Investigating Response from Turbulent Boundary Layer Excitations on a Real Launch Vehicle using SEA

Presented to
The Spacecraft and Launch Vehicle
Dynamic Environments Workshop

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Agenda

- Introduction and Important Questions
- Present Model and Applied Spectra
- Present Locations for Comparison to Shuttle ET Flight Data
- Show the Character of Flight Vibration Data
- Compare SEA Response to Flight Measurements for 5 Locations for Turbulent Boundary Layer (TBL) Study
- Present Analysis Case Matrix & TBL Excitation Parameter Study Trends
- Present Summary and Conclusions
- Future Work

The results presented represent a work in progress.

A table outlining ongoing investigations is provided.

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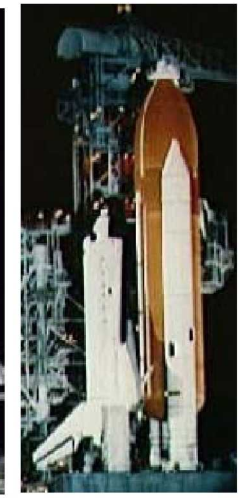
Introduction/Important Questions



- Statistical Energy Analysis (SEA) response has been fairly well anchored to test observations for Diffuse Acoustic Field (DAF) loading by others. Meanwhile, not many examples can be found in the literature anchoring the SEA vehicle panel response results to Turbulent Boundary Layer (TBL) fluctuating pressure excitations. This deficiency is especially true for supersonic trajectories such as those required by this nation's launch vehicles.
- Space Shuttle response and excitation data recorded from vehicle flight measurements during the development flights were used in a trial to assess the capability of the SEA tool to predict similar responses. Various known/measured inputs were used. These were supplemented with a range of assumed values in order to cover unknown parameters of the flight. This comparison is presented as "Part A" of the study.
- A secondary, but perhaps more important, objective is to provide more clarity concerning the accuracy and conservatism that can be expected from response estimates of TBL-excited vehicle models in SEA (Part B).
  - What range of parameters must be included in such an analysis in order to land on the conservative side in response predictions?
  - What is the sensitivity of changes in these input parameters on the results?
- The TBL fluid structure loading model used for this study is provided by the SEA module of the commercial code VA One.

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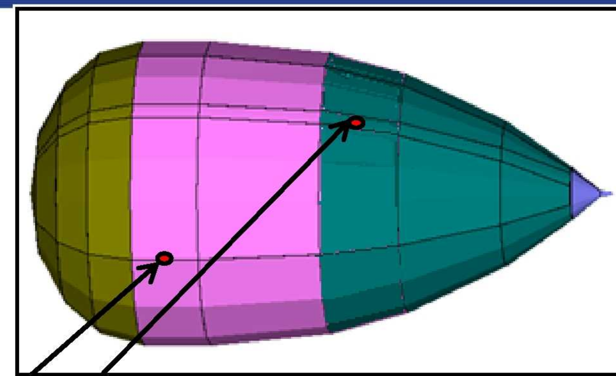
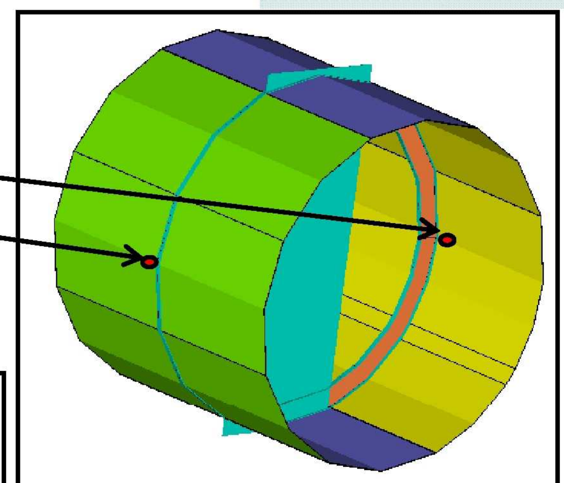
Present Model and Applied Spectra

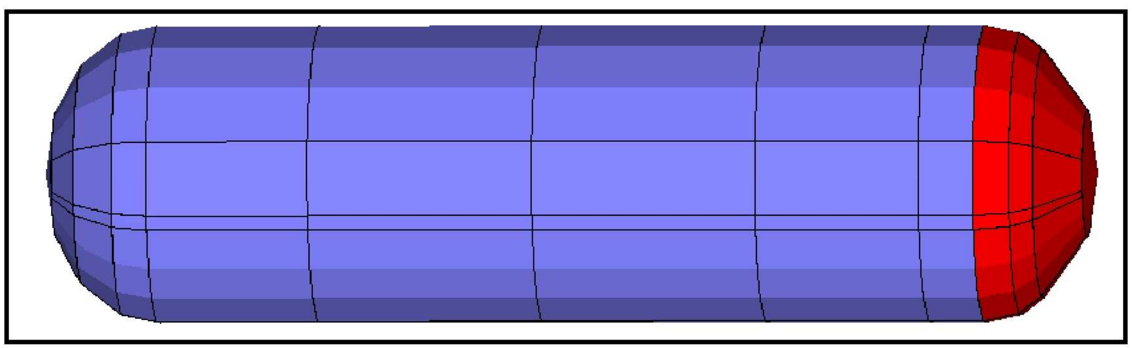
- Ascent excitation spectra used:
  - Zonal environments from Preliminary Vibration, Acoustic, and Shock Design and Test Criteria for Components on the Lightweight External Tank (NASA-RP-1074, Reference 2)
  - Flight Data (Exterior Microphones)
    - STS-5 microphone #T08Y9957A at 67 seconds
    - STS-5 microphone #T08Y9958A at 67 seconds
    - STS-5 microphone #T08Y9954A at 67 seconds
    - STS-5 microphone #T08Y9953A at 67 seconds



Left SRB -Y



Right SRB +Y



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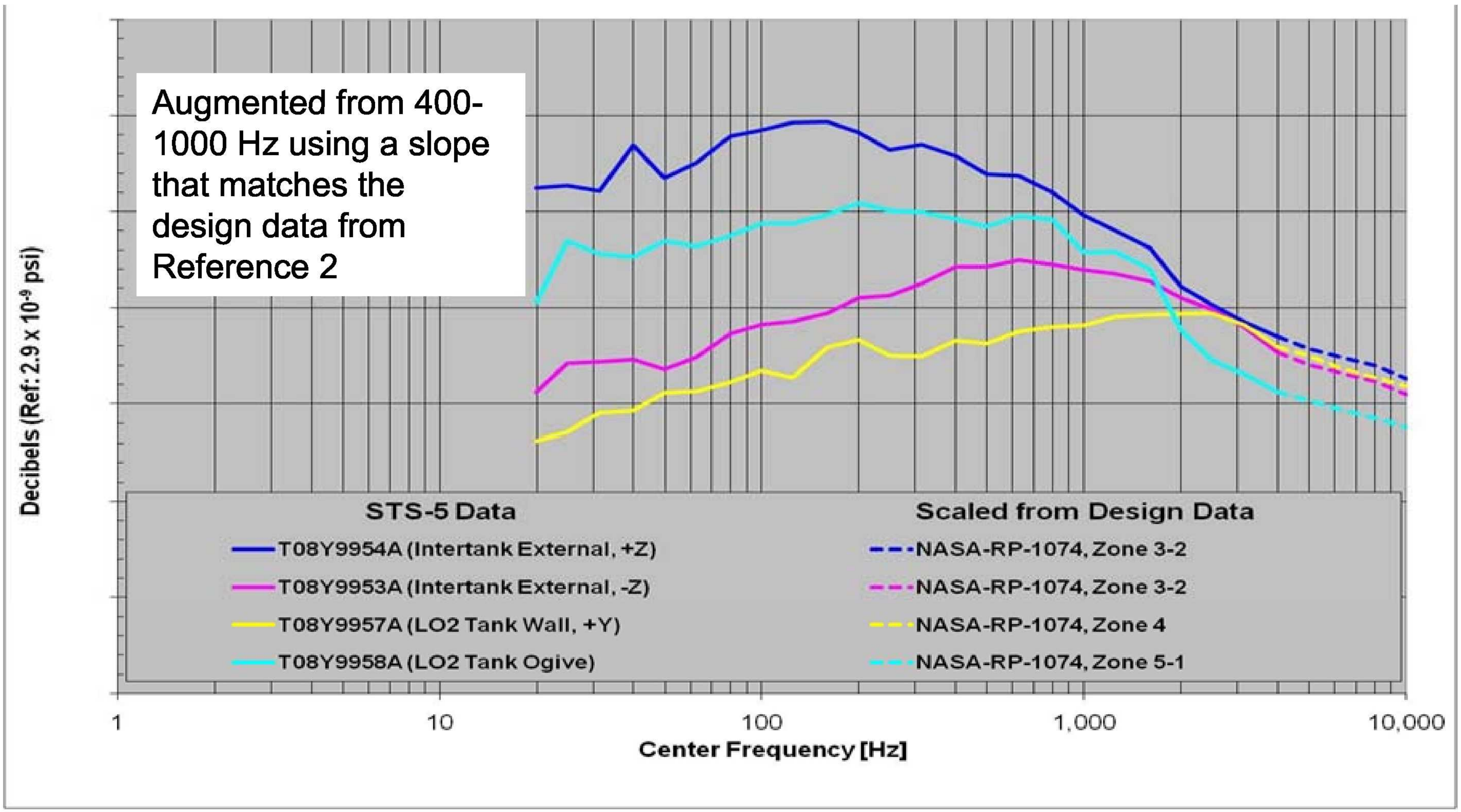
Applied Acoustic Excitation Spectra From STS-5 Microphones at 67 Seconds



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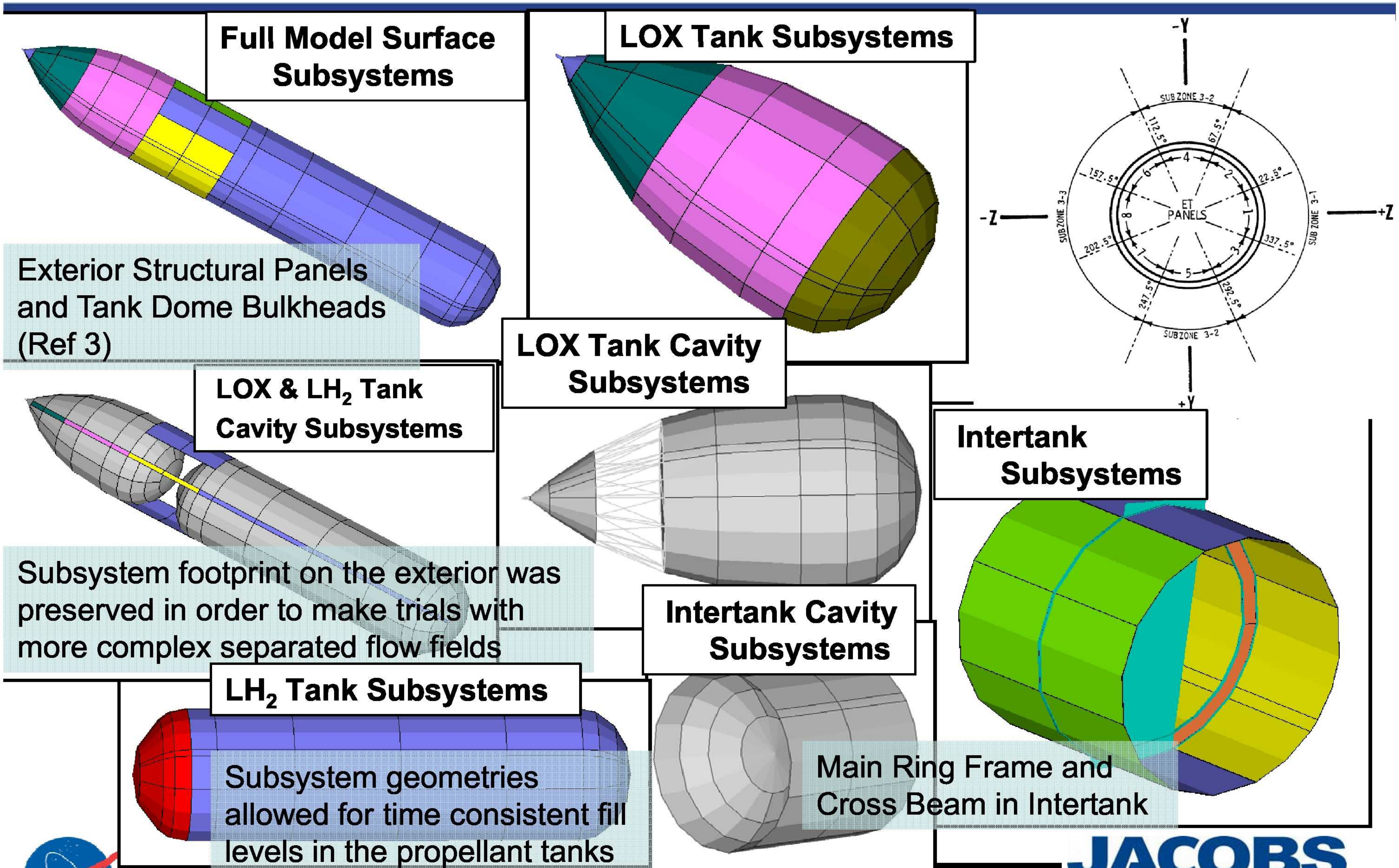
SEA Model Represents Standard Weight ET From Development Flight Era



Exterior Structural Panels and Tank Dome Bulkheads (Ref 3)

Subsystem footprint on the exterior was preserved in order to make trials with more complex separated flow fields

Subsystem geometries allowed for time consistent fill levels in the propellant tanks

Main Ring Frame and Cross Beam in Intertank

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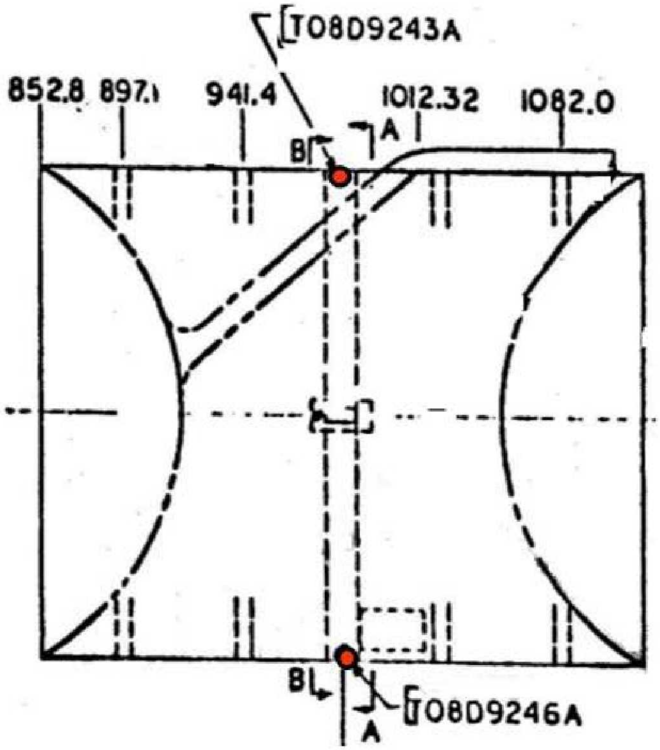
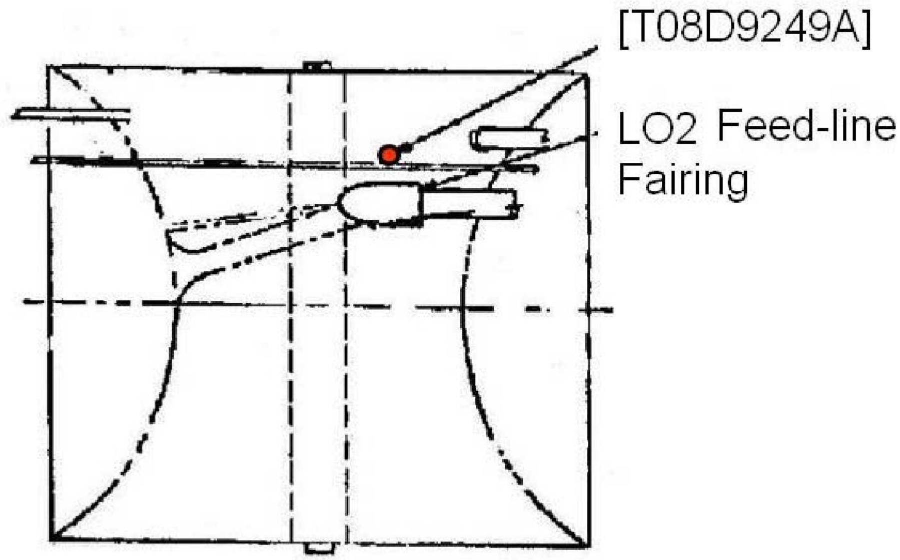
Present Locations for Comparison to Flight Data

- Three Locations in the Intertank:
  - Interface between exterior panels and Main Ring Frame on Orbiter side of the External Tank (Inboard +Z) [T08D9243A, Radial]
  - Similar Panel/Main Ring Frame Interface on the far side from Orbiter (Outboard –Z) [T08D9246A, Radial]
  - On Intertank Wall Near GO_2 Pressurization-line [T08D9249A, Radial]





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Present Locations for Comparison to Flight Data

- Two Locations on the LOX Tank:
  - LO2 Tank Input to Cable Tray Radial (Xt =760) [T08D9992A, Radial]
  - Fwd Ogive On Tank Wall Near GO_2 Press-line [T08D9269A, Radial]

- Later Discussion - [T08D9992A, Radial] out of family measurement.

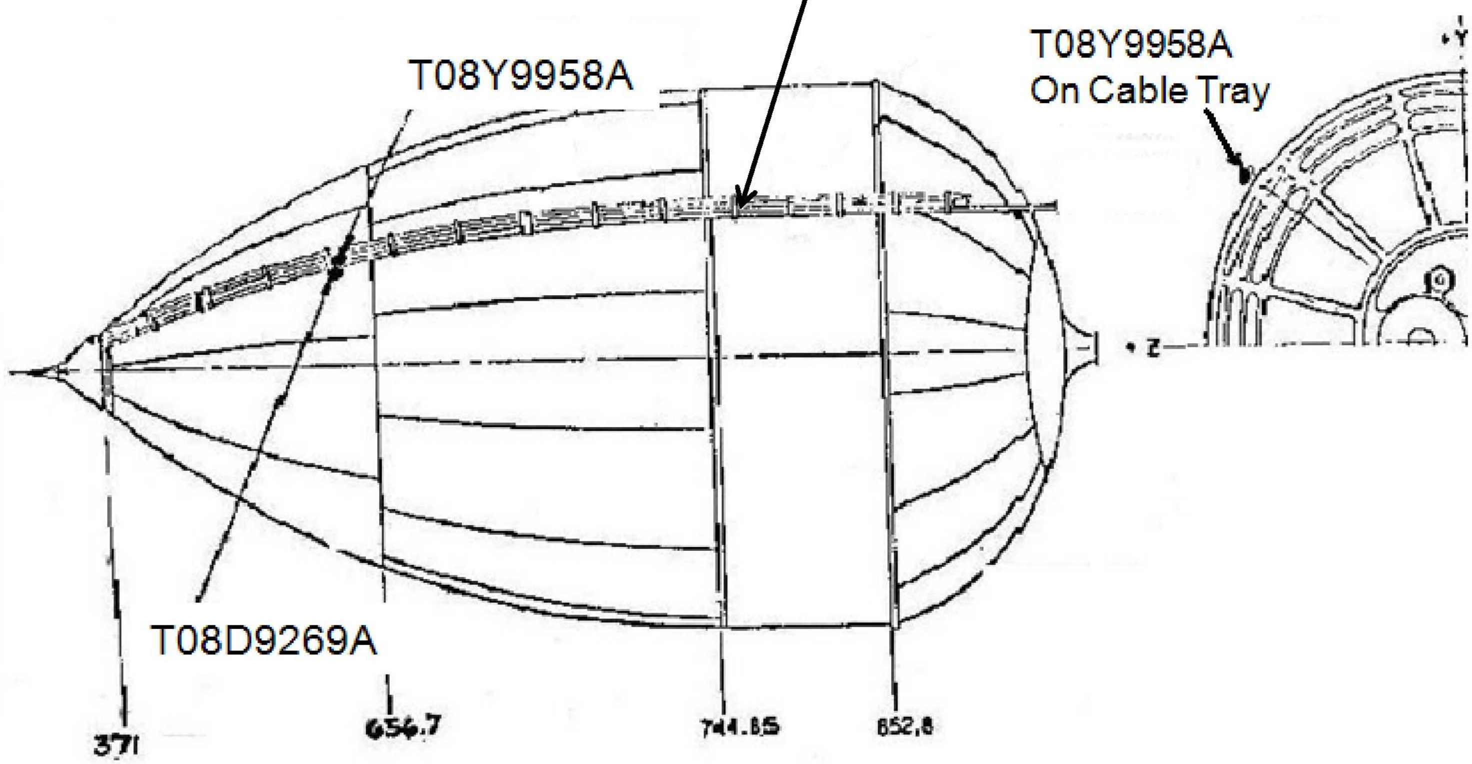
T08D9992A Not pictured in Figure but described in Table Reference 1

T08D9992A	LO_2 Tank Input to Cable Tray, Radial
T08D9993A	LO_2 Tank Input to Cable Tray, Tang. X_T = 760

Test Photo

Typical installation

Location of [T08D9992A, Radial]



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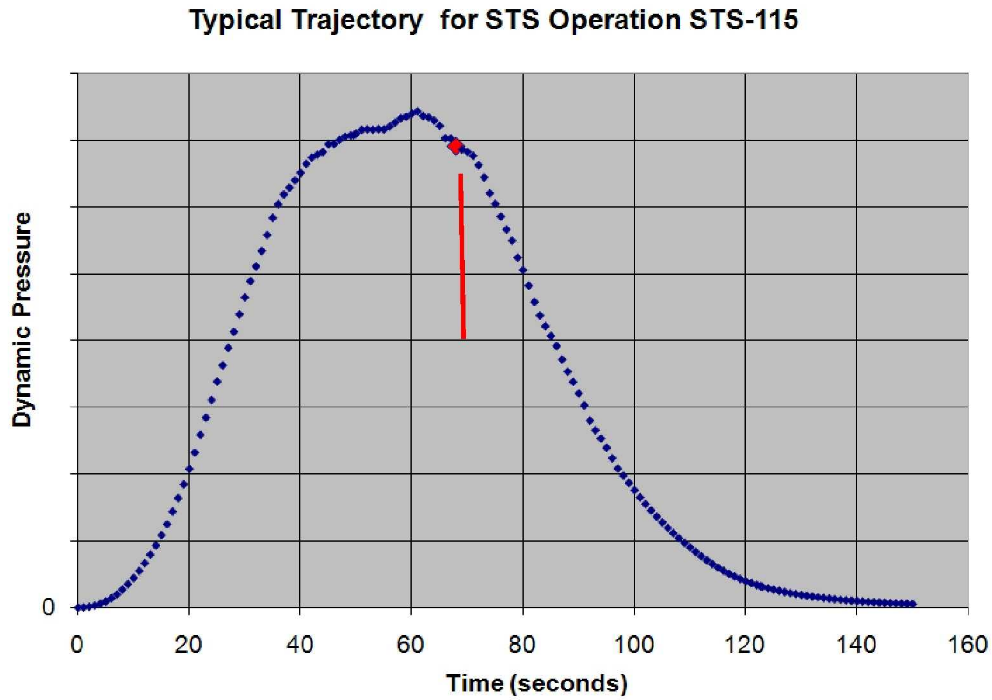
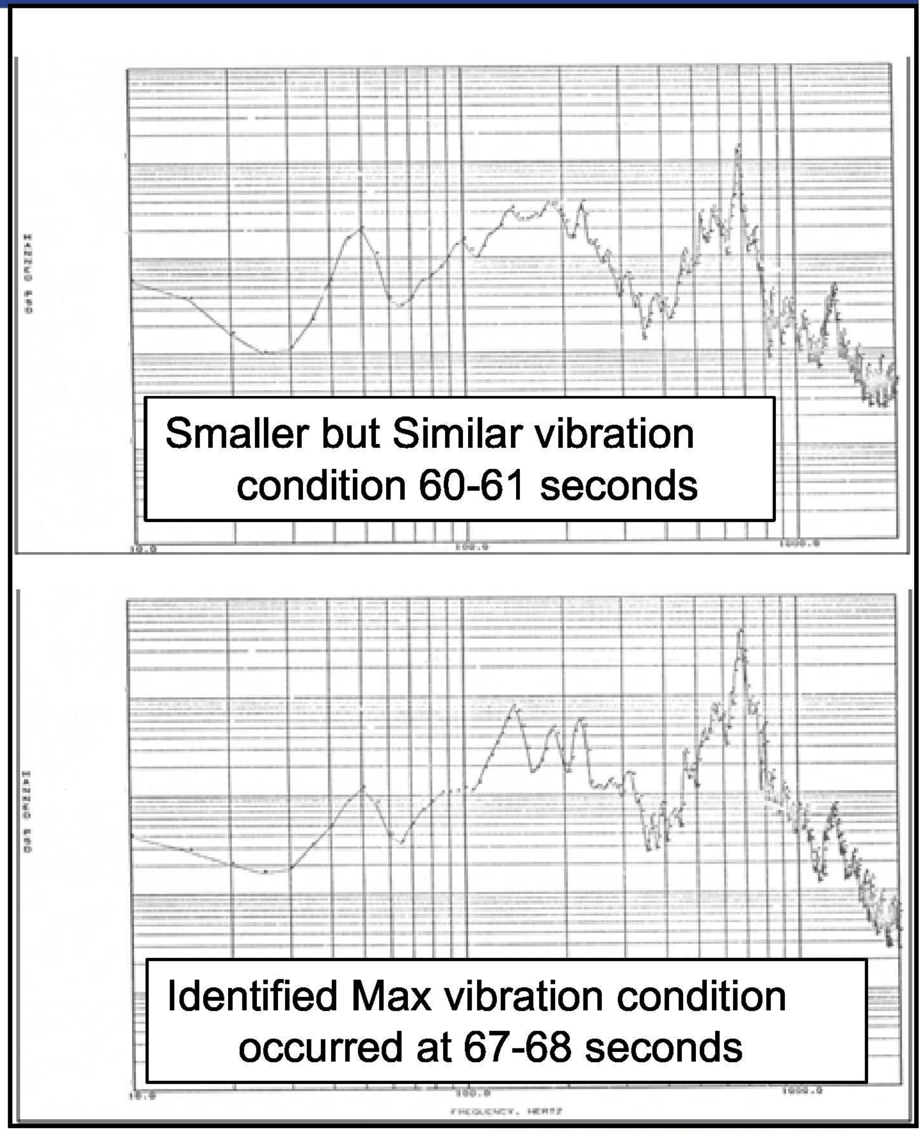
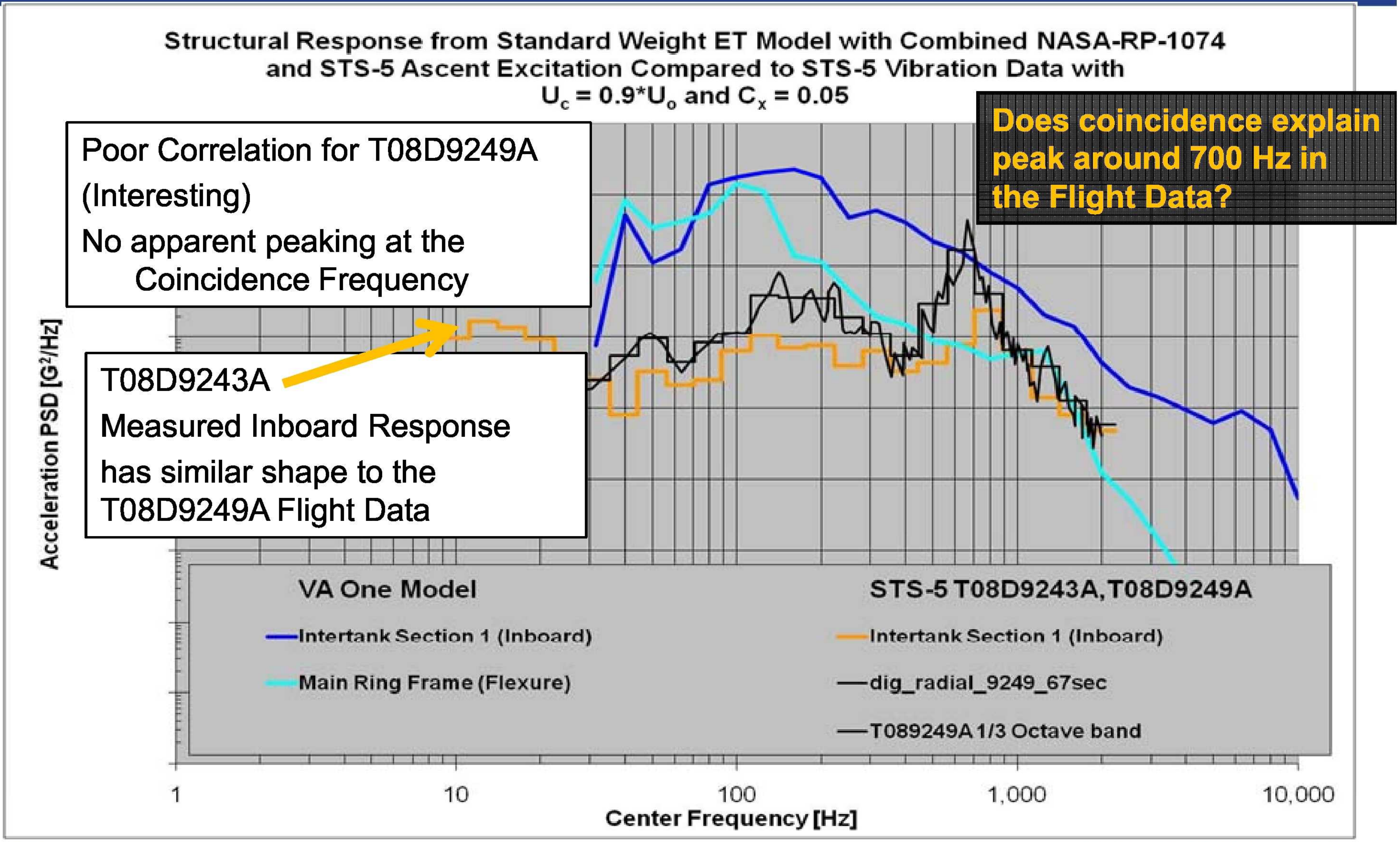
Show Character of Flight Vibration Data & Trajectory Indicator



- Initially, assessed the time when vibration measurements typically were a maximum during the ascent.
- Used free stream velocity = 18,458 in/sec. [STS-5 Trajectory.xls at 67 seconds]
- Future work: Assess the time where pressure measurements were a maximum during the ascent.



Compare SEA TBL Response to Flight Measurements Intertank Panels



Case L99AW05

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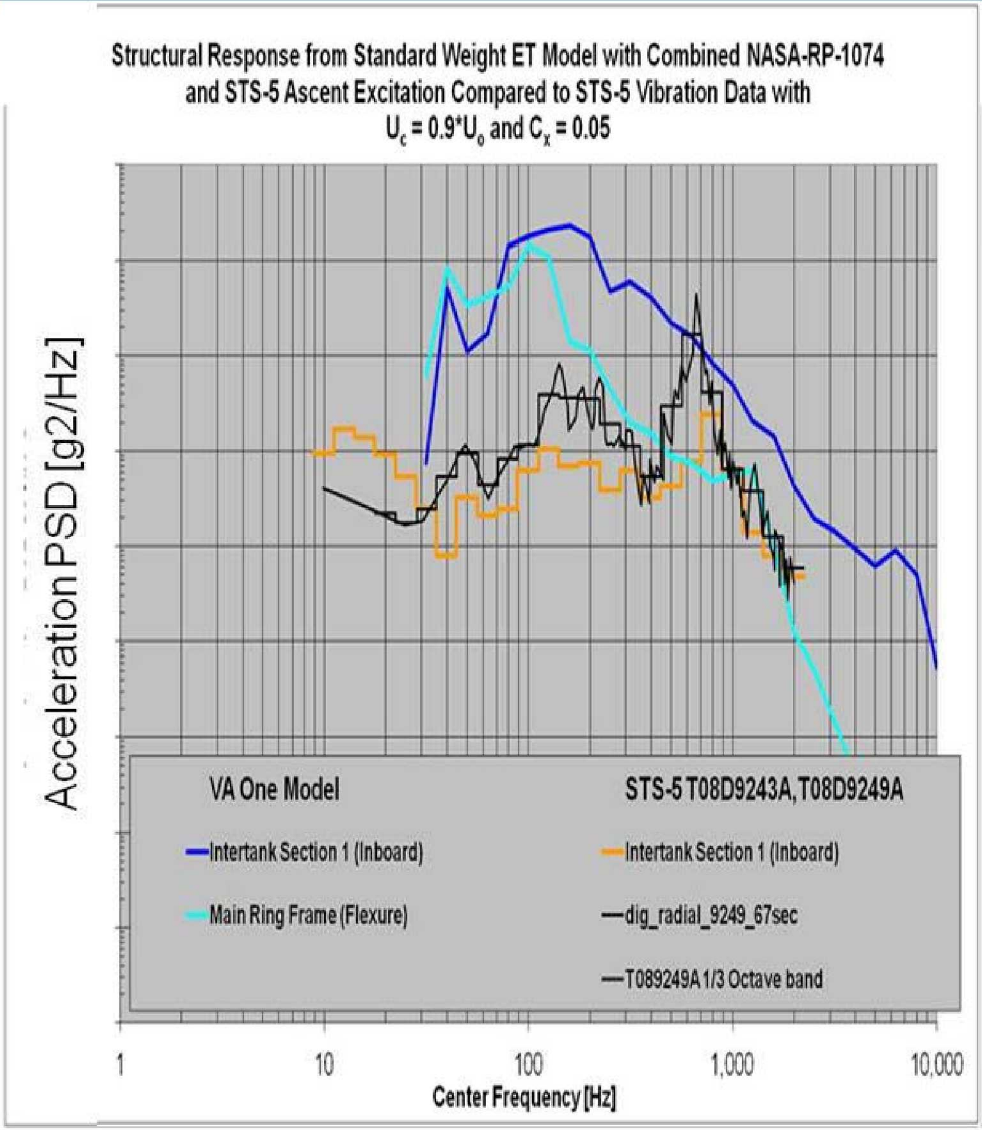
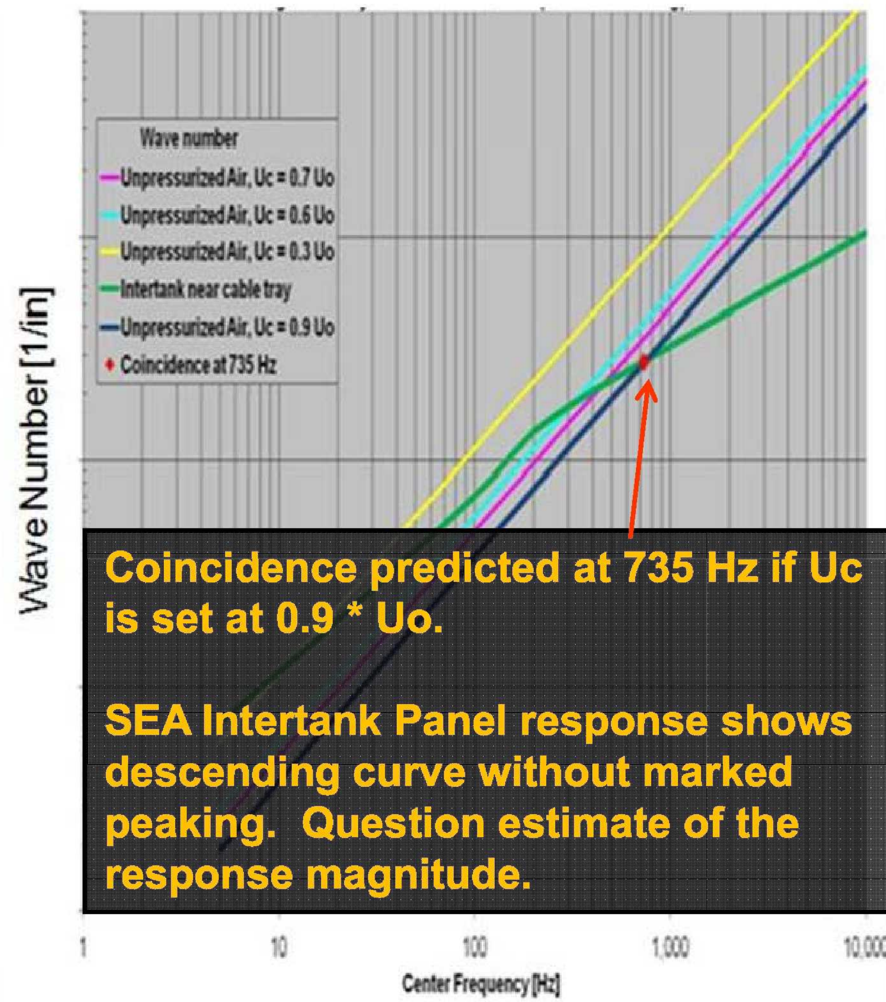
Compare SEA TBL Response to Flight Measurements Intertank Panels





Coincidence predicted at 735 Hz if Uc is set at 0.9 * Uo.

SEA Intertank Panel response shows descending curve without marked peaking. Question estimate of the response magnitude.

Case L99AW05

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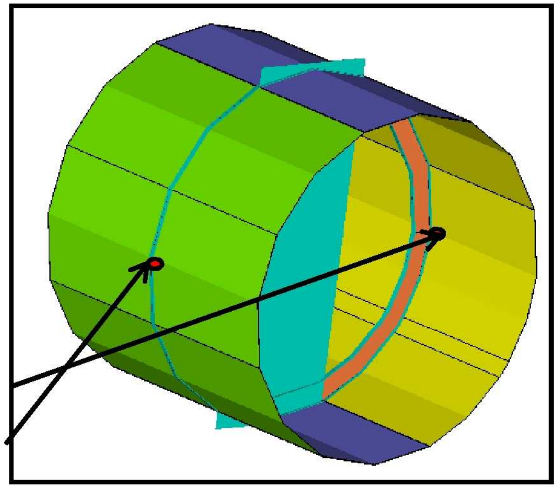
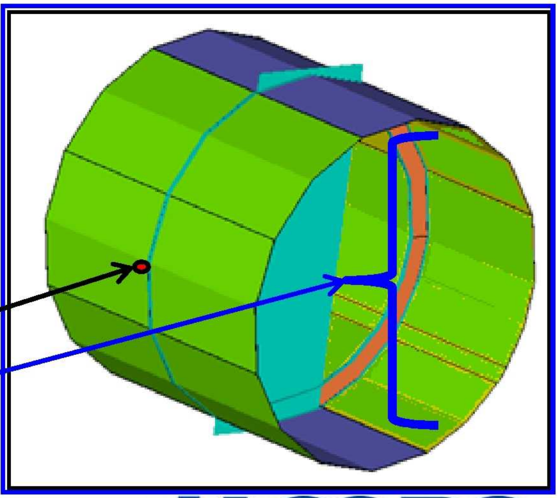
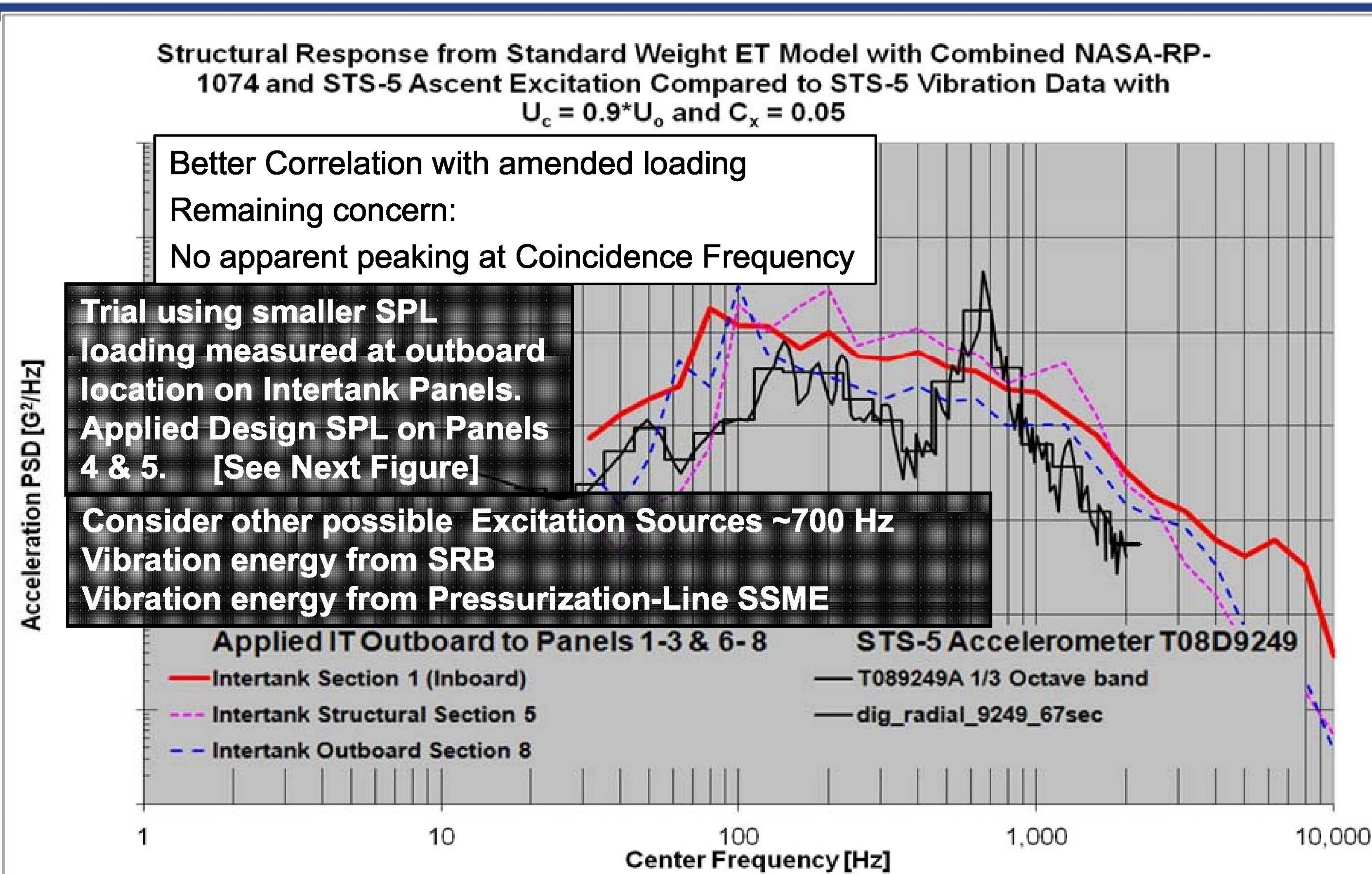
Present Amended External Applied Pressure levels Intertank Only

- Ascent excitation spectra used:
  - **Zonal environments NASA-RP-1074, Reference 2) Panels 4 & 5**
  - Flight Data (Exterior Microphones)
    - STS-5 microphone #T08Y9957A at 67 seconds
    - STS-5 microphone #T08Y9958A at 67 seconds
    - STS-5 microphone #T08Y9954A at 67 seconds
    - STS-5 microphone #T08Y9953A at 67 seconds
- Measurement T08Y9954A may not be appropriate over a large surface. True measurement of local effect.
- Amended External Loading Trial Intertank
  - Apply SPL from the outboard Intertank Microphone to inboard intertank subsystems
    - STS-5 microphone #T08Y9953A at 67 seconds
    - Applied measured pressures from outboard sensor T08Y9953A to inboard subsystems





Compare SEA TBL Response to Flight Measurements
Intertank Panels



Better Correlation with amended loading

Remaining concern:

No apparent peaking at Coincidence Frequency

Trial using smaller SPL loading measured at outboard location on Intertank Panels. Applied Design SPL on Panels 4 & 5. [See Next Figure]

Consider other possible Excitation Sources ~700 Hz
Vibration energy from SRB
Vibration energy from Pressurization-Line SSME

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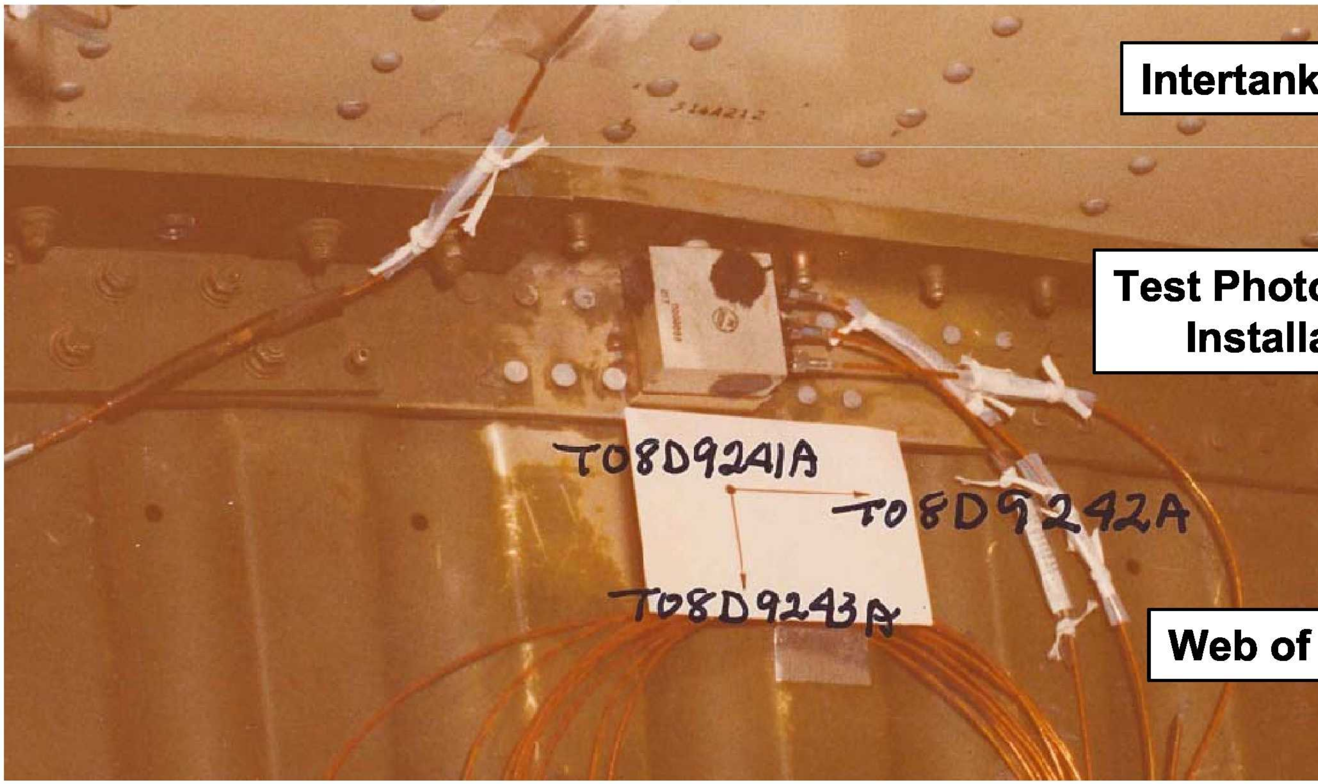
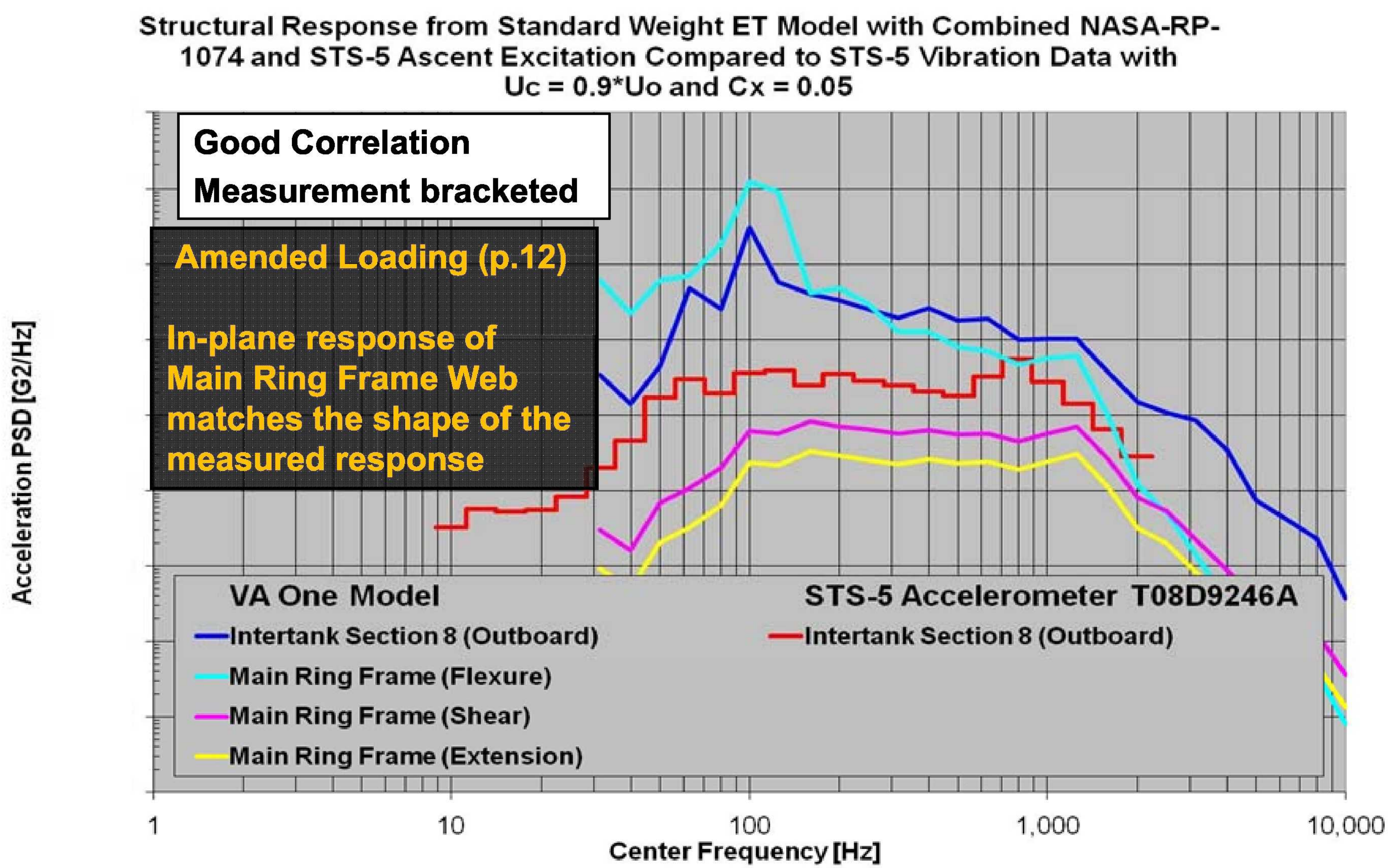
Compare SEA TBL Response to Flight Measurements
Intertank Panel Main Ring Frame Junction

- Photos of the Main Ring Frame accelerometer installation led us to make a comparison to Main Ring Frame Web SEA model subsystems.
  - Interface between the exterior panels and the Main Ring Frame on the Orbiter side of External Tank (Inboard +Z) [T08D9243A, Radial]
  - Interface between the exterior panels and the Main Ring Frame on the far side from the Orbiter (Outboard –Z) [T08D9246A, Radial]



Compare SEA TBL Response to Flight Measurements
Intertank Panel Main Ring Frame Junction



 Case L99AW05 amended

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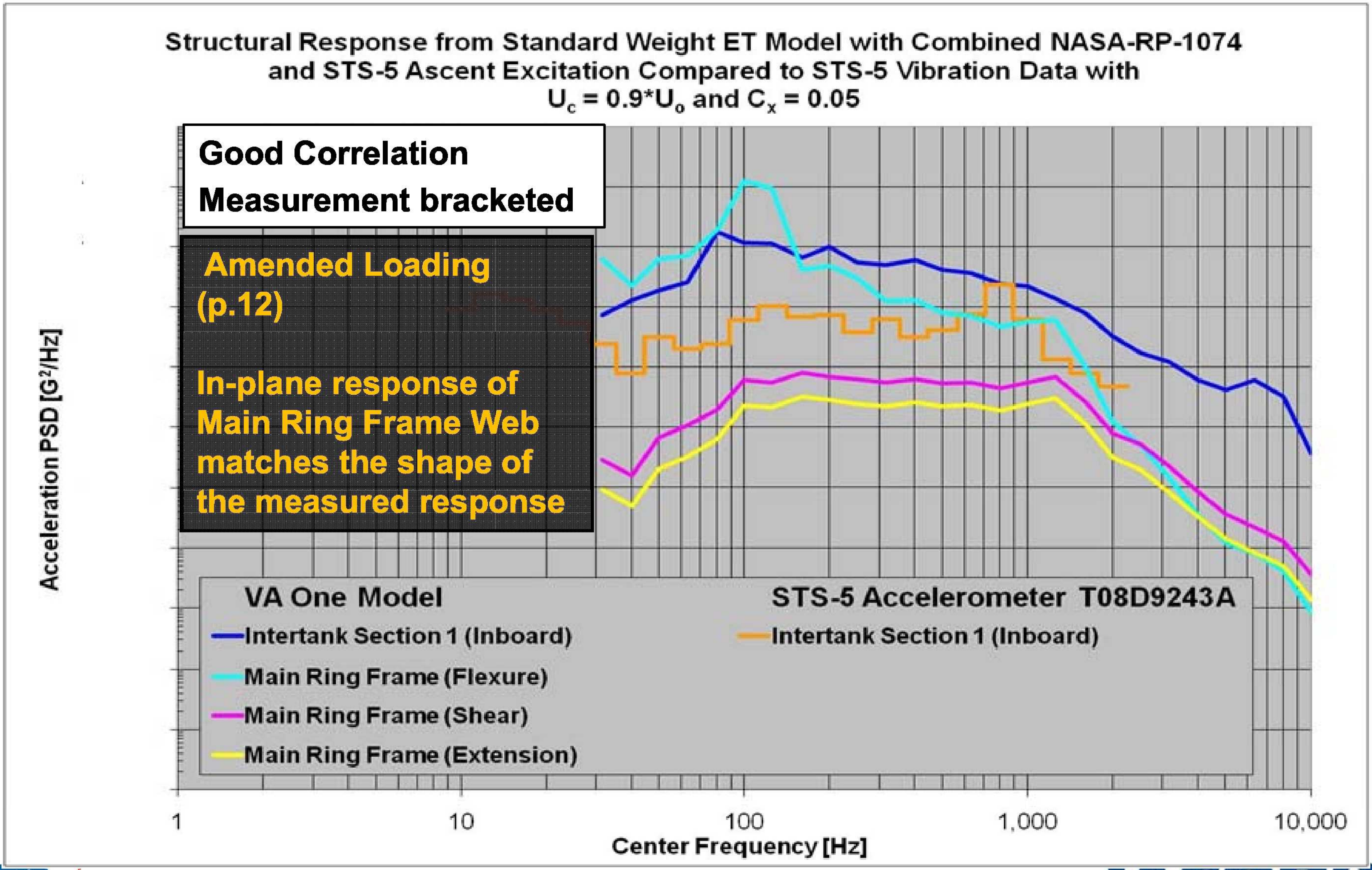
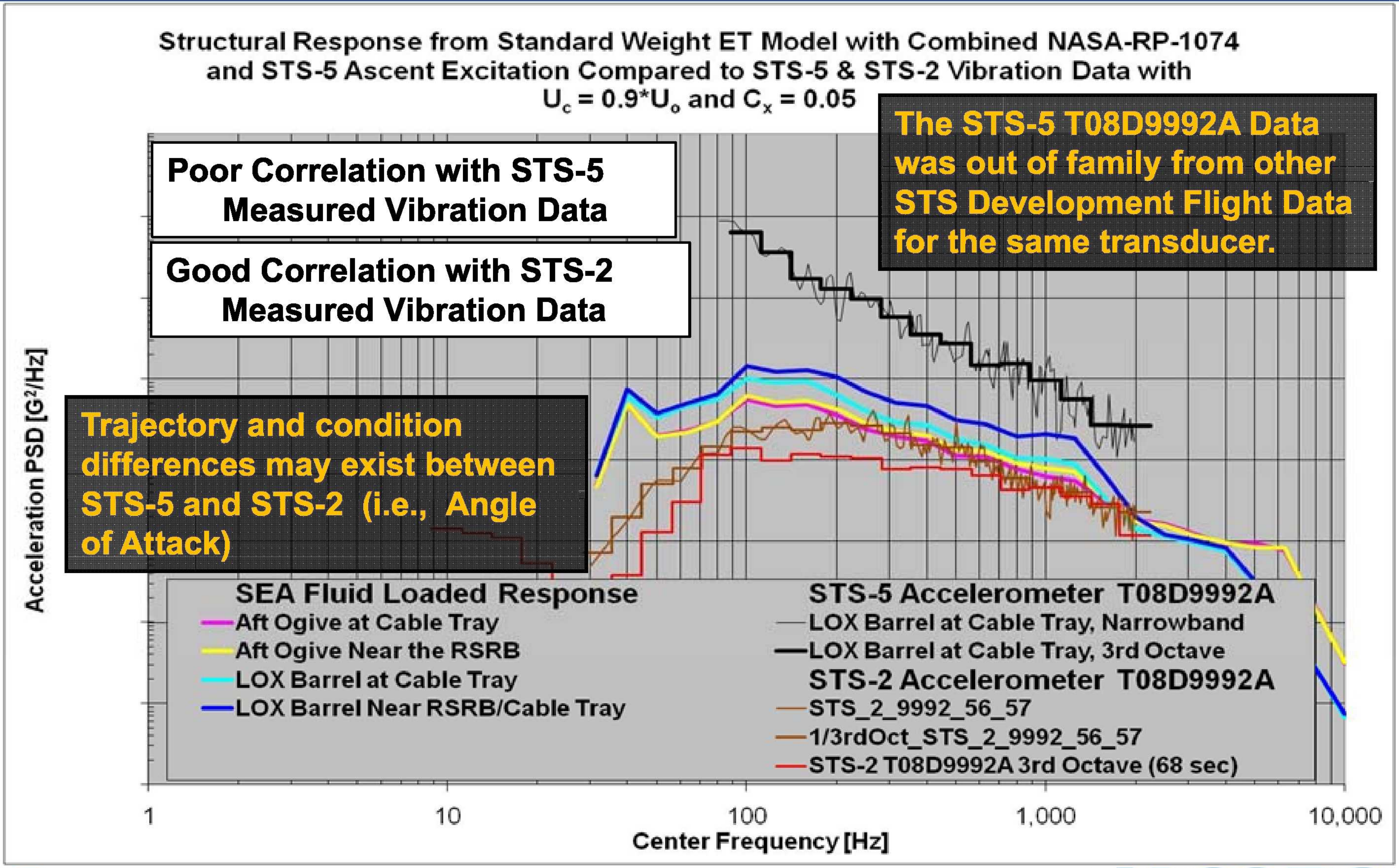
Compare SEA TBL Response to Flight Measurements
Intertank Panel Main Ring Frame Junction

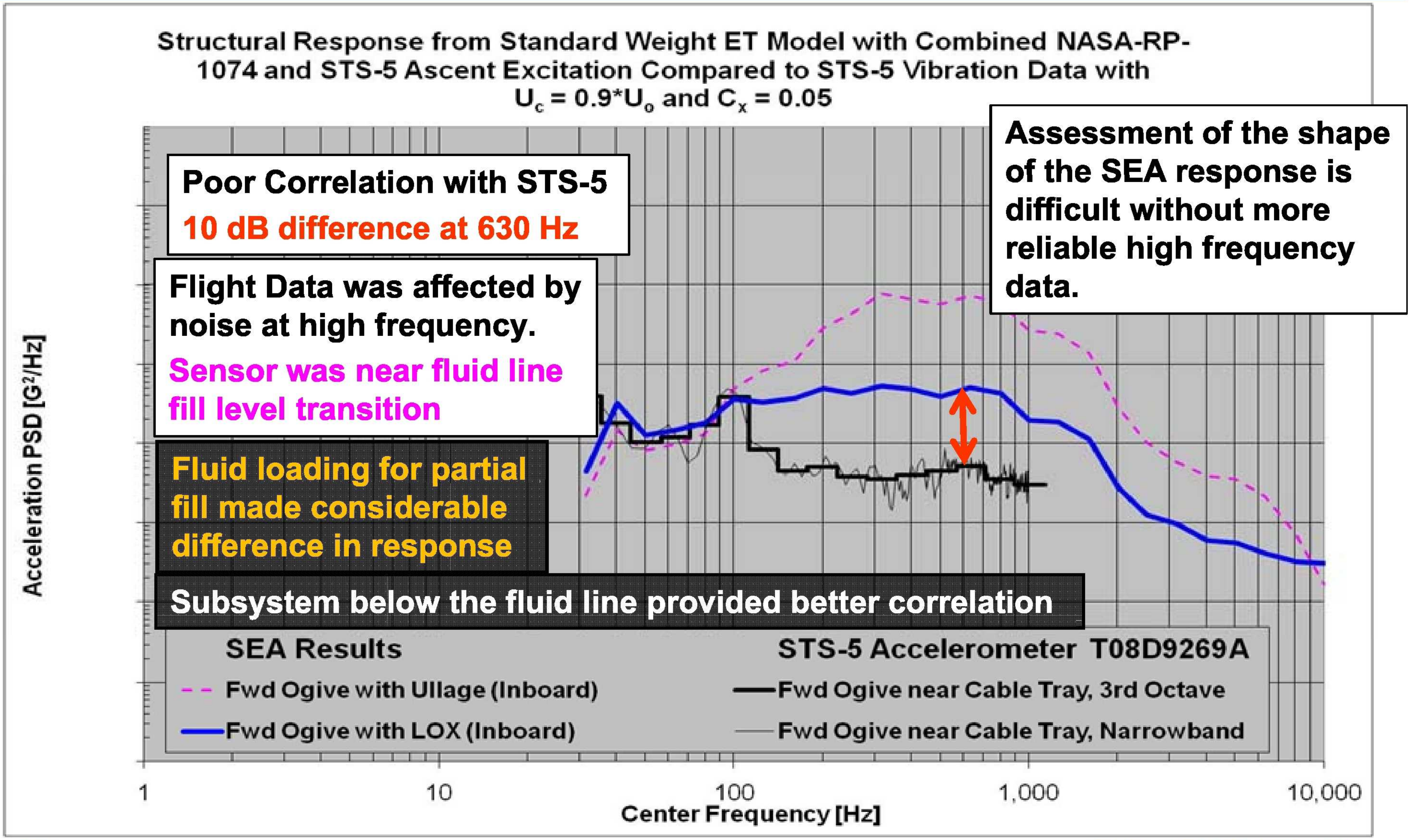


 Case L99AW05 amended

Compare SEA TBL Response to Flight Measurements LOX Barrel and LOX Aft Ogive Locations



Compare SEA TBL Response to Flight Measurements
LOX Tank Fwd Ogive Location



Case L99AW05

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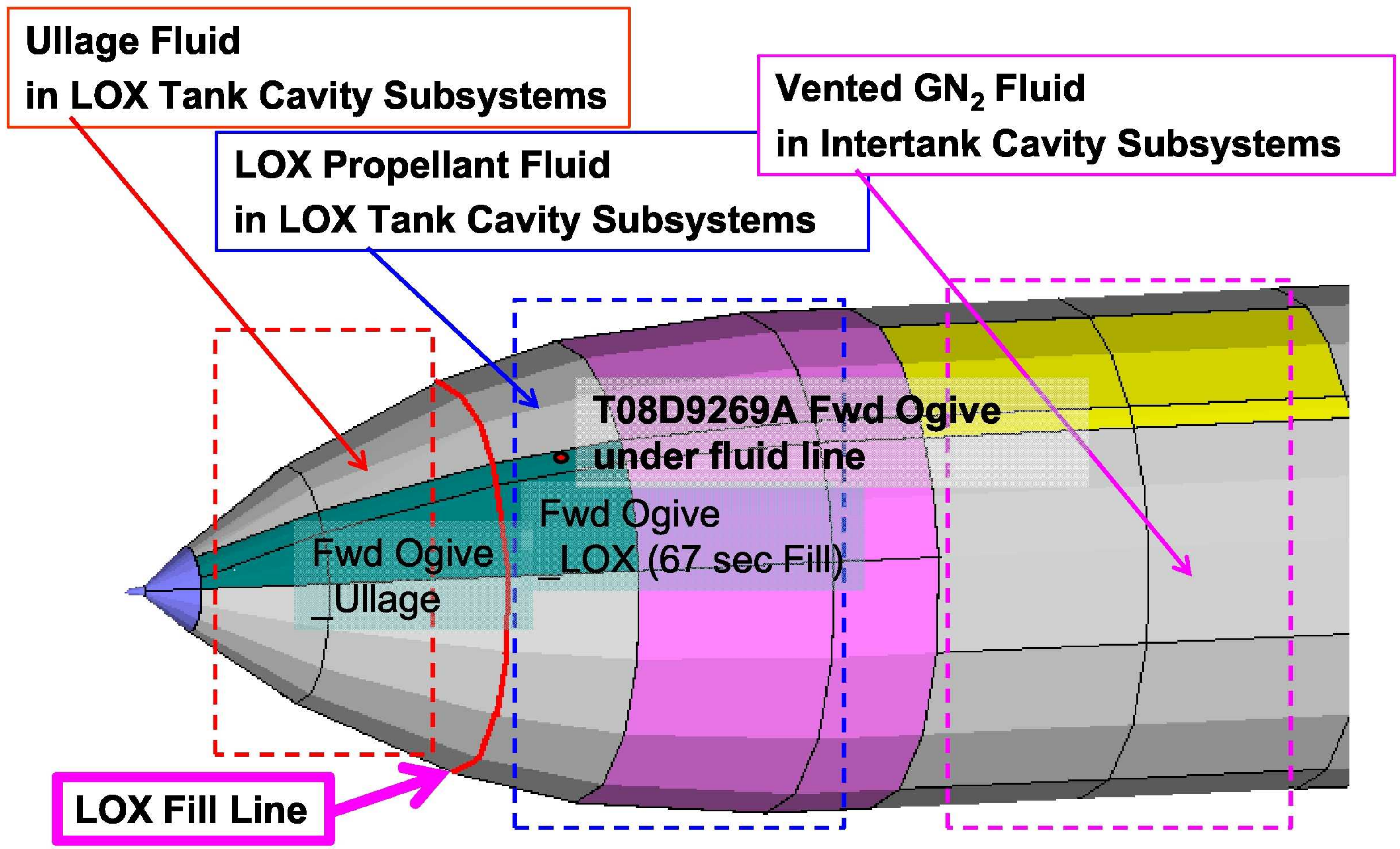
Fluid Treatments that Relate to Subsystem Response Presented LOX Tank Fwd Ogive Location at 67 seconds



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The SEA Analysis Case Matrix used for the Parameter Study

- Blue Highlighted case is presented in comparison to Flight Data ("Wide Open")
- Orange Highlighted cases are presented in the U_c single variable parameter study
- Yellow Highlighted cases are presented in the C_x single variable parameter study

Modeling Case #	Uc Fraction Attached	Uc Fraction Separated	Spatial Correlation Decay Coefficient, Cx
L 63 A U 10	0.60	0.30	0.10
L 63 A W 10	0.60	0.30	0.10
L 65 A U 10	0.60	0.50	0.10
L 67 A U 10	0.60	0.70	0.10
L 69 A U 10	0.60	0.90	0.10
L 73 A U 10	0.70	0.30	0.10
L 75 A U 10	0.70	0.50	0.10
L 75 A U 20	0.70	0.50	0.20
L 75 A U 05	0.70	0.50	0.05
L 75 A W 10	0.70	0.50	0.10
L 77 A U 10	0.70	0.70	0.10
L 79 A U 10	0.70	0.90	0.10
L 83 A U 10	0.80	0.30	0.10
L 85 A U 10	0.80	0.50	0.10
L 87 A U 10	0.80	0.70	0.10
L 89 A U 10	0.80	0.90	0.10
L 93 A U 10	0.90	0.30	0.10
L 95 A U 10	0.90	0.50	0.10
L 97 A U 10	0.90	0.70	0.10
L 99 A U 10	0.90	0.90	0.10
L 99 A U 20	0.90	0.90	0.20
L 99 A U 05	0.90	0.90	0.05
L 99 A W 05	0.90	0.90	0.05
L 99 A W 10	0.90	0.90	0.10

Modeling Case Legend	
L	**Legacy TBL algorithm**
F	**Filled as for Liftoff**
A	**Filled as for Ascent**
U	**Unwetted tanks (= no fluid**
W	**Wetted tanks (= fluid loadi**

- The parameters studied are those that can be selected from the VA One - Legacy Algorithm TBL Dialog Box:
  - U_c
  - C_x, C_y
  - X_0
- U_0 corresponds to the same flight time which typically corresponds with maximum response from the vibration sensors.
- Wanted to learn how to use TBL loading in VA One in order to produce conservative results.
- This study independently confirmed some of the same observations made in Reference 4.
- Range used to vary Convection Velocity as outlined in References 10 and 11.

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TBL Parameters and Structure Interaction

- VA One uses a Spatial Correlation Function to derive the Cross-spectral Density excitation on a vehicle panel:

$$R(\xi,\eta,\omega)=\left(e^{-c_\xi(\omega)\sqrt{k_\xi^2(\omega)+\left(\frac{1}{3\delta^*}\right)^2}|\xi|}\cos\left(k_\xi(\omega)\xi\right)\right)\left(e^{-c_\eta(\omega)\sqrt{k_\xi^2(\omega)+\left(\frac{1}{3\delta^*}\right)^2}|\eta|}\right)$$

- The correlation is both frequency and position dependent on a 2D surface. Coefficients are needed in order to completely define how the TBL will interact with the vehicle panel.

- There are 3 important spatial correlation coefficients that drive this equation:
  - Convection Velocity (governs k_ξ – wavenumber of the fluid in the flow direction)
  - Flow Direction Decay Coefficient (c_ξ)
  - Cross Flow Decay Coefficient (c_η)
  - ξ is the flow direction and becomes x for this analysis
  - η is the cross flow direction and becomes y for this analysis

- The data presented demonstrates how the SEA analytical response of typical ET vehicle panels vary with respect to these parameters.

- An attempt was made to identify parameters that maximized the response.

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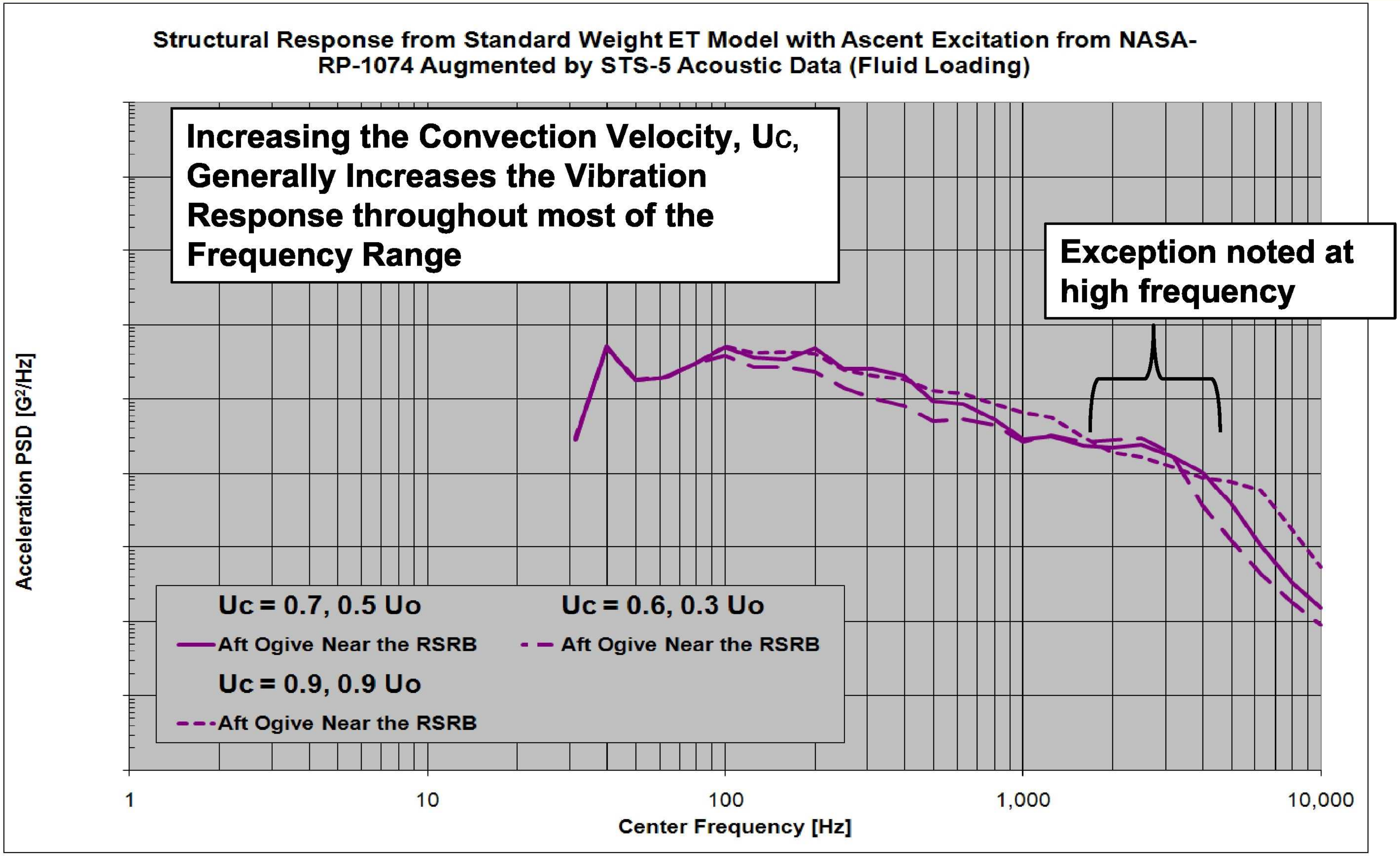
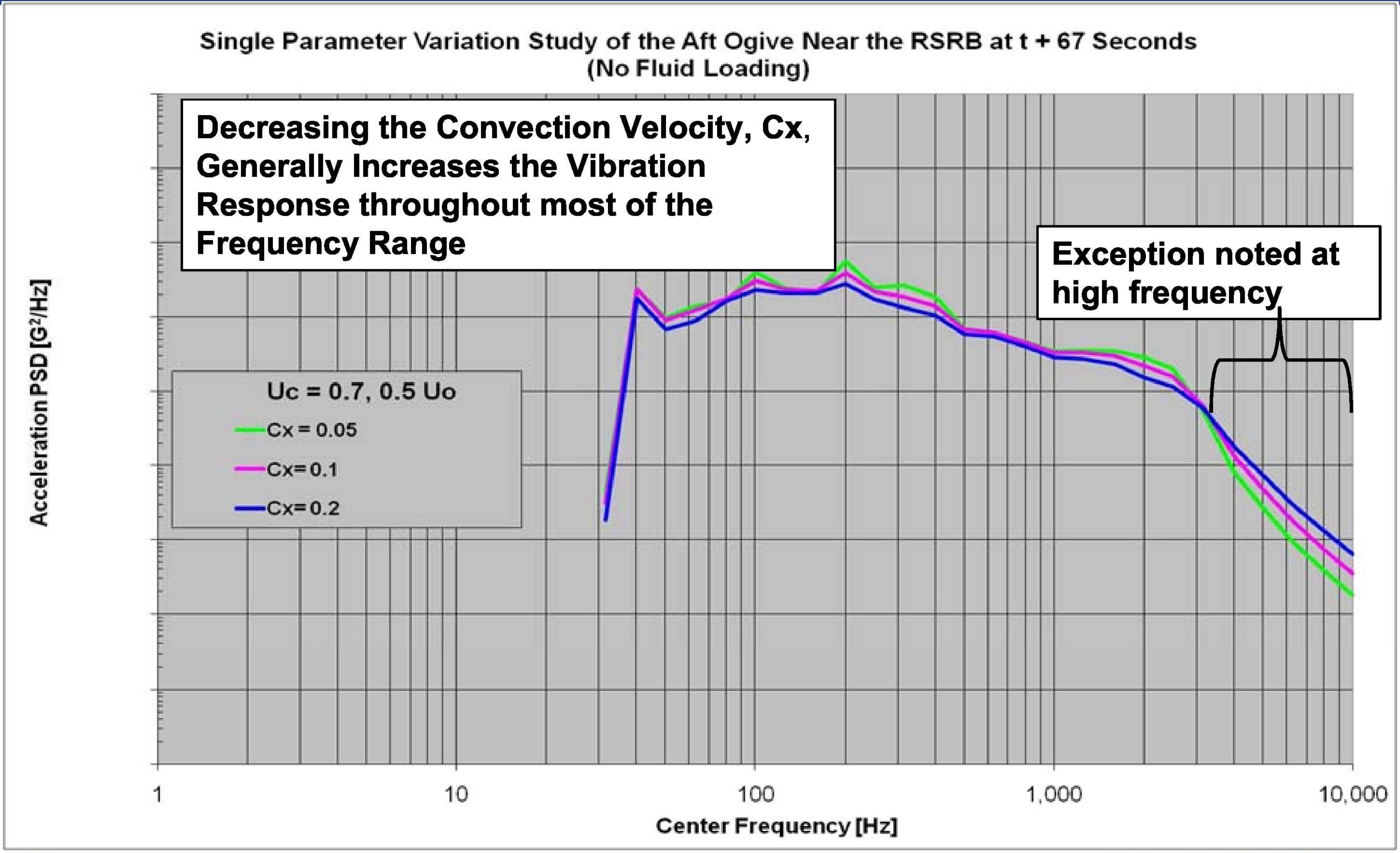
Response Results vary with Convection Velocity



Response Results vary with Decay Coefficient in Flow Direction



Summary and Conclusions

Part A Comparison of the SEA results from the TBL Study to Flight Data (5 locations, at +67 seconds):

- Good Correlation of the SEA TBL Response predictions to the Flight Data was achieved for 3 of the 5 locations:
  - Intertank Panel and Main Ring Frame SEA Response bracketed the measured response at two flight measurement locations (**T08D9243A-**inboard & **T08D9246A-**outboard).
  - The STS-5 (**T08D9992A**) Flight measurement was peculiar. Therefore, the LOX Barrel and LOX Aft Ogive SEA Response were correlated using STS-2 data, which was more in family with the other flights.
- Poor Correlation of the the SEA TBL Responses to Flight data for 2 of the 5 locations:
  - Fwd Ogive Input to Cable Tray/Press-line, (**T08D9269A**): The Subsystem below the Fluid Fill level provided a reasonable shape, but was 10 dB above the measured vibration at high frequency (200-1000 Hz). The Flight Measurement Sensor was located quite near the fluid fill line at time Launch + 67 seconds.
  - Intertank Panels, (**T08D9249A**, local panel vibration near GO2 Press-line): The measured pressure spectrum,T08Y9954A, may reflect a localized phenomena.
    - The Flight Data presents a peak at ~700 Hz, but no similar peak was reflected in the SEA response. Comparison of SEA flexural wave numbers pointed to the coincident frequency. Exploring other possibilities to explain the a peak at ~700 Hz is a Future work endeavor.
    - A trial exciting the Intertank panels with a considerably lower, T08Y9953A, Flight Pressure Spectrum provided better correlation. This did not explain the peaking near 700 Hz, however.

Summary, Conclusions and Future Work

Part B Producing Conservative Response from the SEA TBL Excitations:

- For the cases studied, larger convection velocities tended to maximize response.
- For the cases studied, smaller decay coefficients tended to maximize response.
- The initial parameter study enabled us to learn to use the SEA approach to produce adequately conservative results. The experience will assist us in producing future response estimates.
  - Comparison to flight measurements in Section A was done using a "wide open" approach for the TBL loading (i.e. $U_c = .9\ U_0$, $C_x = 0.05$).
  - The comparisons tended to meet or exceed the measured response.

Future Work:

- Complete a Matrix that assists analysts in determining which variables make the most difference to the response solutions using TBL Algorithms.
- Complete Correlation of the measured liftoff results from the same flight test data.

Future Work Matrix

Physical Property	Heavy Hitter	Less Difference	Notes
Pressure in Tanks		x	
Fluid Loading	X		
Fluid Properties of Cavity	X		
Spatial Correlation Decay Coefficient, C_x	X		
Convection Velocity, U_c	X		
Distance from Leading Edge, X_0	?	?	Trials that fall in both categories
Legacy or Efimstov TBL Algorithm Used	?		Still digesting the results

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References

1. STS-1 thru 5, 7 Flight Data – Unpublished Tables, Figures, Hard Copy Spectral Plots and Test Photos in MSFC Records.
2. NASA-RP-1074, “Preliminary Vibration, Acoustic, and Shock Criteria for Components on Light Weight External Tank (LWT),” Marshall Space Flight Center, February, 1981.
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4. “Vibroacoustic Independent Assessment - Random Vibration Modeling and Predictions,” Niedermaier, O’Keefe, and Go, Presented to the Ares Vehicle Loads Panel, March, 2009.
5. System Definition Handbook for Super Lightweight Tank Volume II, December 1997.
6. MSFC-DOC-782, “STS-5 Measurement Locations - Solid Rocket Boosters and Main Propulsion System,” Marshall Space Flight Center, October 8, 1982.
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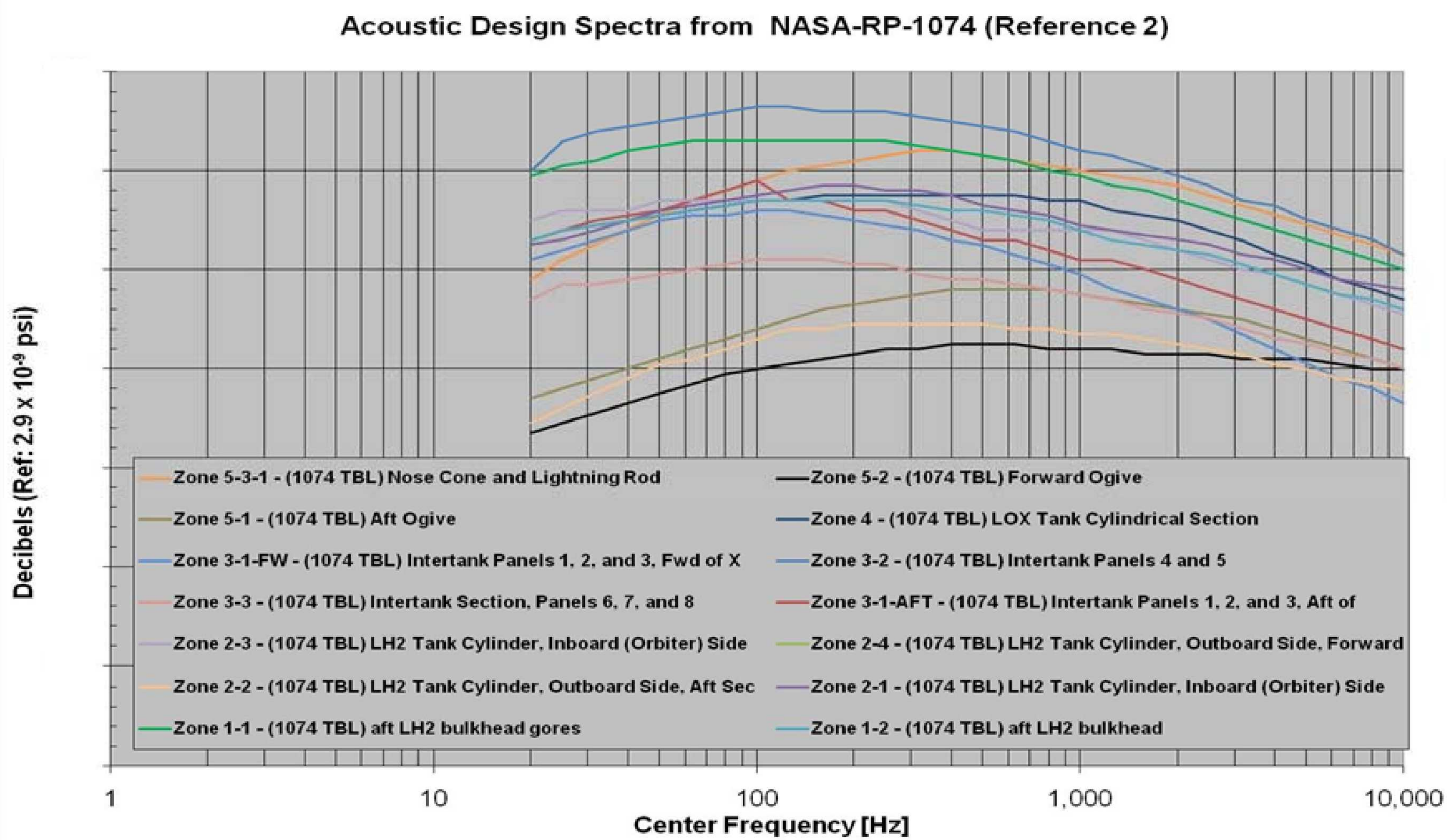
11. “Vibration Response of Space Craft Shrouds to In Flight Fluctuating Pressures,” Cockburn, JA & Robertson, JE, Journal of Sound and Vibration, April, 1974.
12. NASA CR-626, “A Review Of Flight And Wind Tunnel Measurements Of Boundary Layer Pressure Fluctuations And Induced Structural Response,” Bies, Bolt, Beranek and Newman, Inc., May,1966.
13. Advanced External Tank model aet-v1.0-base-12-28-07.dat., Dynamic Concepts Inc.

Back Up - Excitation Zones and Mix of Standard Criteria vs Measured Pressure Spectra



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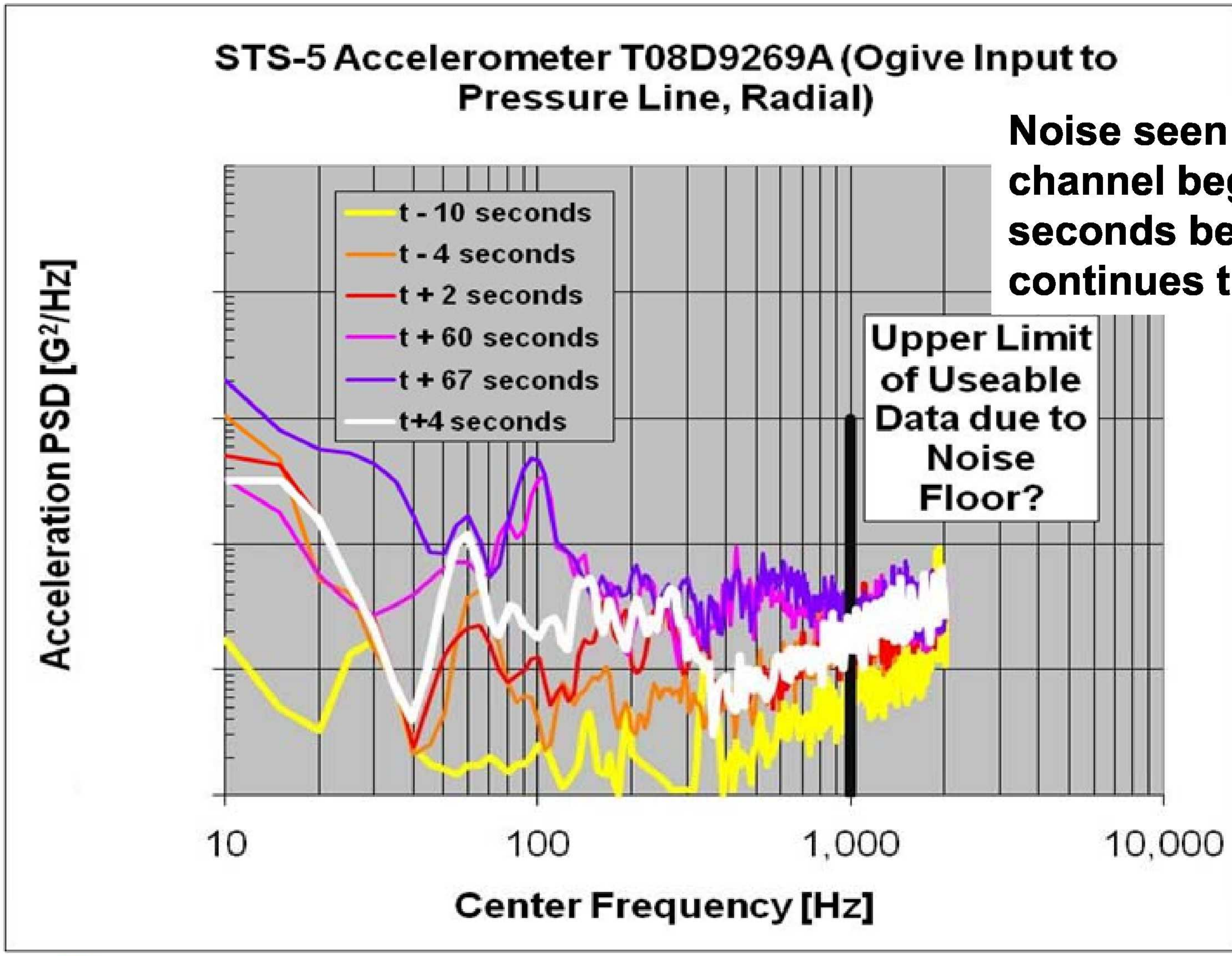
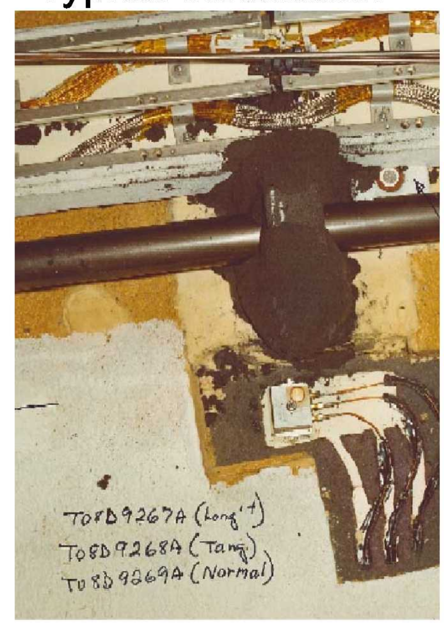
Backup- Flight Measurements vs Noise Floor T08D9269A LOX Tank Fwd Ogive Location



Noise seen on the measurement channel beginning at 10 seconds before launch continues throughout the flight.

Test Photo
Typical installation



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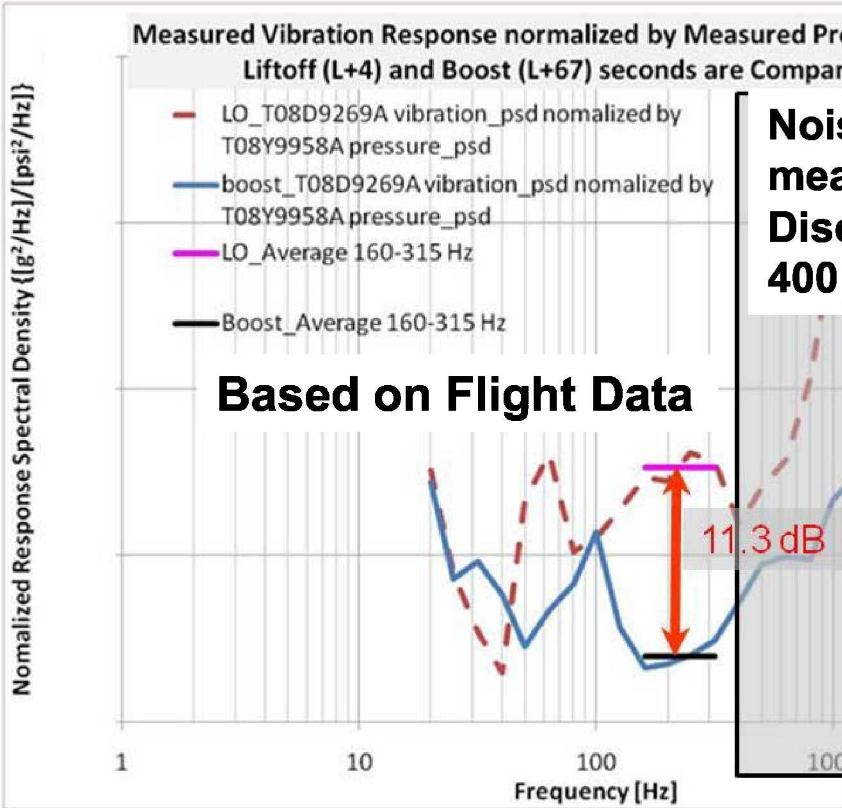
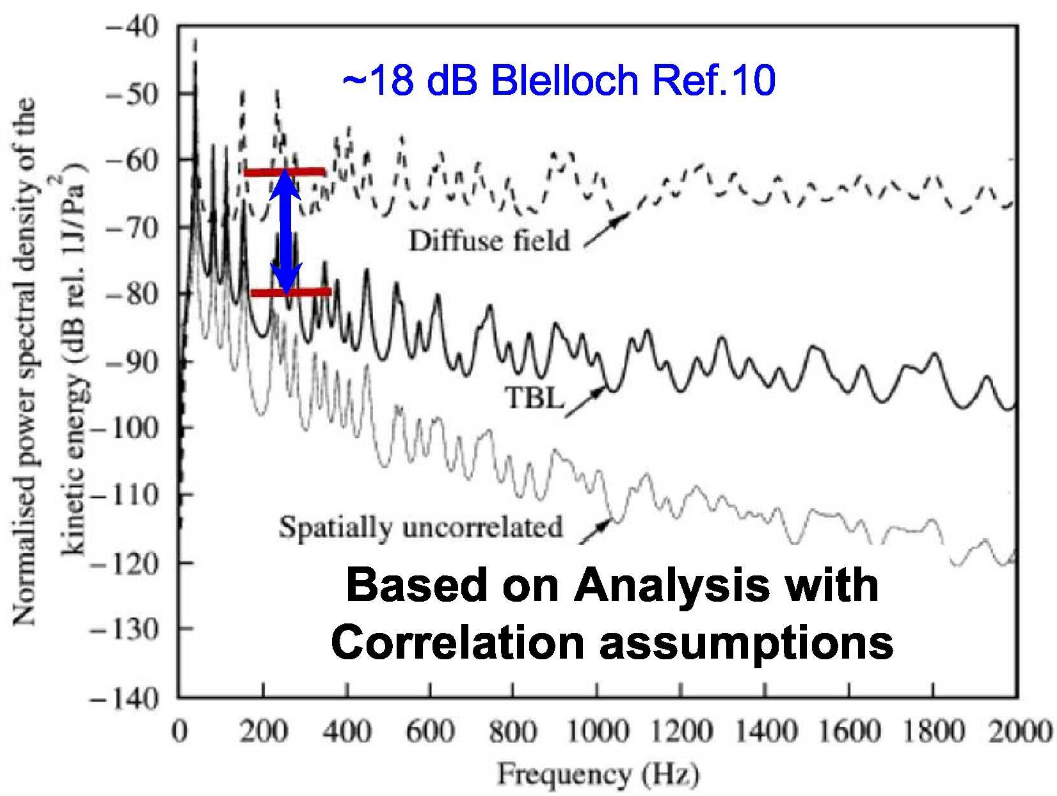
Backup – Normalized Vibration Response
Difference in TBL vs Liftoff Acoustic Response (Flight Data)



Noise Floor seen on the measurement channel Discounting Data above 400 Hz for L+4 Curve



The Difference between Launch and TBL response may be smaller than Reflected by Typical Correlation Assumptions. Compare 11.3 to 18 dB for frequency Bands from 160-315 Hz, (flight data vs analysis respectively).