National Aeronautics and Space Administration

SPACE LAUNCH SYSTEM

Sensor Analysis, Modeling, and Test for Robust Propulsion System Autonomy

CRM SOLUTIONS
innovation in aerospace

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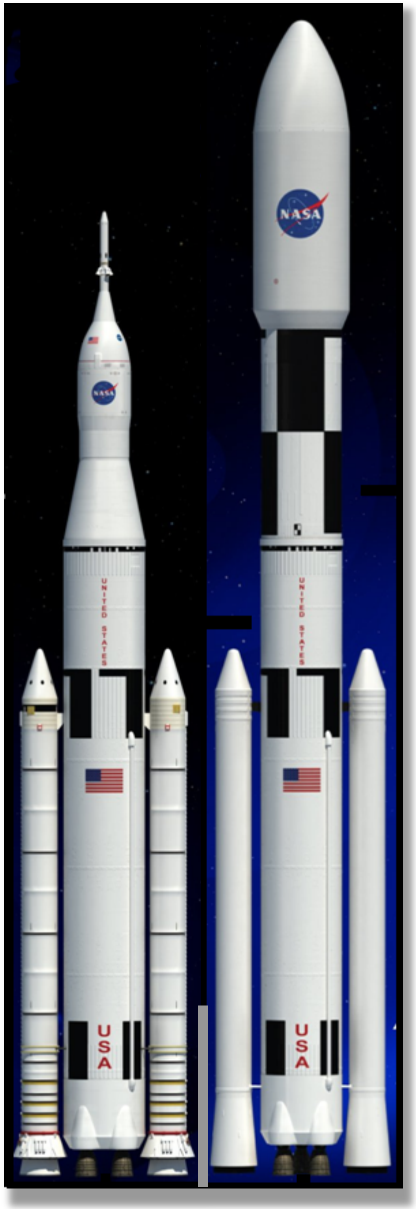
SLS

Introduction

- **Space Launch System (SLS)**
  - NASA-developed, human-rated launch vehicle for large-scale (exploration-class) crew and cargo access
  - Shuttle-derived hardware and processes
  - 26 t (Block I) and 37t cargo (Block II) to TLI
  - First full-scale hot fire test Summer 2019
  - First uncrewed test flight (EM-1) scheduled December 2019

- **SLS Main Propulsion System (MPS)**
  - 4x RS-25E (Space Shuttle Main Engine – Expendable), turbopump-fed, ~490,000 lbf thrust each
  - Liquid oxygen + liquid hydrogen (730,000 gallons of propellants)
  - Helium pressurization of LO2 and LH2 tanks

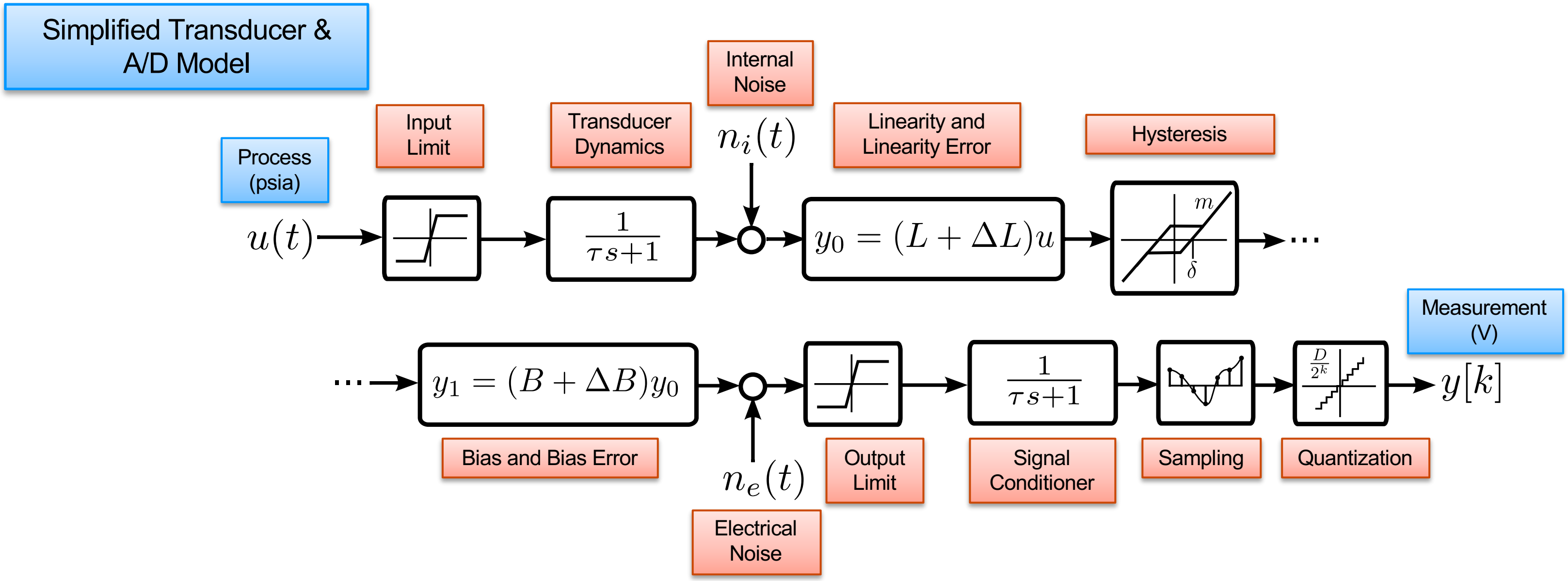
- **Mission & Fault Management (M&FM) and MPS Autonomy**
  - Sensor data qualification & consolidation (SDQC)
  - MPS sensor fault detection, leak detection, caution & warning
  - Ullage pressure (MPS inlet condition) regulation



Main Propulsion System Operational Instrumentation

- **SLS MPS uses over 100 Operational Flight Instrumentation (OFI) Sensor Measurements for Real-Time Fault Isolation and Mission Management**
  - Cryogenic Level Sensor System (CLSS)
  - Active Electronics Pressure Transducer (AEPT)
  - Passive Electronics Pressure Transducer (PEPT)
  - Differential Pressure Transducer (DPT)
  - Ambient Pressure Transducer (APT)
  - Immersion Temperature Probe Assemblies (ITPA/RTD)

- **Many of the critical devices are analog pressure sensors**



Simplified Transducer & A/D Model

Process (psia)

Input Limit

Transducer Dynamics

Internal Noise

Linearity and Linearity Error

Hysteresis

$u(t)$

$\frac{1}{\tau s+1}$

$n_i(t)$

$y_0 = (L + \Delta L)u$

m

δ

$\cdots$

Measurement (V)

$\cdots$

$y_1 = (B + \Delta B)y_0$

$n_e(t)$

$\frac{1}{\tau s+1}$

$\frac{D}{2^k}$

$y[k]$

Bias and Bias Error

Output Limit

Signal Conditioner

Sampling

Quantization

Electrical Noise

Analysis Approach (Model Fidelity/Availability)

- **Each device can be assigned a model fidelity and availability score based on modeling capability**

Sensor Model Fidelity	Description	Model Score s_{model}
High-Fidelity	Existing contractor-vetted DMM supported by test data delivered as software module with defined APIs	0.10
Medium-Fidelity	Contractor-vetted DMM is based only on analysis and not supported by test	0.25
Limited-Fidelity	NASA internally developed model based on data derived from ED and other sources	0.50
Low-Fidelity	No model implemented but sufficient data and/or experience exists to produce one internally or via action to contractor	0.75
No-Model	Insufficient data exists to characterize sensor performance and no model is available (s_{avail} = 1.00 by default for this case)	1.00

Sensor Model Availability	Description	Availability Score s_{avail}
Production Ready	Model implemented in all relevant design and verification simulations (VM M&FM, SIL/SITF, GSDO) with V&V process completed and documented and can support all SLS CONOPs	0.10
Limited	Model not implemented in all simulations or only for algorithm design; V&V not completed or documented; does not support all operational use cases	0.50
Not Implemented	Model is not implemented or tested for design or verification	1.00

Analysis Approach (Criticality and Risk)

- **Each device function can be assigned a criticality score using data from existing Space Launch System M&FM and FMECA products**

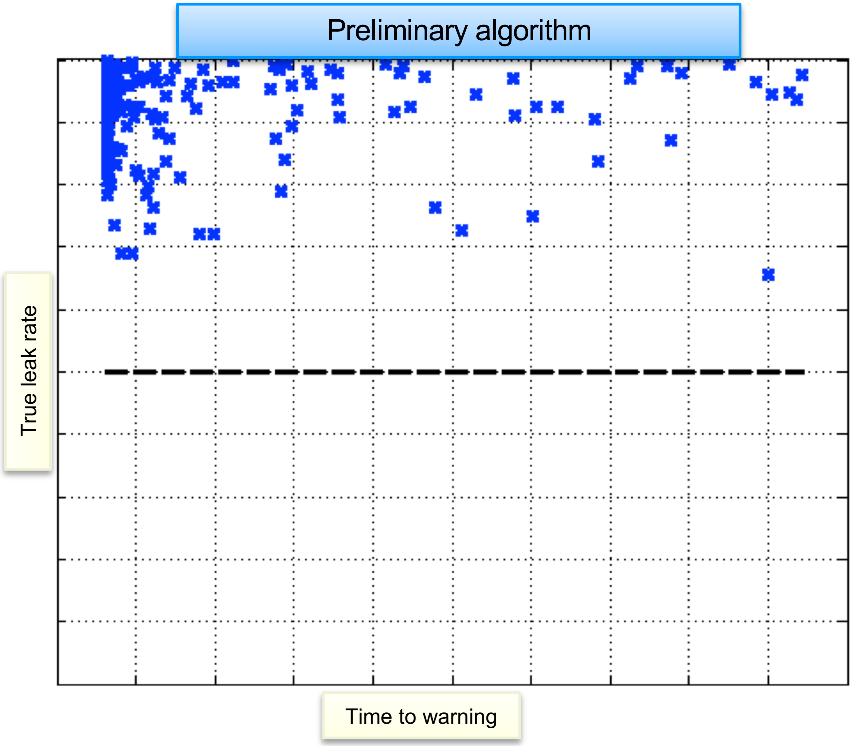
Sensor Criticality	Description	Criticality Score s_{crit}
Inconsequential	Sensor classified as OFI but not used for any software functions other than logging or telemetry	0.10
Operational Concern	Used in software functions but only for generating C&W and no automated actions	0.25
Mission Impact	Incorrect interpretation of sensor data may affect level of redundancy or operability of non-mission critical components, but will not compromise performance	0.50
Mission Critical	Incorrect interpretation of sensor data will result in actions that may result in loss of mission or abort, e.g., LCC scrub or early CSE engine shutdown	0.75
Safety Critical	Incorrect interpretation of data poses imminent threat to vehicle integrity and/or crew safety, e.g., loss of MPS pressurization control or uncontained engine failure	1.00

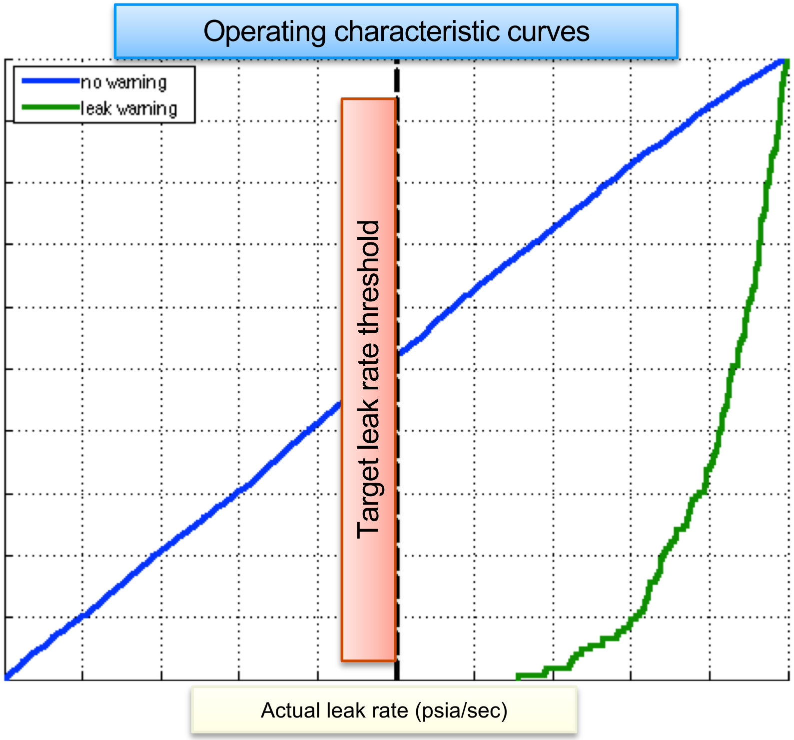
- **Sensors are reviewed and assigned scoring based on criticality to ground and flight functions**
- **Scoring used to perform risk quantification: $s_{risk} = s_{crit} \times s_{model} \times s_{avail}$**
  - Sensors sorted by risk factor reviewed to determine action plan

Motivation – Helium Leak Detection

- **Primary motivation for task team study was automatic detection of MPS helium leaks**

- **Detection of small helium leaks is difficult in presence of noise**
  - Simple algorithm (finite differencing with persistence) versus PVT-mass model of tank
  - Leak rate of a few psia/sec over a several second interval versus normal consumption rate
  - Statistical assessment performed by uniformly dispersing an *M*=2*N* size population around the target threshold, then applying binomial sampling methods





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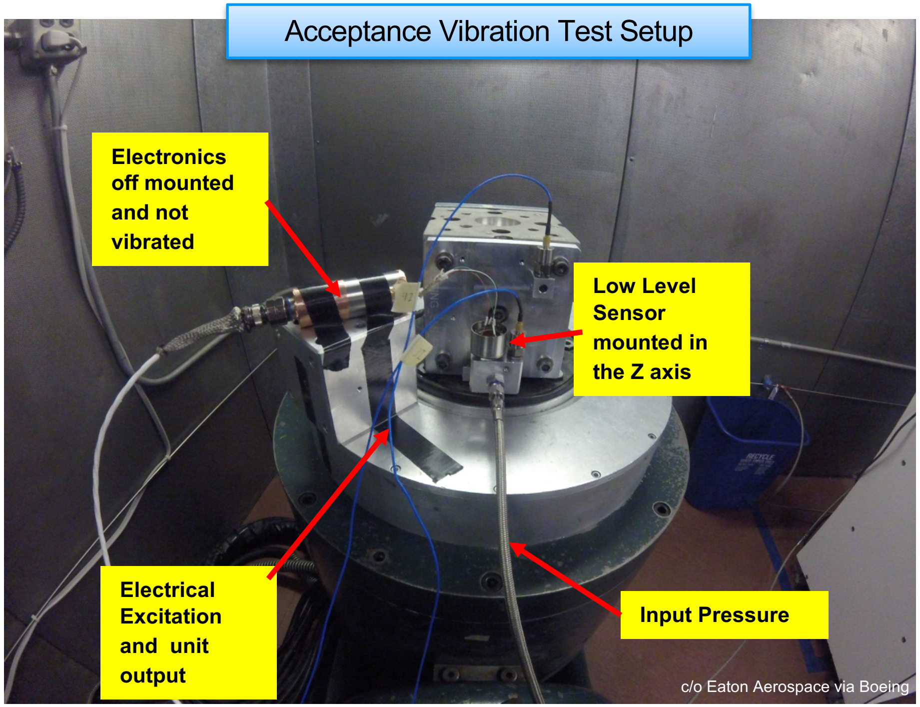
Pressure Transducers

- **Software design verification testing initially revealed risk areas**
  - Preliminary software design used ideal sensor outputs in early verification testing
  - Credible sources of noise include environments (e.g., aeroacoustics) and EMI
  - Initial vendor sensor hardware requirements far exceeded necessary performance

- **A team was organized to develop a test-validated sensor model from first principles**
  - Validated using acceptance vibration test data
  - Start with simple model approach – noise, scale factor, bias
  - Use validated model for Monte Carlo assessment of algorithm performance



Acceptance Vibration Test Setup

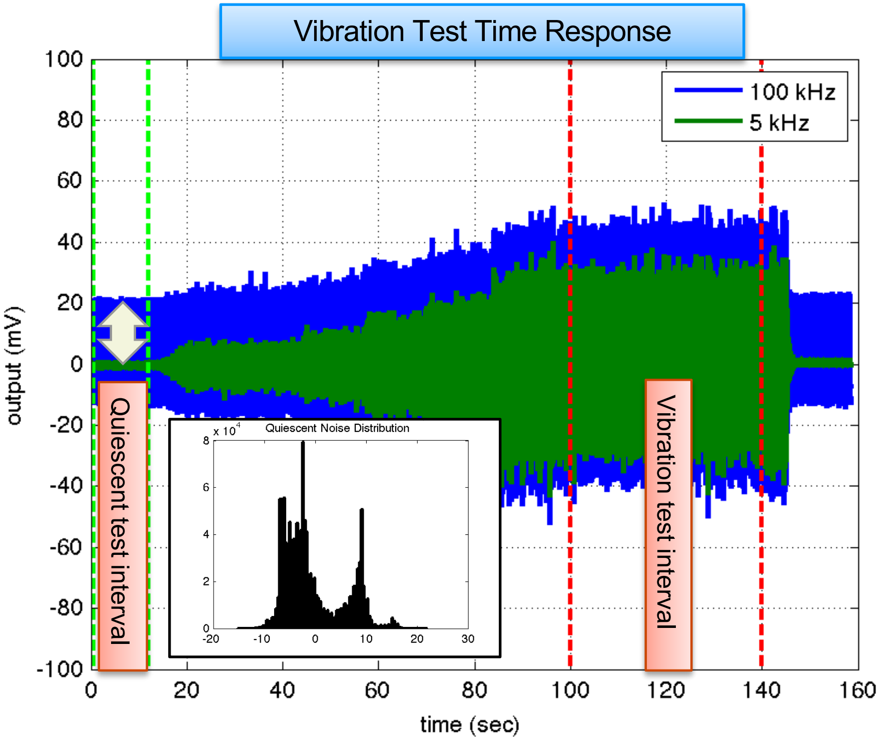
Electronics off mounted and not vibrated

Low Level Sensor mounted in the Z axis

Electrical Excitation and unit output

Input Pressure

c/o Eaton Aerospace via Boeing

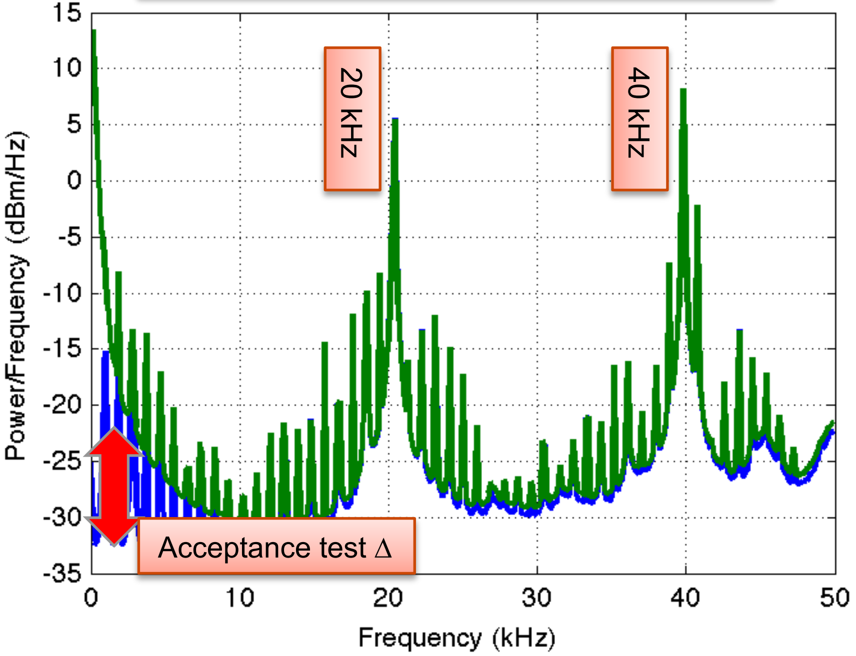


Vibration Test Time Response

Test Data Spectral Analysis

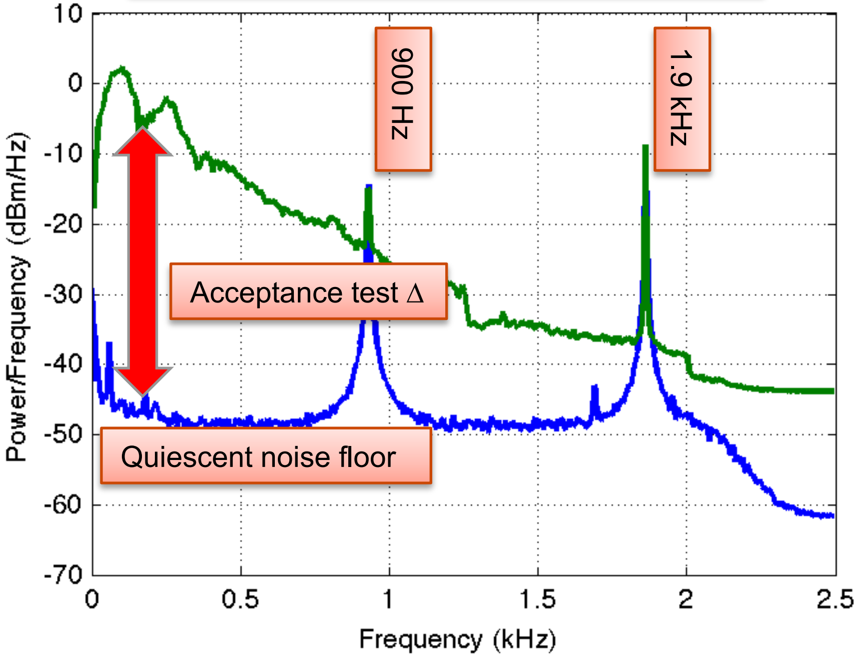
- **Spectral analysis showed a wideband interference spectrum consistent with signature of a switched mode power supply**
  - Consistent with vendor assertion that noise source is dominated by high frequency electronics switching noise
  - Harmonics as low as 900 Hz and probably above 60 kHz (>50 kHz DAQ BW)
  - Vendor requirements drove very fast output electronics, but no noise specification
  - Noise RF spectrum assessed as potential EMI risk for colocated equipment

Pressure sensor test spectrum (high bandwidth)



Acceptance test Δ

Pressure sensor test spectrum (low bandwidth)



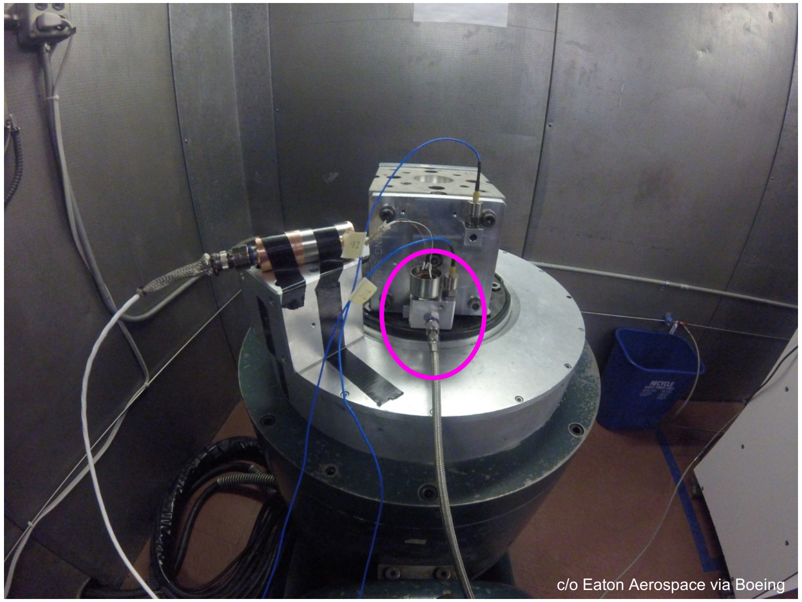
Acceptance test Δ

Quiescent noise floor

Background Denoising

- **Mean spectral subtraction method* used to reconstruct the vibe spectrum**
  - Isolate vibration induced sensor response
  - Reveals possible mechanical resonances in test fixture
  - Polynomial fit of spectrum informs noise power model
  - Response is consistent with input spectrum specification

- There are no known mechanical resonances in the sensor below several kHz
- All data show a consistent peak around 100 Hz – follows input spectrum
- Possibly mode of sensor manifold & pressure feedline attached to shaker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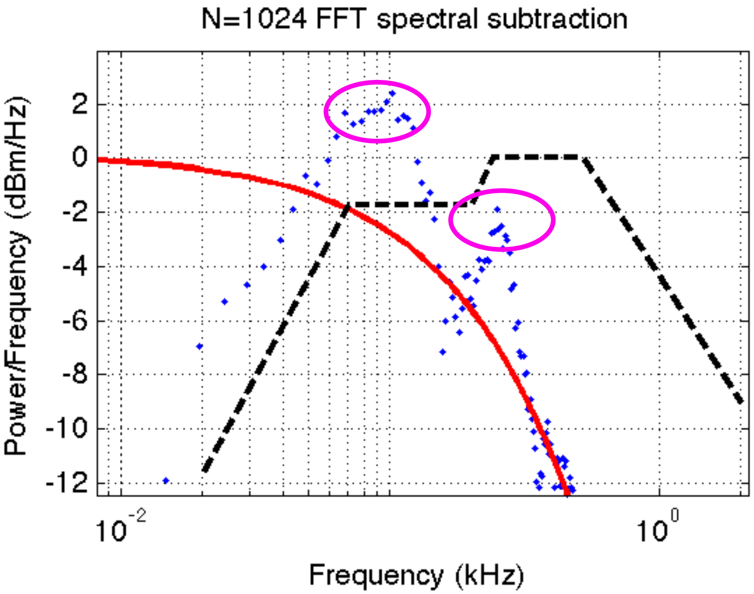
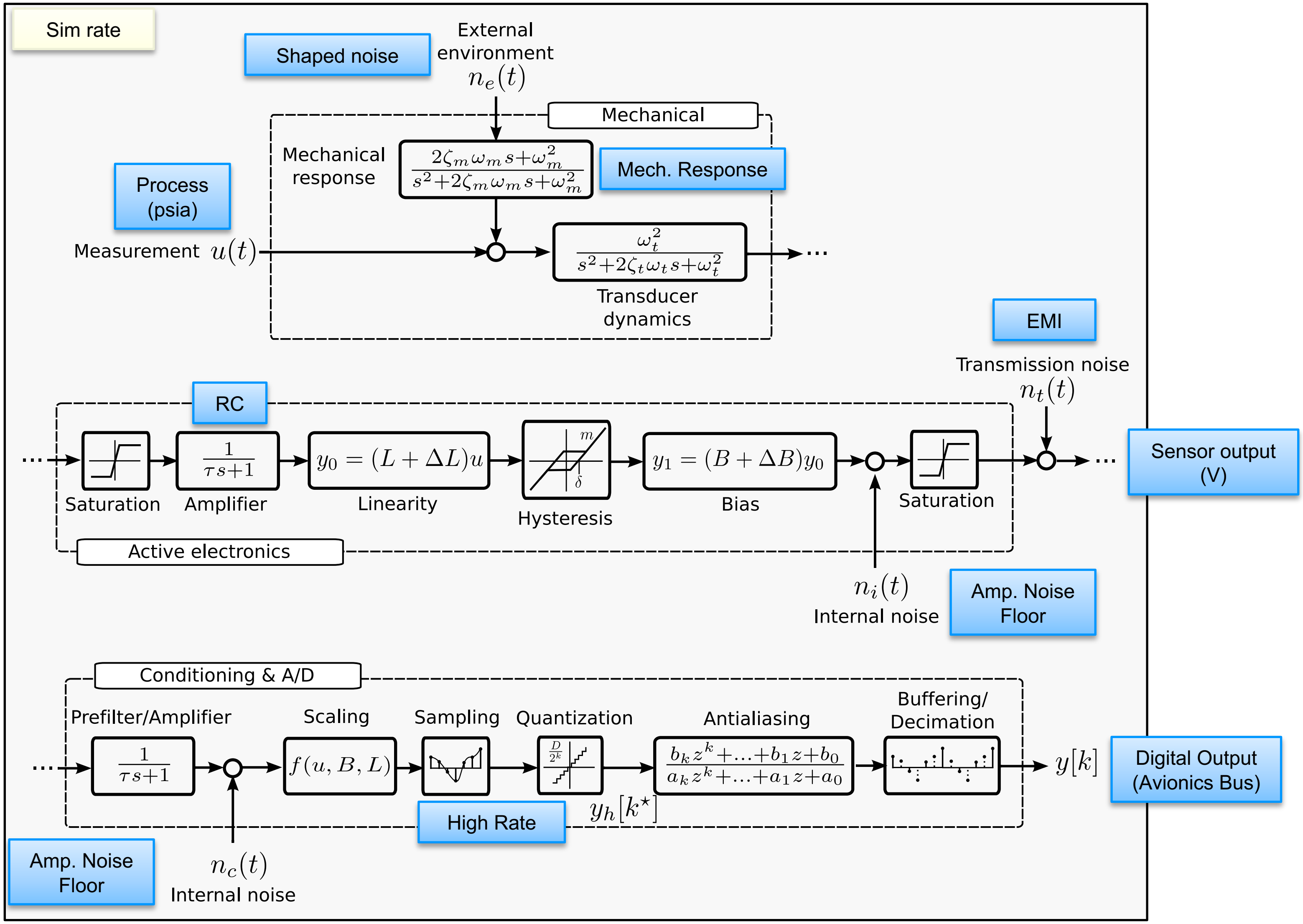


*1024-pt rectangular FFT with window averaging

Advanced Sensor Model

- **Complex noise spectrum motivated development of a more advanced sensor model**



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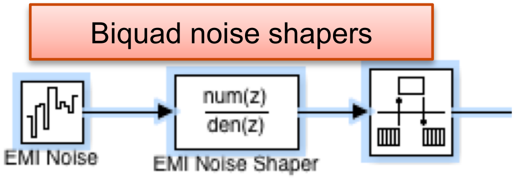
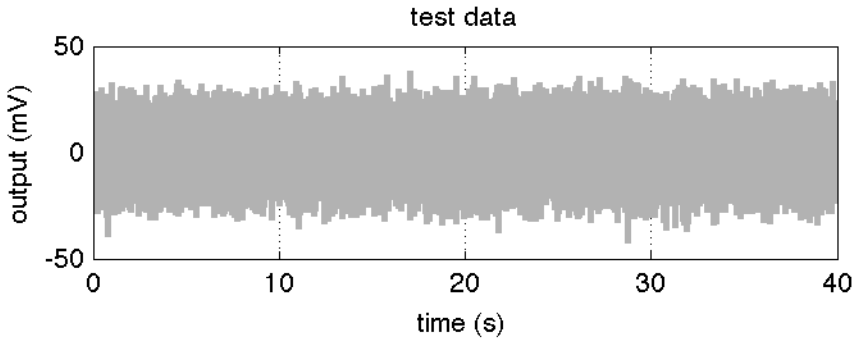
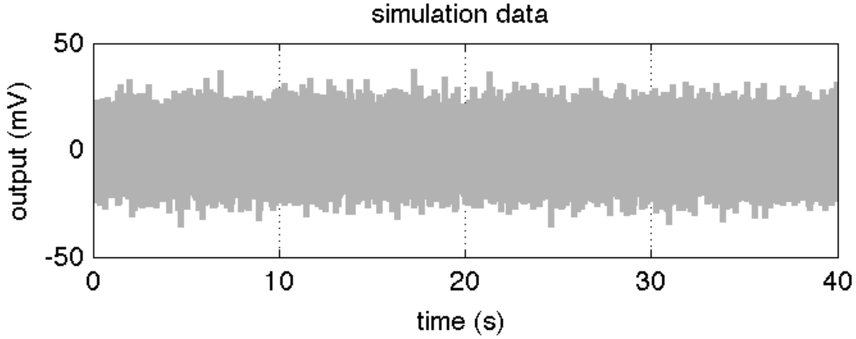
Background Noise Model Validation

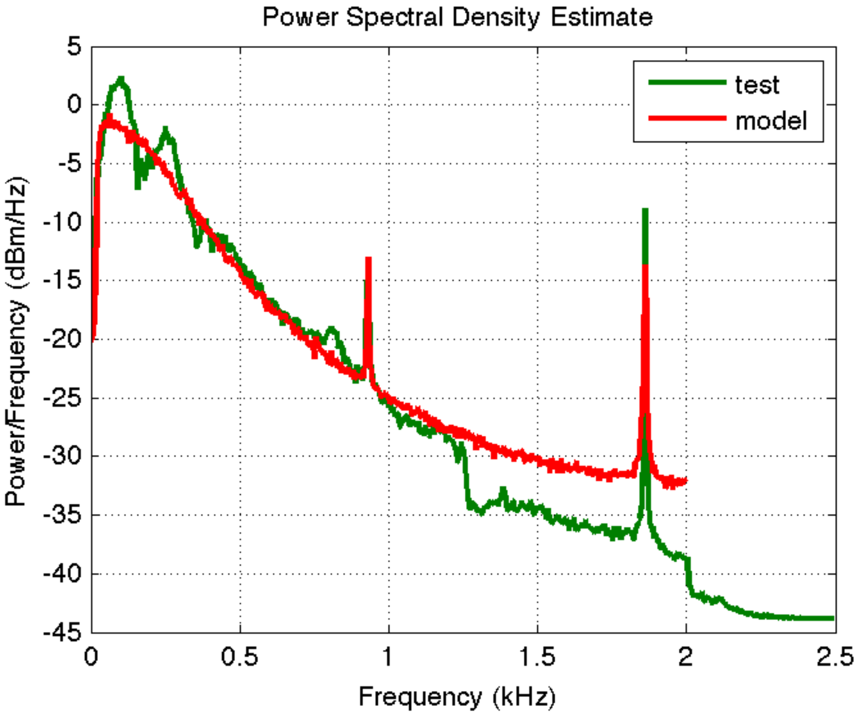
- **Background noise model implemented in an "electronics noise" module**
  - Two continuous time inverse notch filters in biquadratic form
  - Captures two "modes" that are known to be power supply harmonics
  - ZOH discretization to 4th order filter at a high real-time execution rate



$$T(s) = \frac{as^2 + s\omega_0(k-b) + c\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$



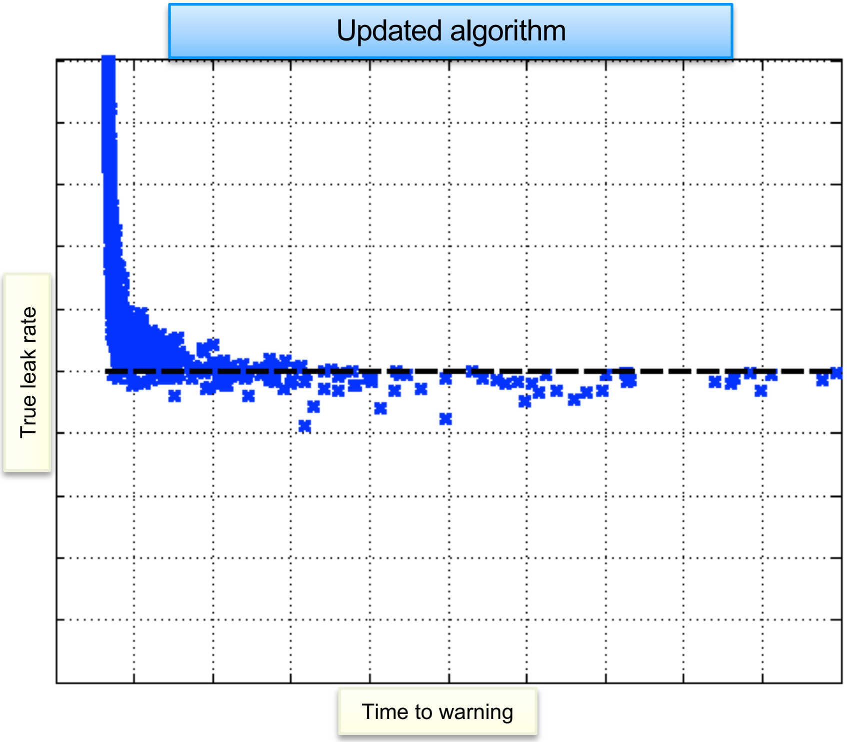


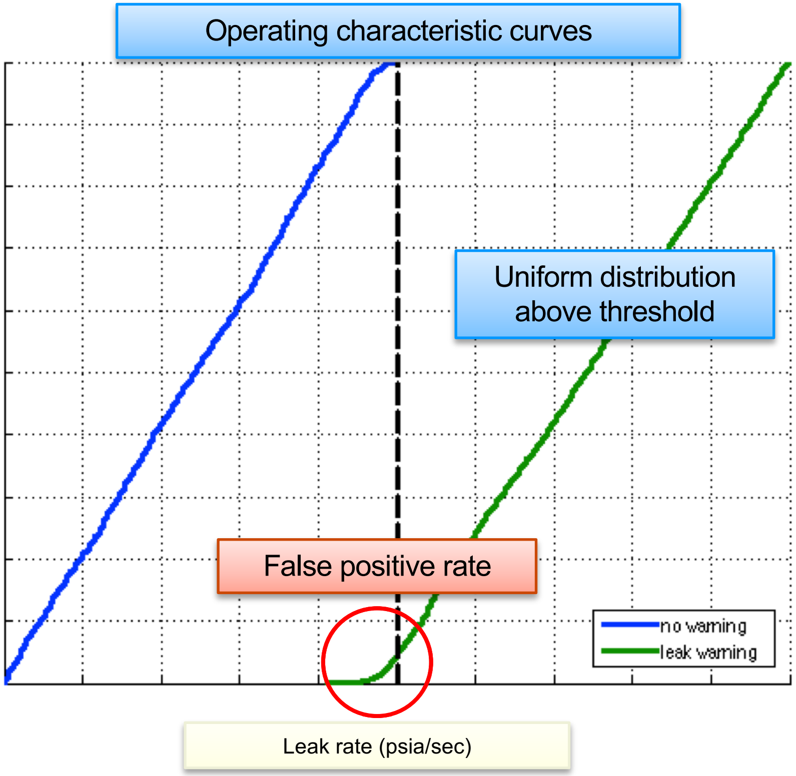


Model provides a high-fidelity reproduction of test noise spectrum

Monte Carlo Analysis Example

- **Software redesign implemented noise filtering appropriate to predictions**
  - Single parameter first-order low pass was sufficient with insignificant software overhead
  - Drastically improved discrimination performance but higher false positive rate
  - False positives driven by sensor errors (bias, scale factor)
  - Design tuning (frequency response) can adjust algorithm bias


Updated algorithm


Operating characteristic curves

Uniform distribution above threshold

False positive rate

Summary and Lessons Learned

- **Autonomy (e.g., FDIR, control) is subject to the limitations of physical sensors**
  - Early design specifications should leverage engineering judgement for reasonableness checks and systems-level implications
  - Otherwise, vendors build what you tell them to
  - Performance limitations should come from the physics, not poor requirements

- **A proper understanding of non-Gaussian noise sources is crucial even for simple functions**
  - May require special handling (filtering, algorithms)
  - Antialiasing of sensor measurements is crucial in flight induced environments

- **Autonomy is a system-level exercise that benefits from model-based engineering (MBE)**
  - Software engineers may lack hardware experience and systems visibility
  - Mechanical engineers may lack amplifier/DSP insight
  - Electronics & avionics engineers may lack hardware/structure/vibration insight
  - Systems engineers may formulate specifications disjoint with functional goals
  - MBE can help identify gaps and connect interfaces