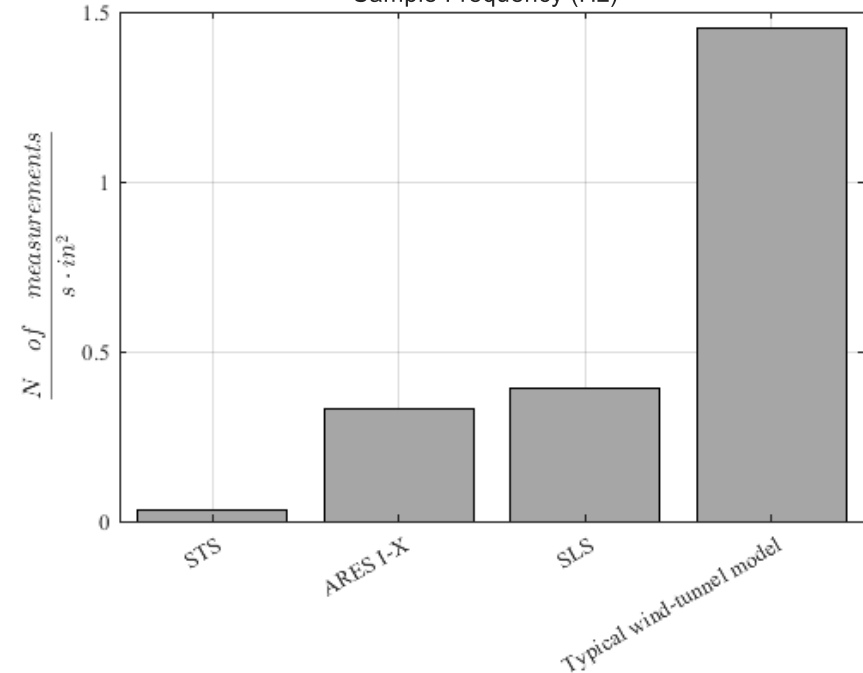
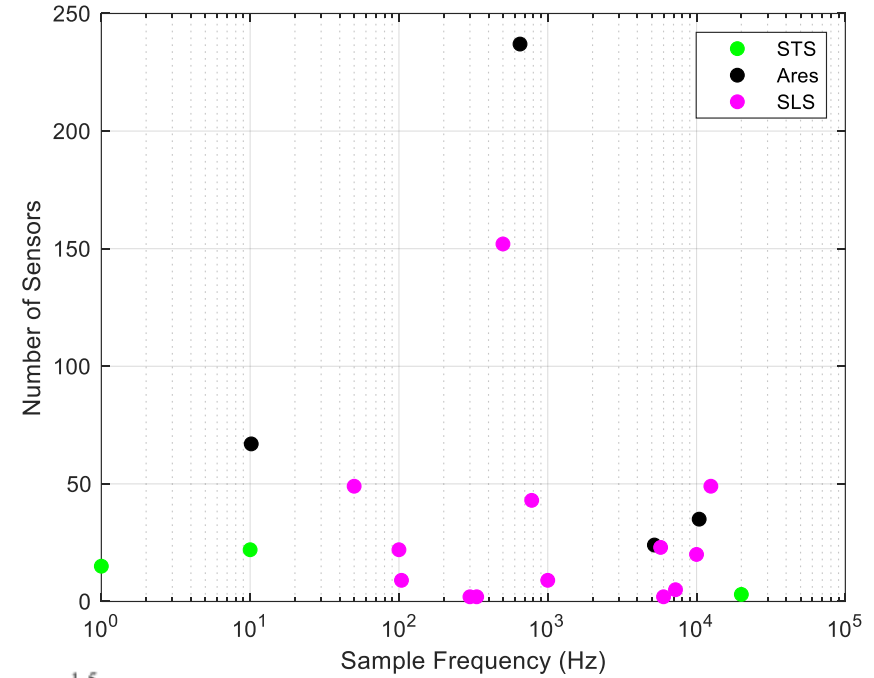
DFI Summary

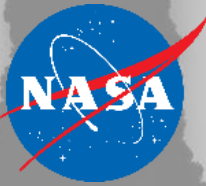
- SLS and Ares I-X: DFI contribution to unsteady aerodynamics is similar
 - Expected considering Artemis inheriting DFI architecture from Constellation
- STS DFI is insufficient (in sampling frequency and spatial density) to perform unsteady aerodynamics analysis
- The benefit of multiple launches may be further explored
 - Motivation for development of signal processing tools for measurements with non-uniform sample rates



IMF Signal Visualization Summary

- IMFs were used to visualize flight data with some success
- A more robust way to identify characteristic frequency of each IMF is needed
- Further work is planned to use with Artemis II flight data
- Ability to quickly analyze data with variable sample rate





Questions?

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