Spectral Mass-Gauging of Propellant Tanks

M. Khasin and J. Feller, NASA Ames Research Center, Moffett Field, CA;

M. Corbetta and J. Rogers, KBR Wyle Services, LLC, Moffett Field, CA;

B. Helvensteijn and A. Kashani, MEI, Moffett Field, CA
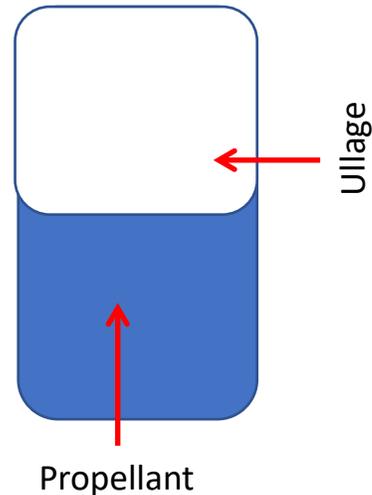
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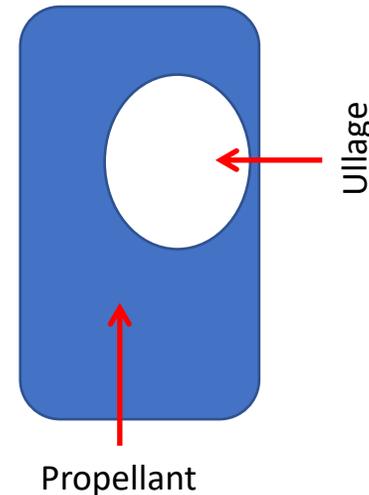# A problem: mass-gauging propellants in micro-g

- Deep space exploration requires instrument to assess (gauge) the remaining mass of the propellant in the tank

1-g (earth gravity)

Ullage

Propellant

"No gravity" (deep space)

Ullage

Propellant

Weyl's Law

Spectral Mass Gauging (SMG) is based on *Weyl's Law* (Weyl 1911, Arendt et al. 2009):

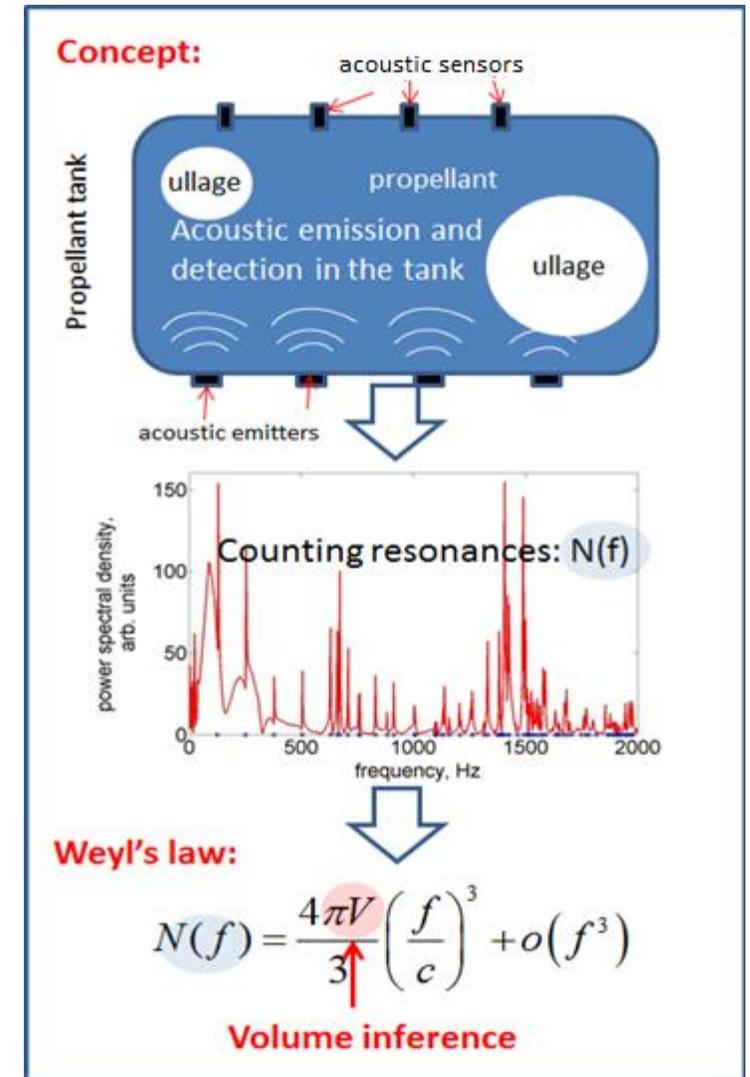$$N(f) = \frac{4\pi V f^3}{3c_L^3} + \frac{\pi A f^2}{4c_L^2} + o(f^2), \qquad f \to \infty$$

- *V* is the volume of the space occupied by the liquid
- *A* is the (minus) total surface area of the liquid domain for (compliant) rigid wall boundary conditions.
- c_L the sound velocity in the liquid

- **Purpose:** Provides propellant-configuration *model-free* mass-gauging.

- **Features:**
  - Uses acoustic resonances counting function in propellant tank;
  - Is based on rigorous results from spectral theory, the Weyl's Law
    - ✓ Does not require modeling the propellant configuration
    - ✓ Non-intrusive

- **Concept of Operations**
  - Tap on the tank wall (*mechanical actuator)*
  - Excite *acoustic resonances* in the liquid;
  - Resonances are *detected* (via accelerometers)
  - Information *processed* by electronics and mode counting software,
  - *The liquid volume is inferred* based on Weyl's law.

- **Technologies to Enable the Concept**
  - Sensors, actuators, electronics and data-processing and inference software

J. R. Feller, A. Kashani, M. Khasin, C. B. Muratov, V. V. Osipov, and S. Sharma. Spectral mass gauging of unsettled liquid with acoustic waves. Technical report, NASA TM–2018 219876, 2018.

Concept: acoustic sensors

Propellant tank

ullage   propellant

Acoustic emission and detection in the tank   ullage

acoustic emitters

Counting resonances: N(f)

power spectral density, arb. units

frequency, Hz

Weyl's law:

$$N(f) = \frac{4\pi V}{3}\left(\frac{f}{c}\right)^3 + o\left(f^3\right)$$
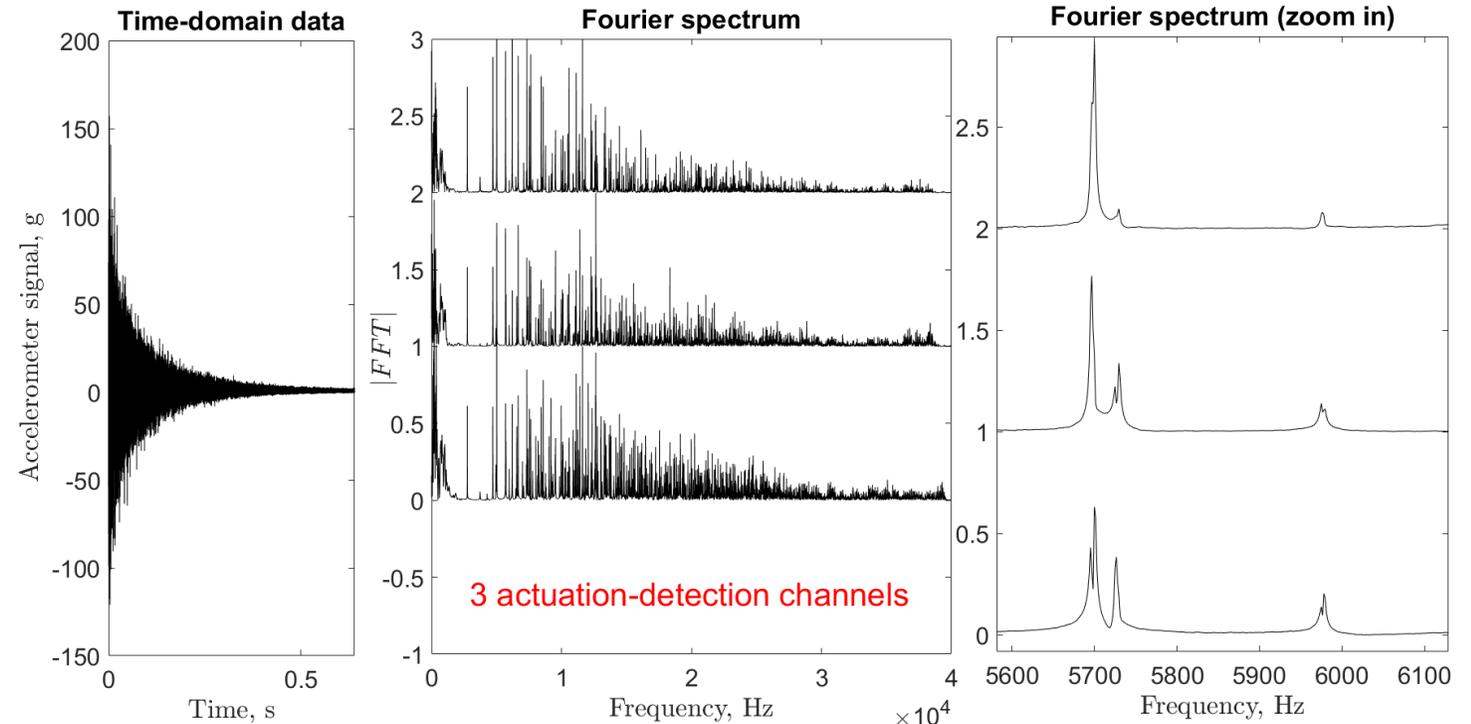
Volume inference

- Error in volume inference predicted for the thin-walled Titanium tank used in our tests.

- Application of Weyl's Law to the tank spectrum leads to an error of ~5% in the shown frequency range.

- Implementing the wall corrections derived in Ref. [1] reduces the error to ~0.5% in this range.

Error in a full-tank volume inference by averaged Richardson extrapolation
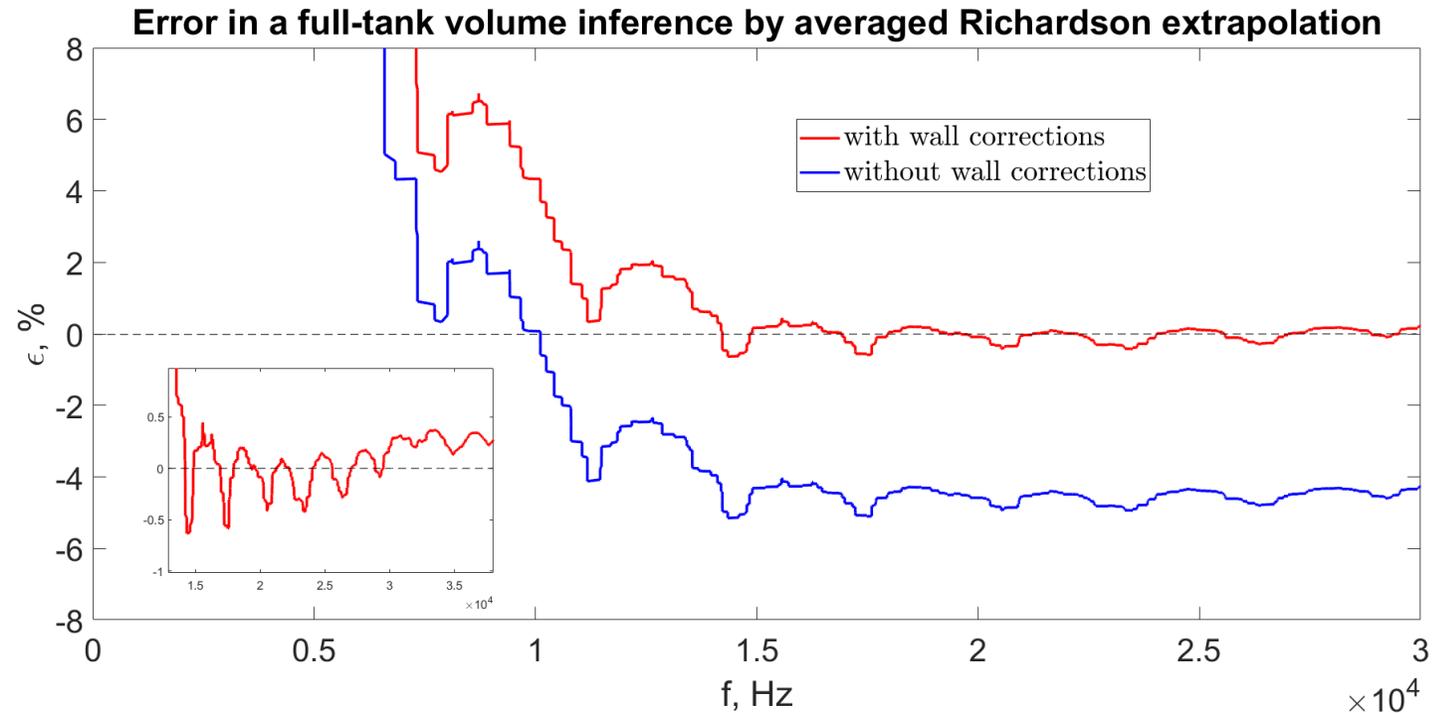
[1] C. Muratov, J. Rogers and M. Khasin, Acoustic modes of a spherical thin-shell tank for liquid propellant mass gauging: theory and experiment. Submitted to J. Acoust. Soc. Am. (2022)

Our approach:

Local spectrum identification using supervised machine learning (physics-informed convolutional neural network) trained *on synthetic spectra*.

Error in volume inference

The error in volume inference depends on three dimensionless groups:

$$\overline{|\epsilon|} \sim \left(\left(\frac{R}{H} \right)^{3-\alpha} \frac{\Gamma_0 R}{c \, \rho_m} \right)^{3\beta/2}, 0 \leq \alpha \leq 3, \ \beta \approx 2.5$$

R-characteristic lengthscale of the tank
H-fill level (shortest lengthscale of the liquid configuration)
Γ_0-acoustic damping rate in the full tank
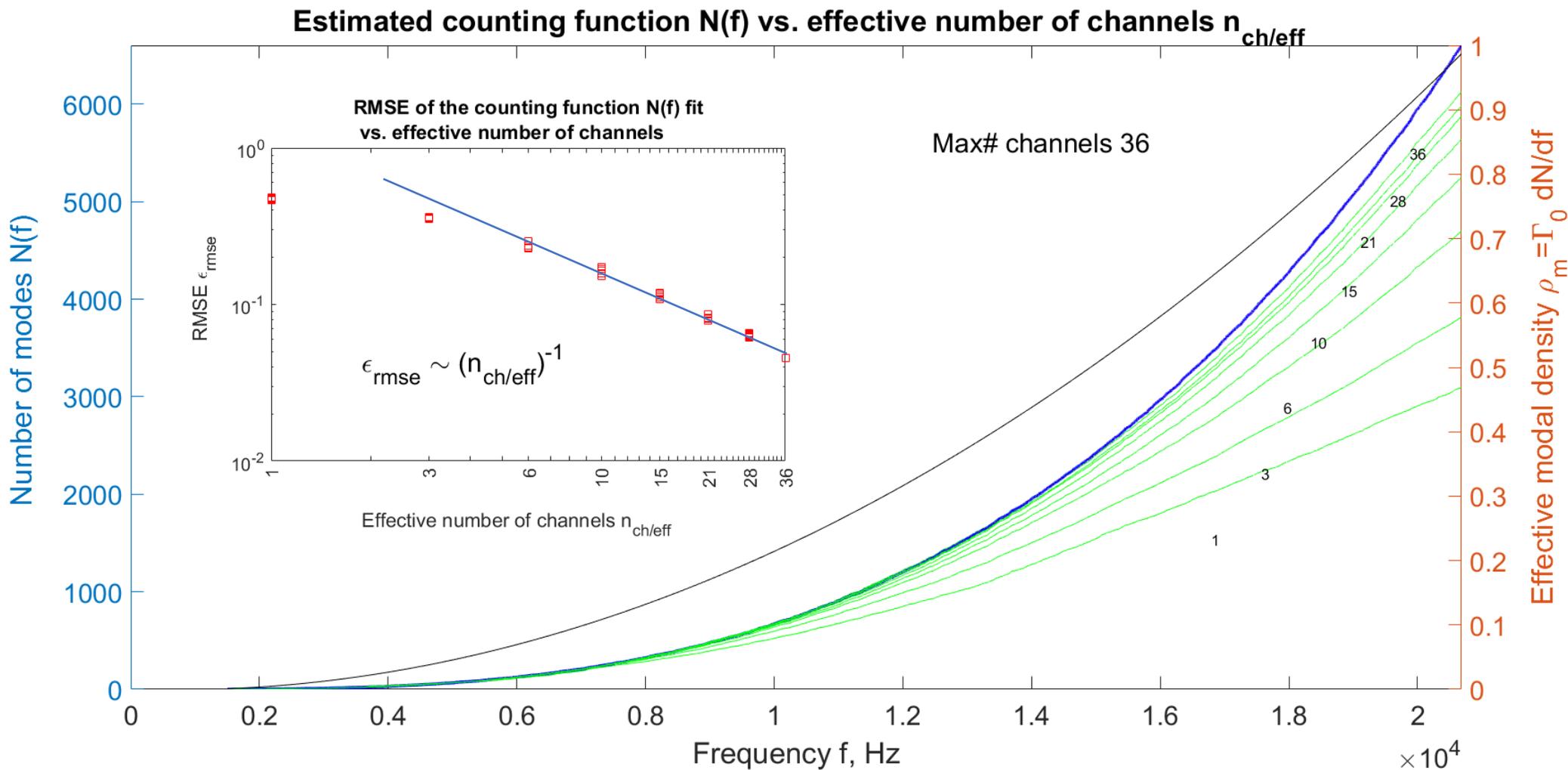c-speed of sound in the liquid

1. The propellant tank vibrations quality factor $Q = c/(\Gamma_0 R)$

2. The liquid configuration aspect ratio R/H

3. The maximal effective modal density ρ_m resolvable by the mode-counting software. It depends on:
    - Number of data channels
    - Signal to noise ratio (S/N)
    - Interference from the shell-modes

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Constraints on the synthetic data

Our synthetic training spectra are vibration spectra of rectangular resonators with random aspect ratios and compliant walls (Dirichlet BC), subject to the constraints above.

Estimated counting function N(f) vs. effective number of channels $n_{ch/eff}$

RMSE of the counting function N(f) fit vs. effective number of channels

$\epsilon_{rmse} \sim (n_{ch/eff})^{-1}$

RMSE ϵ_{rmse}

Effective number of channels $n_{ch/eff}$

Max# channels 36

Number of modes N(f)

Effective modal density $\rho_m = \Gamma_0 \, dN/df$

Frequency f, Hz

$\times 10^4$

Mode function $N(f)$ and effective modal density $\rho_m(f)$ for a box resonator, $V = 0.957m^3$
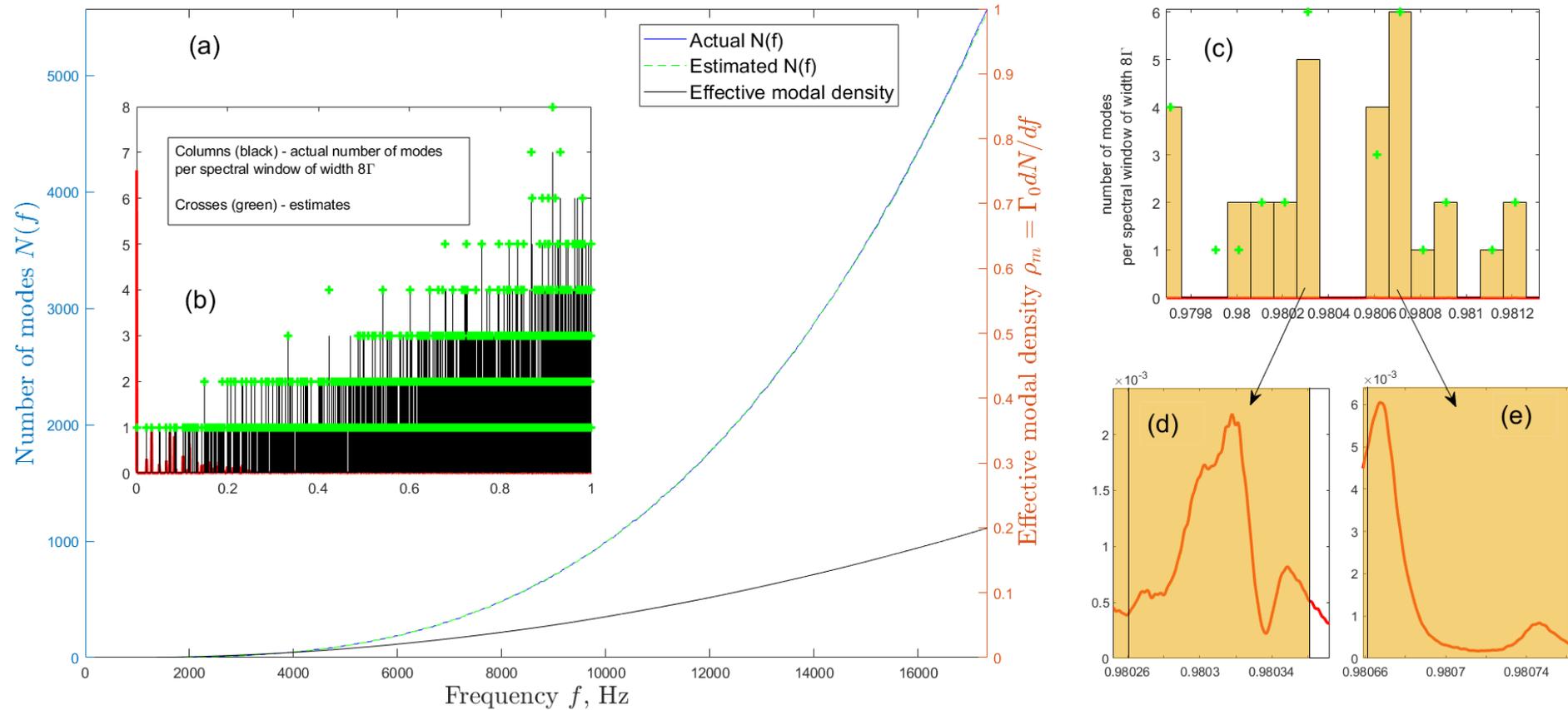
- MLSI-estimated mode-counting function N(f) vs. the actual one from synthetic data;
- The fit is excellent up to $\boldsymbol{\rho_m = 0.2}$ corresponding to $\boldsymbol{N \approx 5500}$ modes.

Box: X=0.99136, Y=0.77028, Z=1.2532; V=0.95697; max aspect ratio:1.6269
Weyl's formula;4 Richardson iterations: t1=0.25, t2=0.25, t3=0.25, t4=0.25

Box: X=0.99136, Y=0.77028, Z=1.2532; V=0.95697; max aspect ratio:1.6269
Frank's formula;4 Richardson iterations: s1=0.5, s2=0.5, s3=0.5, s4=0.5
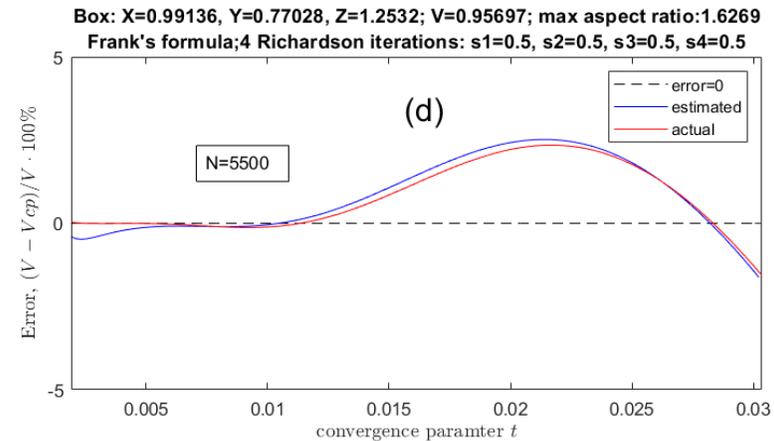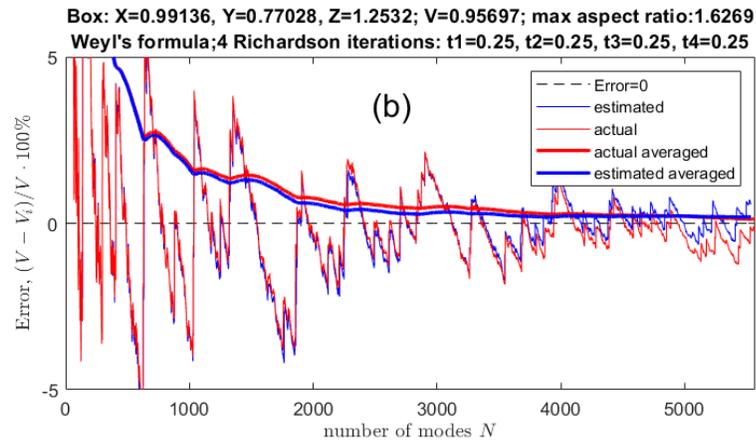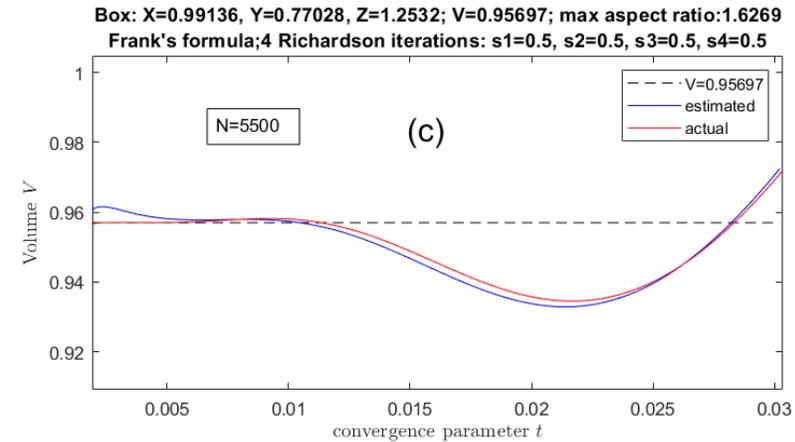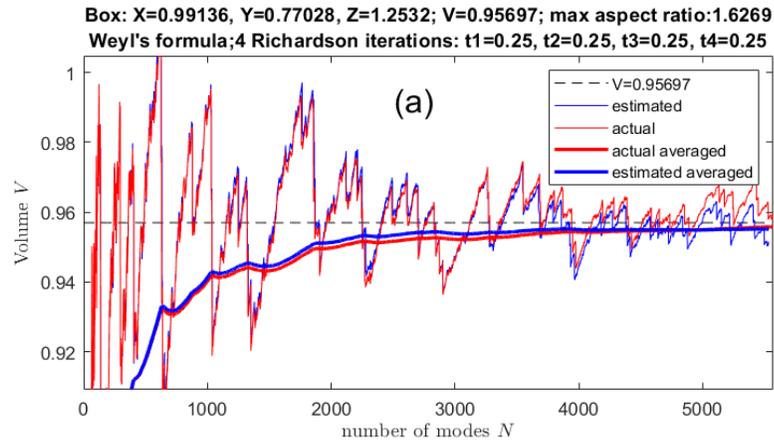
- Volume inference from the MLSI-estimated mode-counting function;
- The inference error is <1% for both Weyl's Law (b) and Frank's Law (d) inferences.

Objective 1:

Collect acoustic spectra for each actuator/accelerometer pair—with the tank at various fill levels and internal pressures.

Qualitative assessment of spectra.

Post-test: Infer liquid volume from analysis of spectra; compare with measured liquid level (from capacitance gauge).

Objective 2:

Characterize performance of actuators and accelerometers at cryogenic temperatures.

- ## Test Tank
  - Surplus flight propellant tank. Produced for Mariner program.
  - Same as CRYOTE tank.
  - 6Al4VTi.
  - Spherical, 30 in. dia.; 0.05 in. wall thickness.
  - Capacity: 220 liters.

- ## Instrumentation
  - Array of acoustic actuators and accelerometers, distributed on outside surface of tank. Concentrated on lower half of sphere.
    - 8 actuators (Ledex solenoids).
    - 12 cryogenic accelerometers (PCB/Kistler).
  - Capacitance gauge (liquid level gauge): Cryomagnetics Model LM-510.
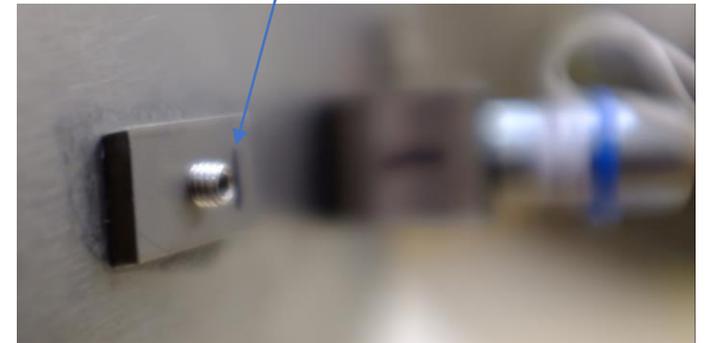 - Thermocouples: Tank wall, support structure, solenoid.
  - Tank pressure gauge.

accelerometer

solenoid actuator

- Actuator brackets and accelerometer studs epoxied to tank wall.

- Adhesive: Scotchweld 2216.

- Test bonds made to 6Al4VTi sheet; dunk-tested in LN2.
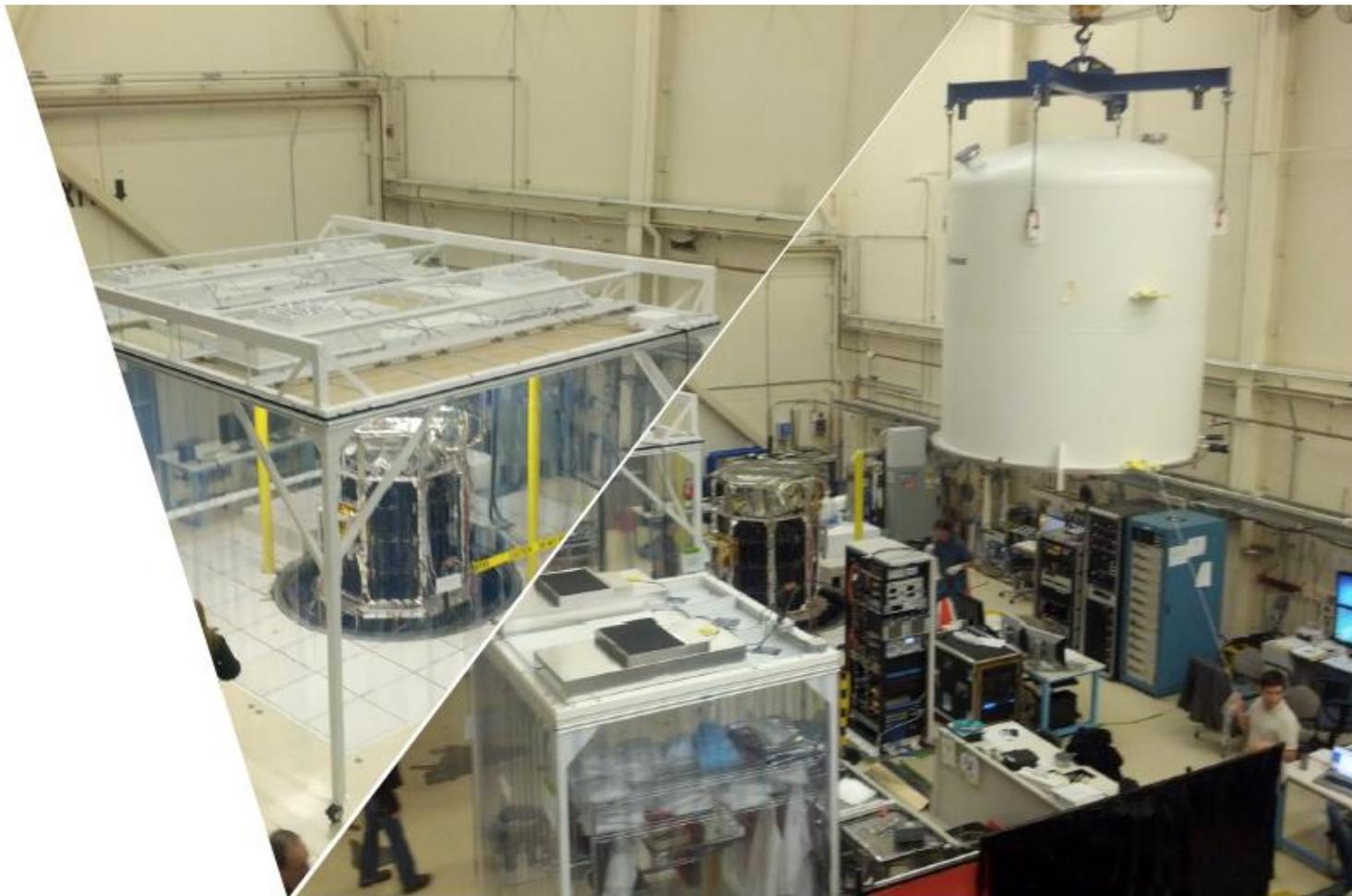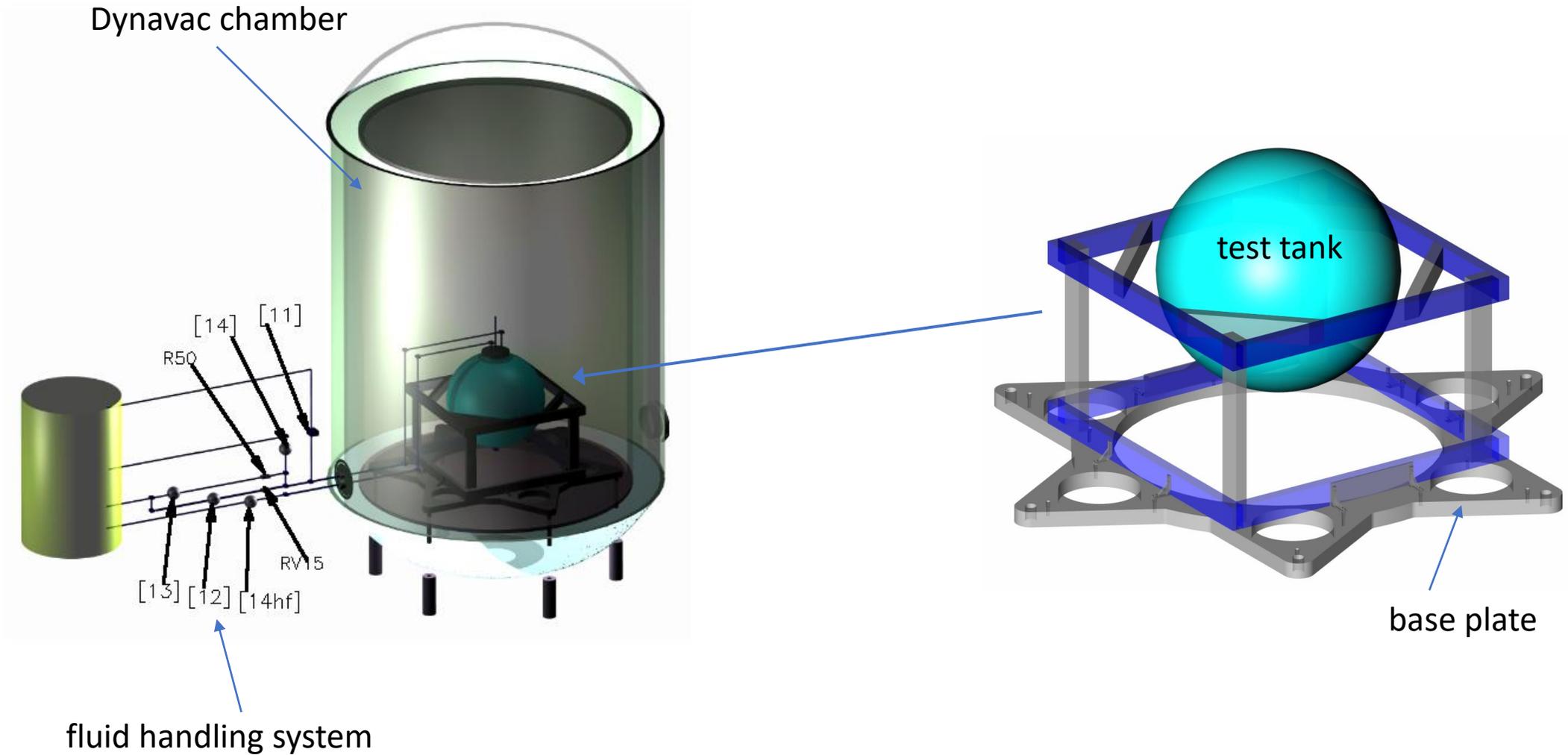
accelerometer

accelerometer stud

Dynavac
T-Vac Chamber

- Ames Engineering Evaluation Lab (EEL).

- Dynavac thermal vacuum chamber.
  - Internal volume: 6 ft. dia. X 10 ft. tall
  - LN2 thermal shroud

Chamber opens by removing top hat via crane. Equipment Under Test (EUT) must me lowered into bottom half of chamber. Bottom half of chamber recesses ~3ft into false floor (~2ft step down to Base Plate). EUT may be manually lowered or with use of crane. Using crane may require engineered lift points and a lift determination of critical vs non-critical lift...
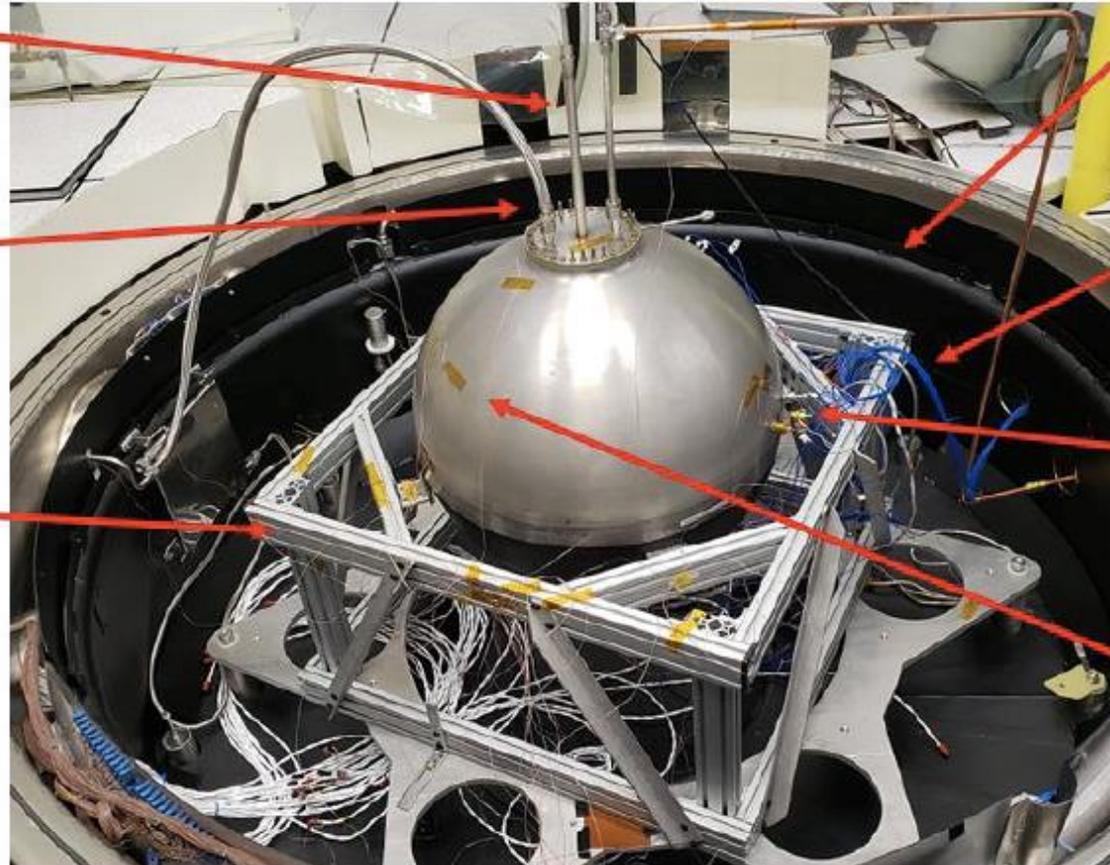
SMG LN2 Test: Test Tank Installation

Dynavac chamber

fluid handling system

test tank

base plate

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Liquid Nitrogen Level Sensor

Liquid Nitrogen Fill & Vent

Aluminum '80/20' Support Frame, Anchored to Base
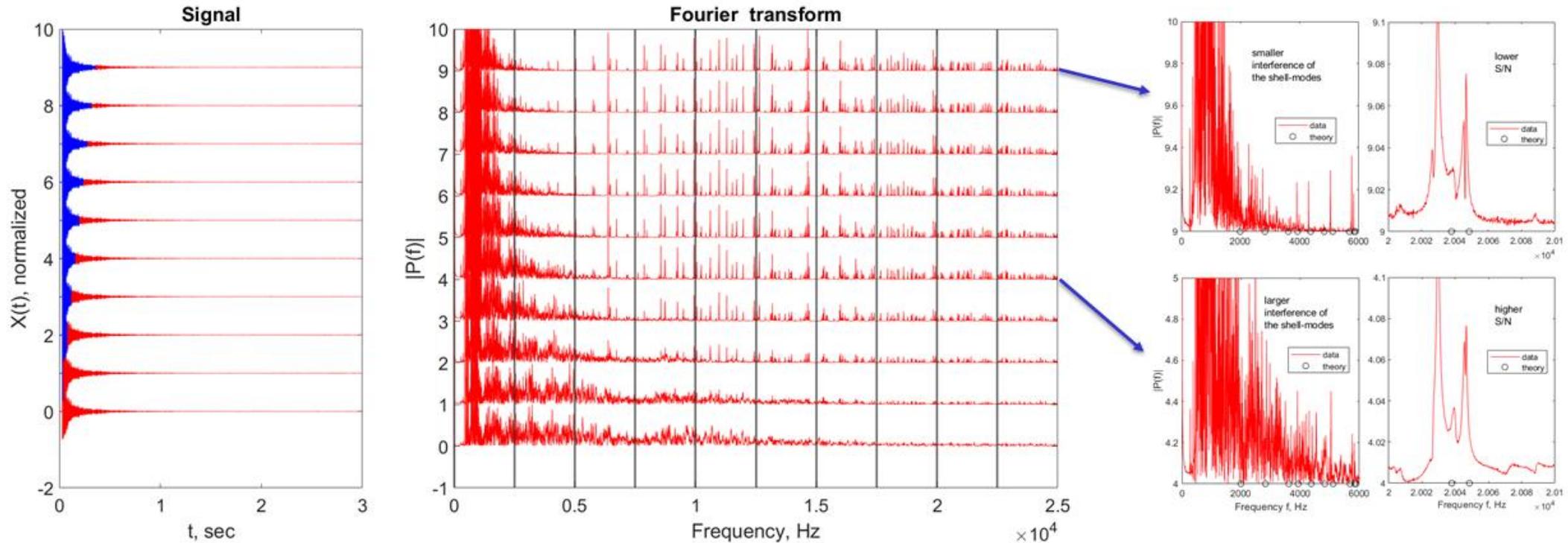
Liquid Nitrogen 'Shroud'

Accelerometer Cables

Accelerometers and Actuators (for scale)
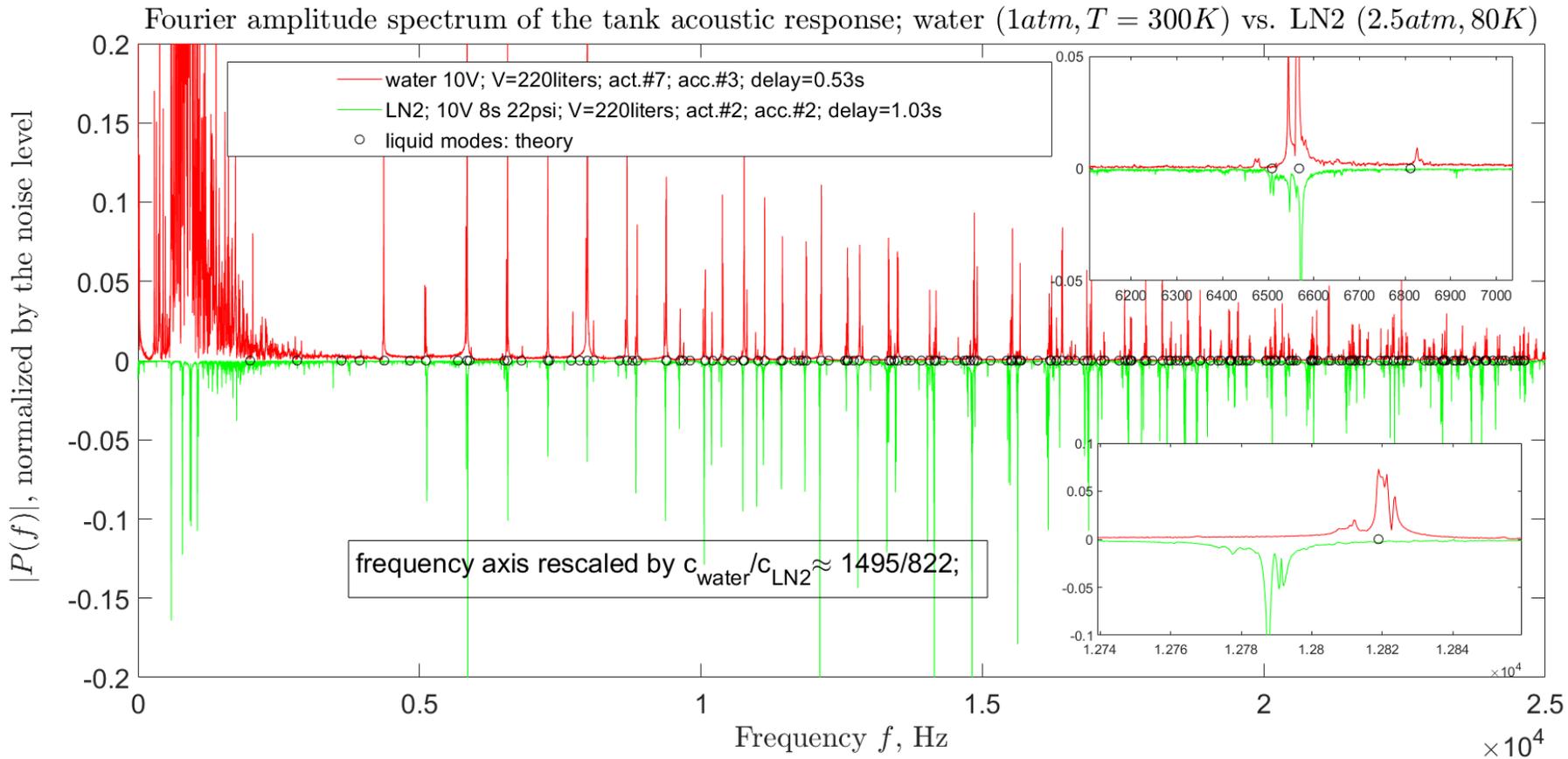
Thermocouples (Kapton Tape attachment)

Time delay approach to shell-modes elimination [1]:

- Shell-modes "die out" exponentially faster than the liquid modes;
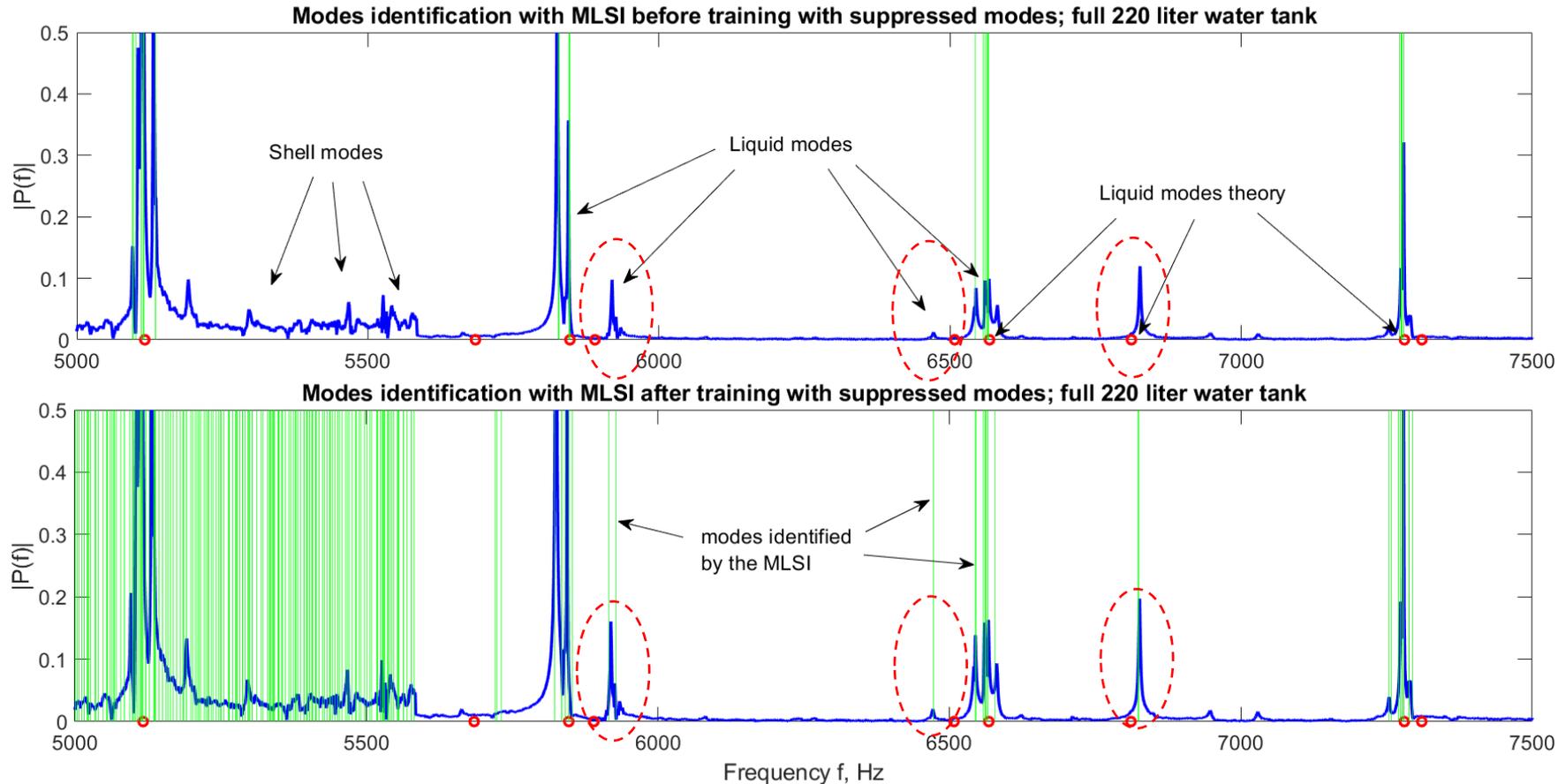- Elimination of the shell-modes comes at the expense of decreasing signal to noise.

[1] L. Delzeit, J. Feller, B. Helvensteijn, A. Kashani, M. Khasin and V. Osipov, Spectral Mass Gauging of Liquids with Acoustic Waves, 50th International Conference on Environmental Systems ICES-2021-293 12-15 July 2021

Fourier amplitude spectrum of the tank acoustic response; water $(1atm, T = 300K)$ vs. LN2 $(2.5atm, 80K)$

- Fourier spectrum for LN2 tank is qualitatively very similar to the water tank tests.
- Liquid modes correspond very well to the theoretical predictions.
- Shell-modes appear to be relatively suppressed in the LN2 tank.

Modes identification with MLSI before training with suppressed modes; full 220 liter water tank

Modes identification with MLSI after training with suppressed modes; full 220 liter water tank

- **"Quiet" modes** (suppressed in ALL data channels; encircled) were observed;
- Baseline MLSI model predictions miss the "quiet" modes;
- A modified model (trained on synthetic data with "quiet" modes) counts the "quiet" modes but is sensitive to the shell-modes.

Case study: ROM-based spectrum identification for a rectangular tank and 10 x 10 MIMO
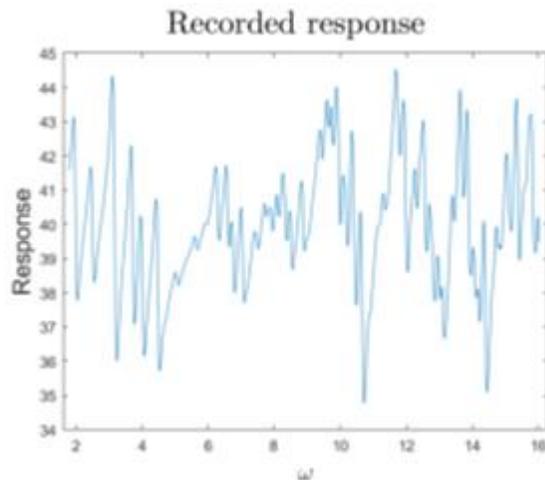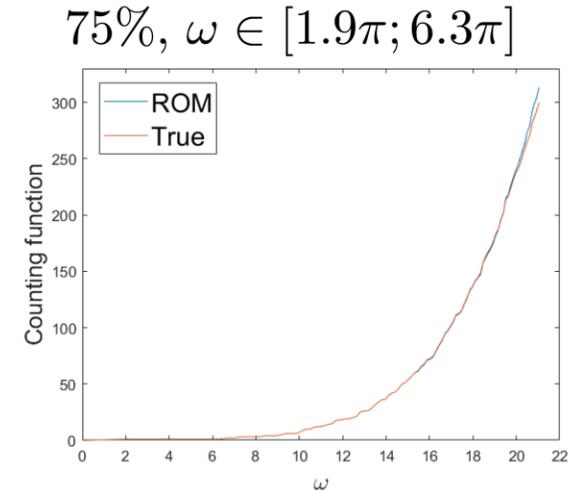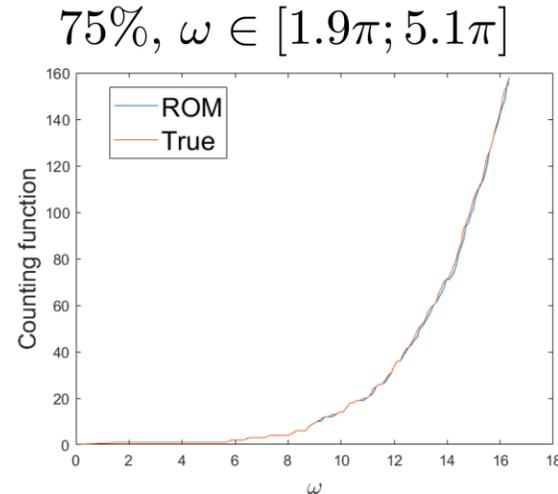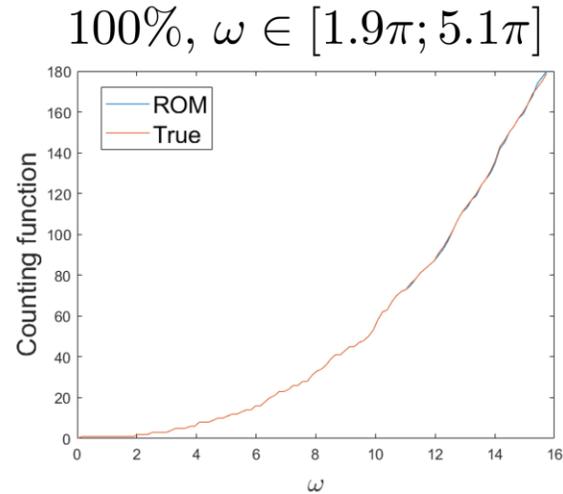
- ~180 modes are present in the range of application;
- High effective modal density of $\rho_m = 2$, i.e., to two modes per half-width on average;
- This is by **an order of magnitude larger** than the density achieved by the neural network-based ML;
- ROM-based approach allows resolution which scales as $\rho_m \sim M$ with the number of channels;

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Summary

- ❑ S/W and theory
  - ✓ Acoustic data pre-processing and characterization:
    - • S/N estimation and optimization
    - • shell-modes elimination,
    - • estimation of frequency-dependent losses
  - ✓ MLSI developed and has reasonable accuracy for synthetic data: ~1% for model configurations
  - ✓ Volume-inference algorithm: theory, scaling and code (scaling of the error, tank wall correction to the liquid mass inference, renormalized Weyl's Law for finite low frequency cut-off)
  - ✓ Assessment metrics for S/W and data

- ❑ H/W, data and procedure
  - ✓ High-quality acoustic data from cryogenic LN2 tank has been obtained:
    - • various fill levels
    - • multiple data channels
    - • range of pressures
  - ✓ Control parameters to improve the resolution have been identified:
    - • actuation voltage
    - • number of data channels
  - ✓ Artifacts in the data identified which interfere with the data processing:
    - • "quiet" modes
    - • pressurization effects (ullage ringing)

Identified gaps

❑ S/W and theory
- ✓ Deterioration of accuracy is predicted for low fill levels and liquid configurations of high aspect ratio;
- ✓ Simulation of acoustic spectra for low-level and complex propellant configurations is needed to confirm;
- ✓ SMG of such configurations will require either
  - • orders of magnitude increase in the number of data channels (e.g., with MEMS based sensors), or
  - • orders of magnitude increase in the mode resolution (e.g., with ROM-based ML)
- ✓ Further improvement of the current MLSI model can be achieved with:
  - • training with both shell-modes and "quiet" modes
  - • optimization of renormalization techniques to remove the sensitivity to low-frequency counting error
- ✓ Understanding high pressure effects (ullage modes ringing)
- ✓ Understanding the origins of the acoustic damping and its scaling with parameters of the tank

❑ H/W, data and procedure
- ✓ Increase S/N (voltage up)
- ✓ Excitation of "quiet" modes
- ✓ Development/testing MEMS-based actuators and sensors