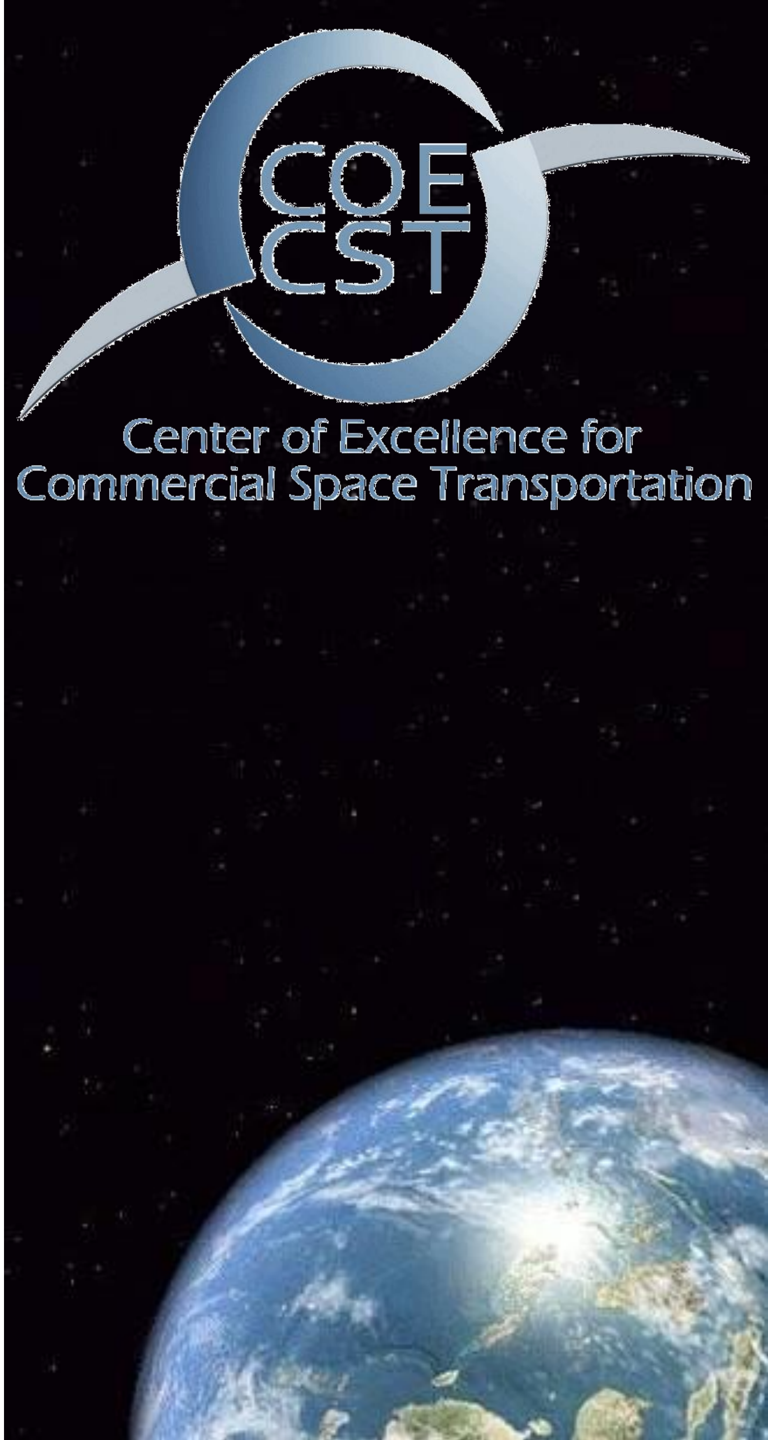
COE CST Third Annual Technical Meeting:

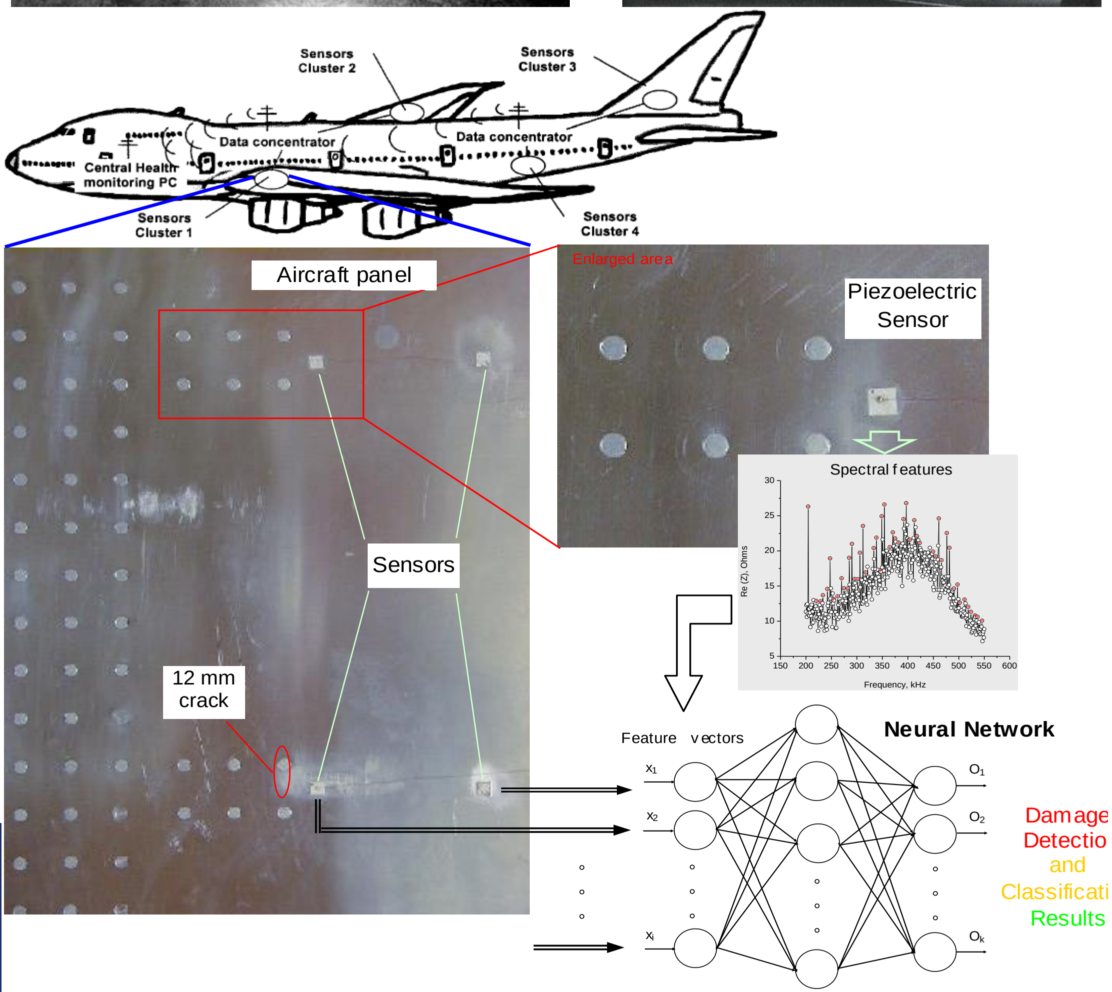
Task 228: Magneto-Elastic Sensing for Structural Health Monitoring

Andrei Zagrai and Warren Ostergren

29 October 2013



Aircraft Structural Condition Assessment

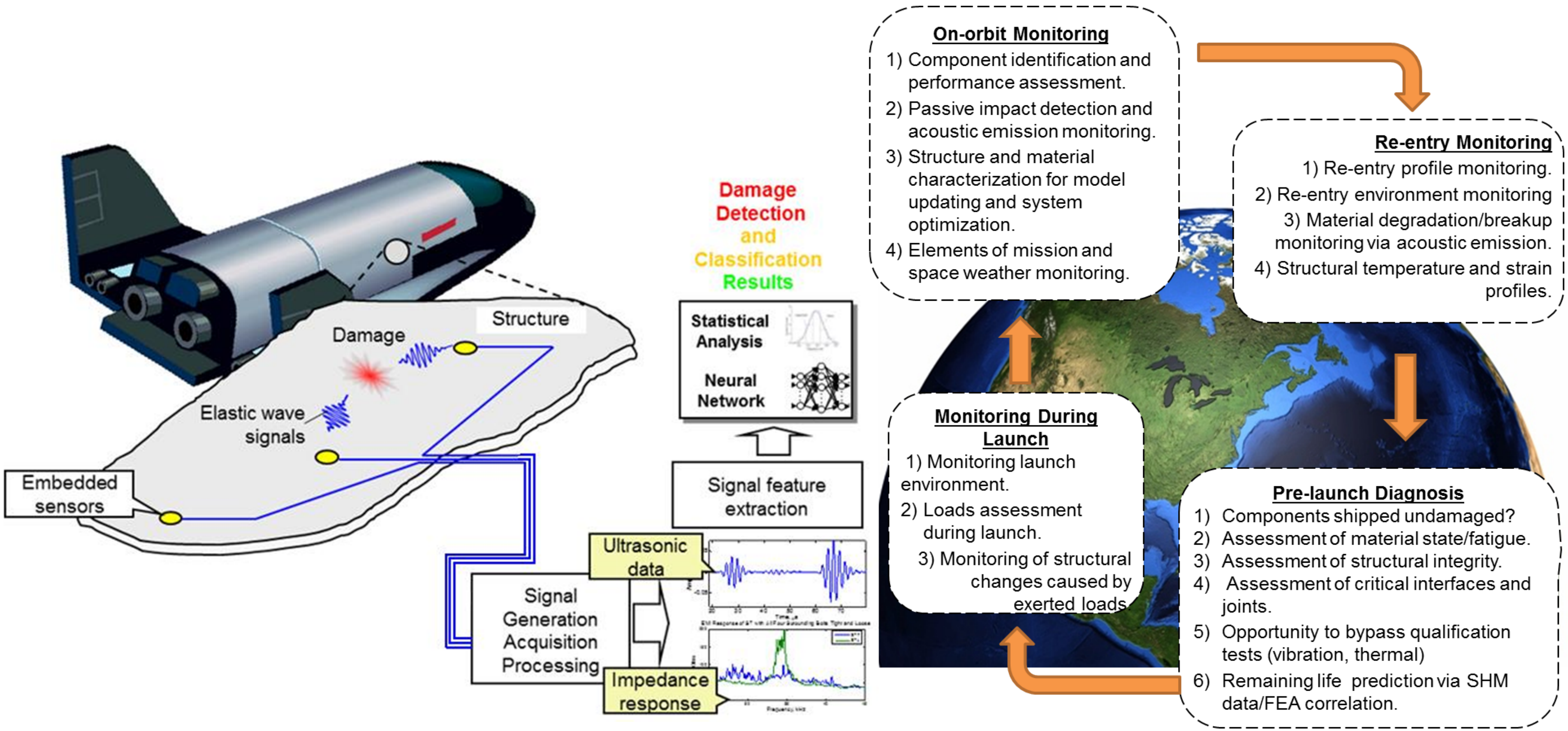


- PAST/CURRENT
  - Pre-flight critical components assessment
  - In-flight data (control, voice, communication, altitude, etc.) recording in “black box”
  - Mandatory periodic inspections (often manual) of structural elements (downtime!)
- +CURRENT/FUTURE
  - In-flight video
  - Improved inspections (corrosion, composites)
  - Automatic structural condition assessment using EMBEDDED sensor system
  - Real time structural assessment

Spacecraft Structural Condition Assessment

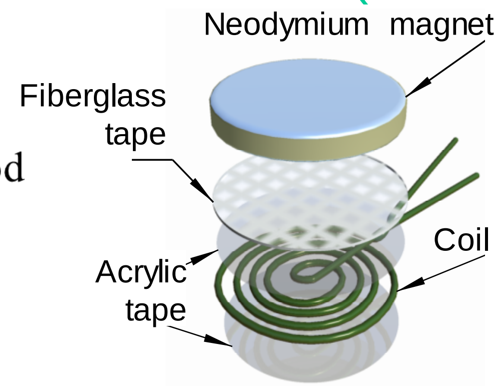
- Operational loads on spacecraft are higher, it fatigues faster
- No guidelines on what and how often to assess
- Likely require special sensors
- Data recorder WILL NOT be similar to aircraft “blackbox”, Guidelines?
- Currently no work on this subject in emerging commercial space industry. Companies are busy developing launchable systems.
- If structural safety will be regulated, what are critical issues and potential solutions?

Flight Safety: Certification/anomaly detection

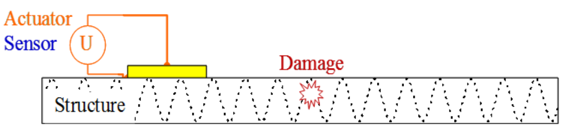


SHM Strategies for Commercial Space Vehicles

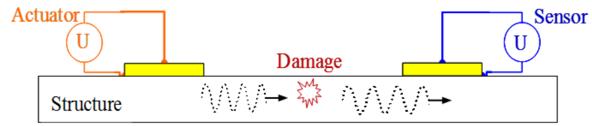
Magneto-elastic Active Sensor (MEAS)



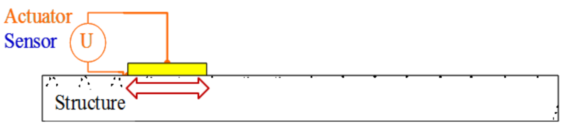
Electro- mechanical impedance



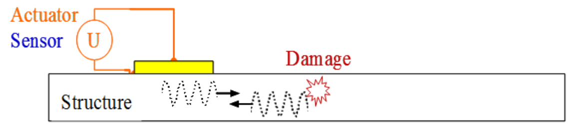
Wave propagation: Pitch-catch method



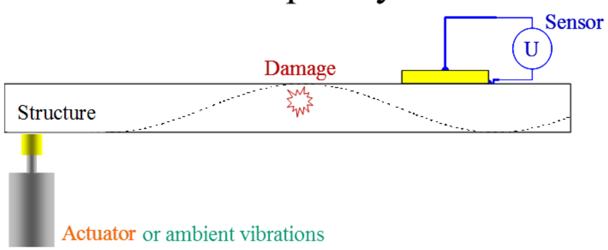
Dynamic strain measurement



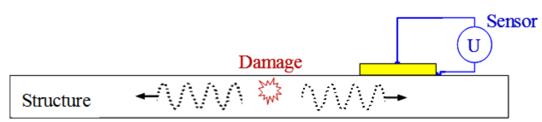
Wave propagation: Pulse-echo method



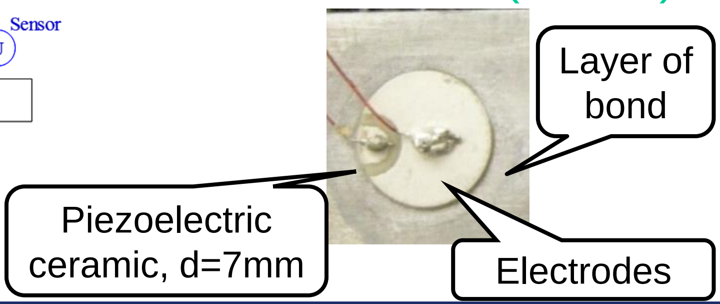
Low frequency vibrations



Acoustic emission



Piezoelectric Wafer Active Sensor (PWAS)



Focus on appropriate sensors + off-the-shelf hardware

Purpose of Task

- Demonstrate utility of various SHM strategies during suborbital space flight
- Investigate potential of magneto-elastic active sensors and embeddable thin wafer piezoelectric sensors to record acoustic emission activity due to structural fatigue and thermal damage
- Develop portable hardware for electro-mechanical impedance SHM

Team Members

Task 228 NMT Team

- Blaine Trujillo (GR ME)
- Joel Runnels & William Masker (UG ME/EE) (Graduated)

- Andrei Zagrai & Warren Ostergren

Collaborators

- Igor Sevostianov (MAE NMSU)
- Whitney Reynolds
  (AFRL Space Vehicles)

038 BS NASA FOP Flight Team

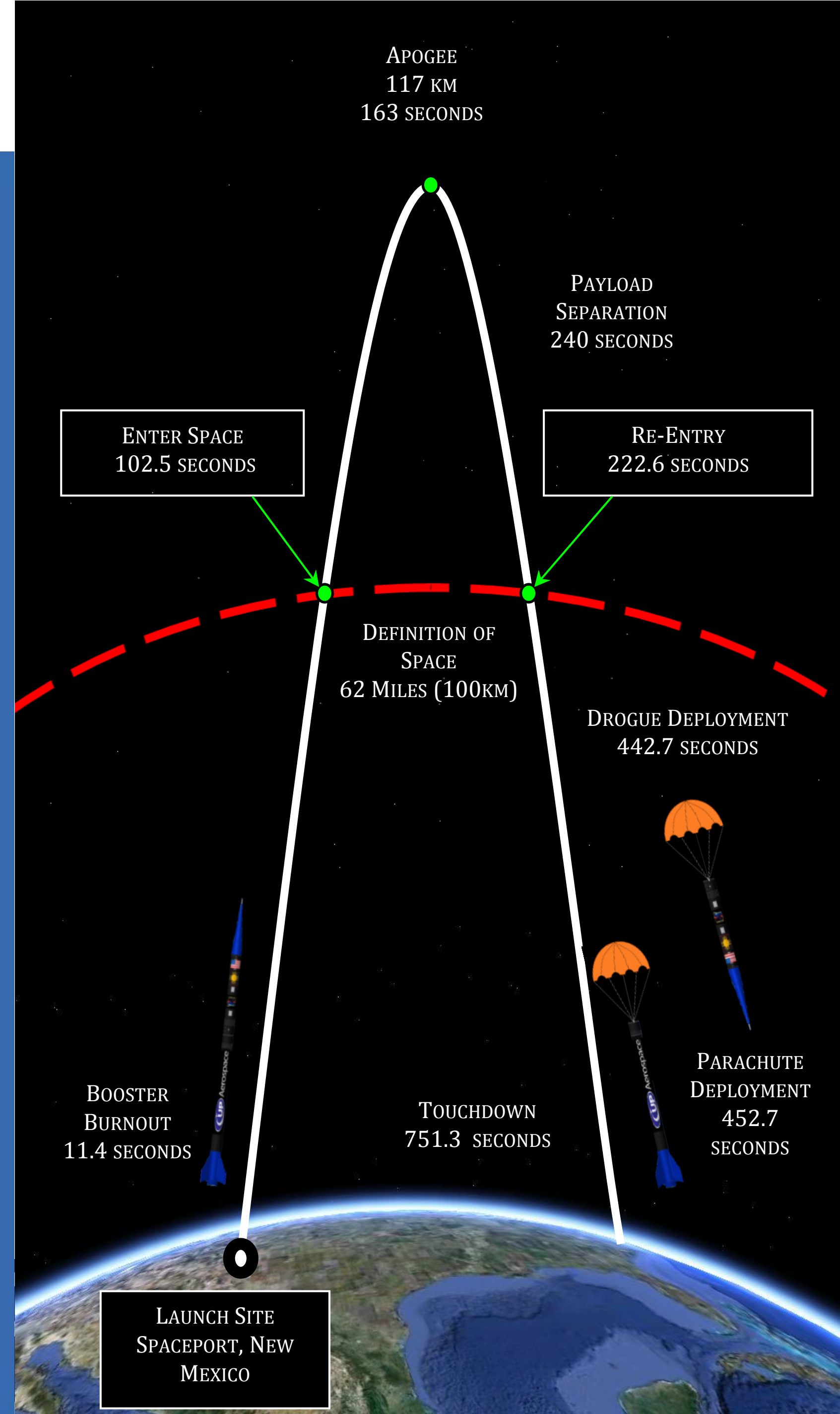
Andrei Zagrai (NMT), Nickolas Demidovich (FAA), Ben Cooper (NMT), Jon Schlavin (NMT), Chris White (NMT), Seth Kessler (Metis Design Corporation), Joe MacGillivray, Sam Chesebrough, Levi Magnusion, Lloyd Puckett, Karen Tena, Jaclene Gutierrez, Blaine Trujillo, Tiffany Gonzales. (NMT-undergrads)

SL8 – Suborbital Mission

New Mexico Spaceport commercial launch of SpaceLoft rocket on November 12, 2013.

- **Goal**: Test innovative sensing technologies for real-time assessment of spacecraft structural integrity.

- **Results**: Experimental data on influence of space environment on structural dynamic signatures associated with spacecraft's integrity.



SL8 Rocket

- Size: The SpaceLoft® XL has an overall height of 20.0 feet, a maximum diameter of 10.4 inches, and a maximum lift-off weight (including payload) of 780 pounds in its standard mission configuration.

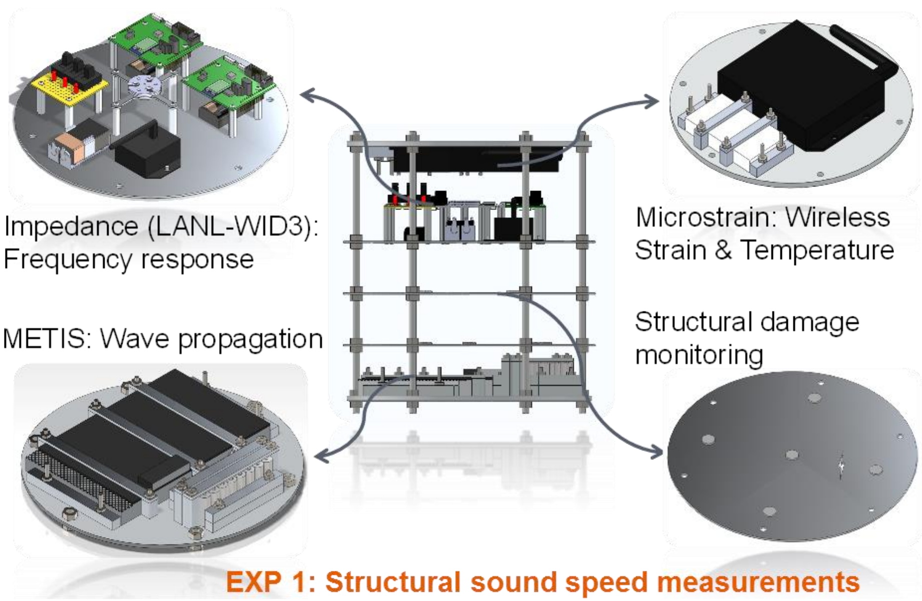
- Payload Mass: The SpaceLoft® XL can transport up to 110 pounds of payloads and experiments to a nominal apogee of 117 km. With lower-mass payloads, the rocket can be configured to reach 140 miles.

- Vehicle Spin, De-spin and Attitude Orientation: For maximum trajectory accuracy, the SpaceLoft® XL vehicle is spun during the boost portion of the flight. The nominal spin rate is 6.9 cycles per second, which is typically achieved within 12.0 seconds into the flight. Once the vehicle is out of the atmosphere the booster is separated and the de-spin system is automatically deployed which results in a residual rotational rate of less than 5 degrees / second.

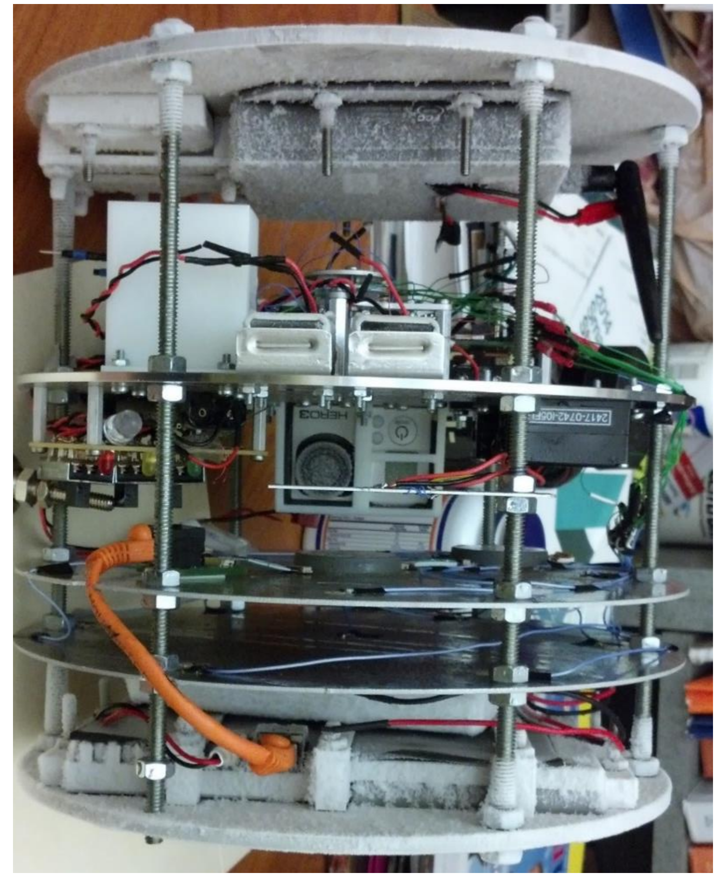
SL8 – Payload

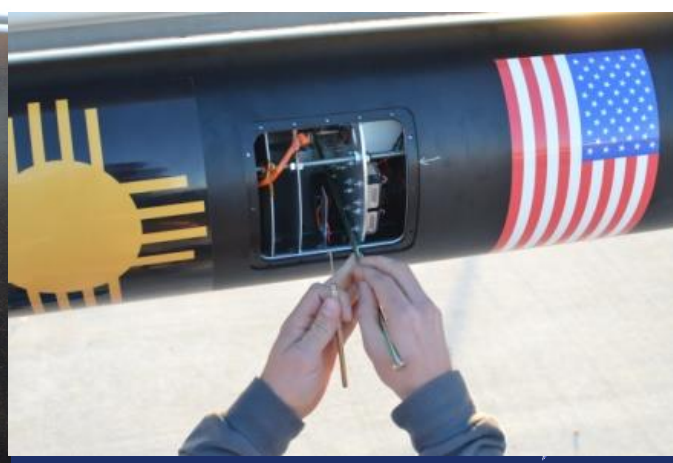
EXP 5: Electro-mechanical impedance structural dynamic measurements

EXP 6: Wireless strain and temperature sensing

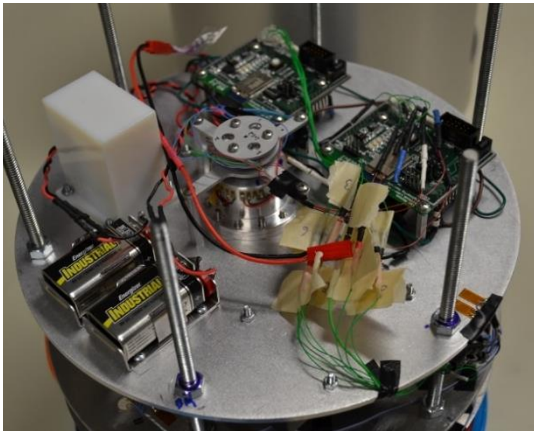


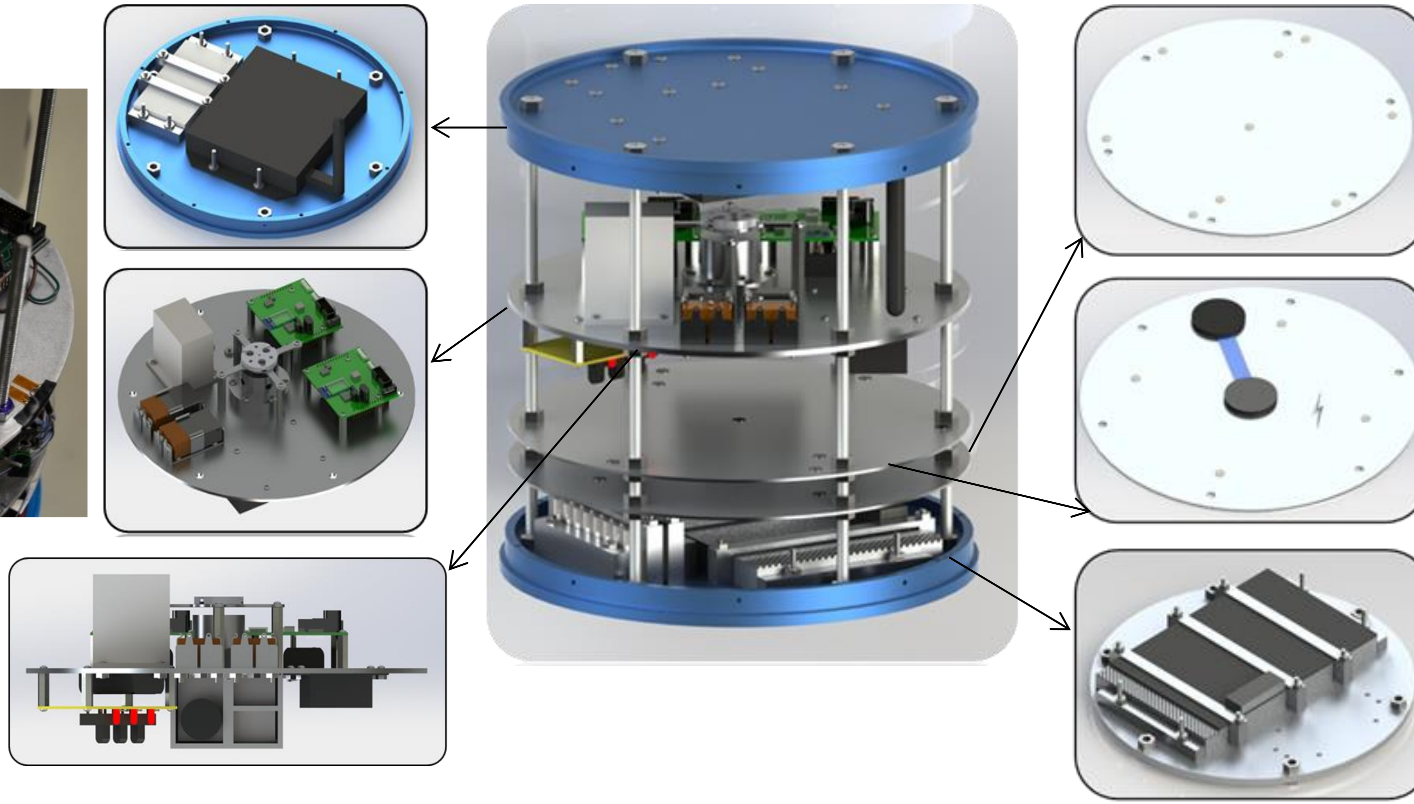
EXP 1: Structural sound speed measurements
EXP 2: Crack detection
EXP 3: Loose bolt detection
EXP 4: Acoustic emission (AE) measurements

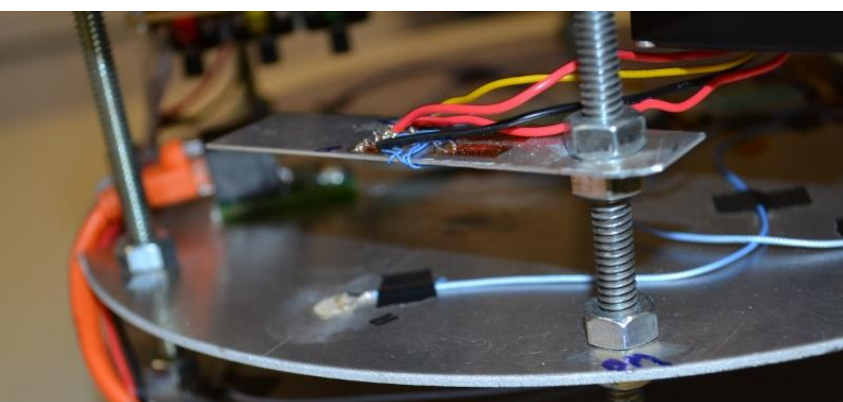


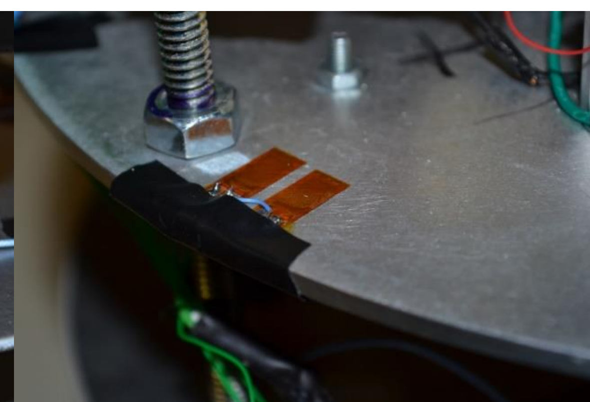


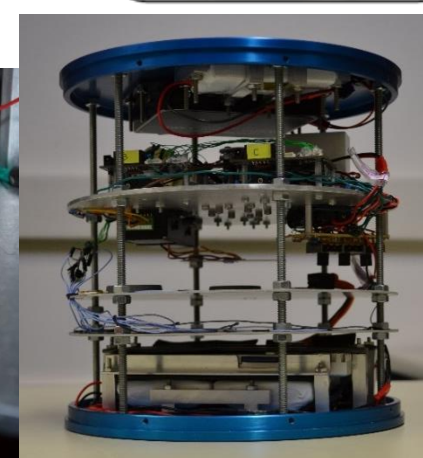
SL8 – Payload



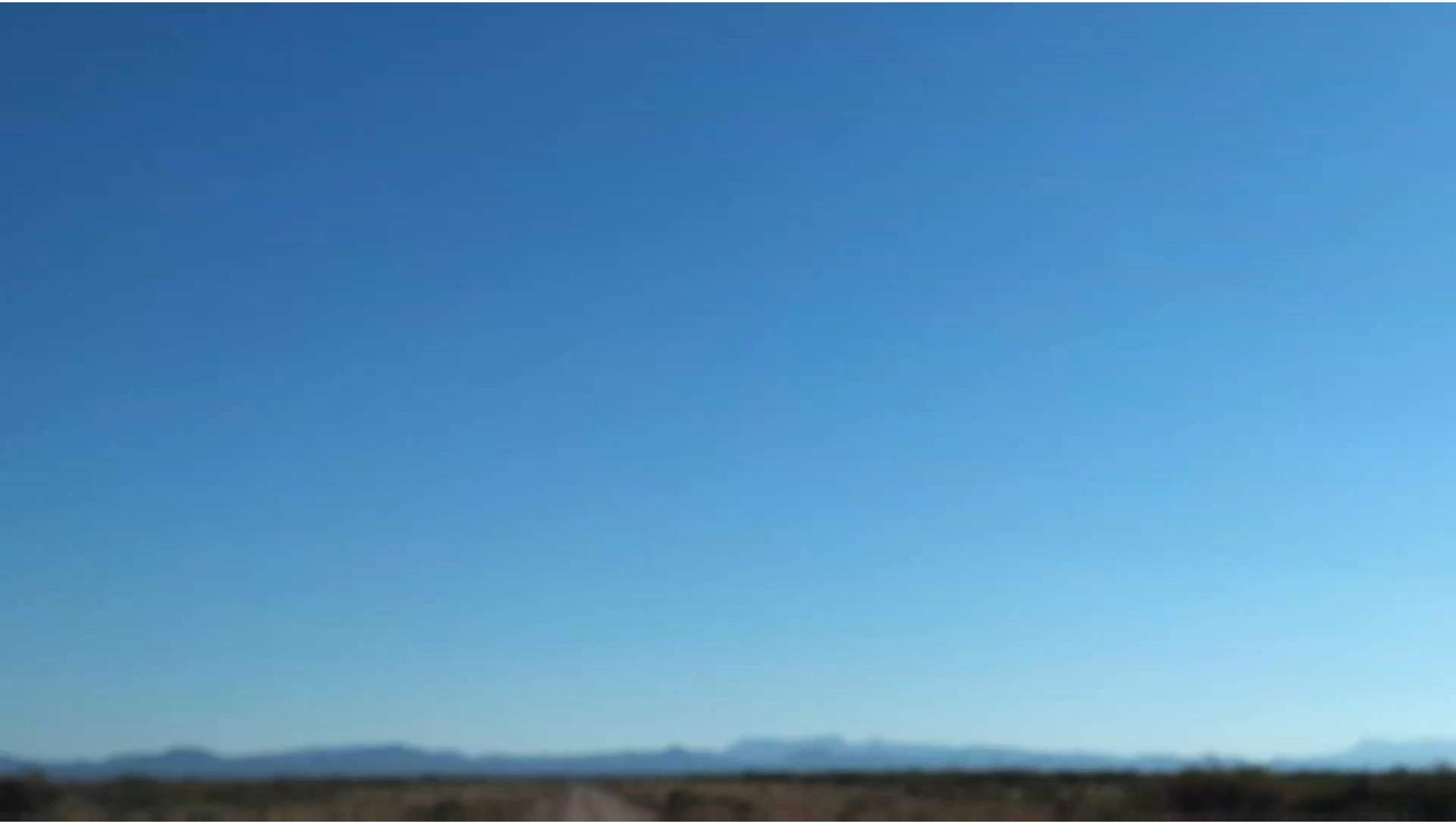




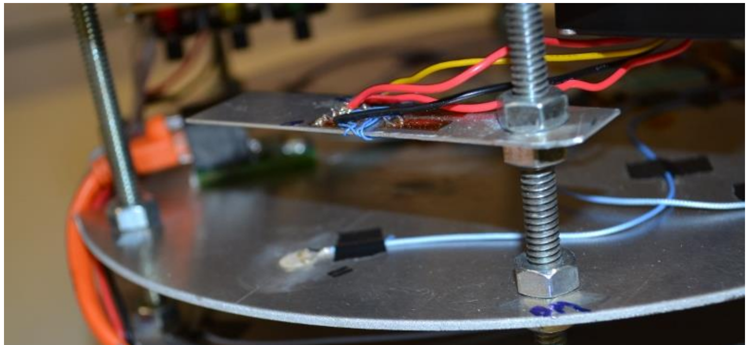


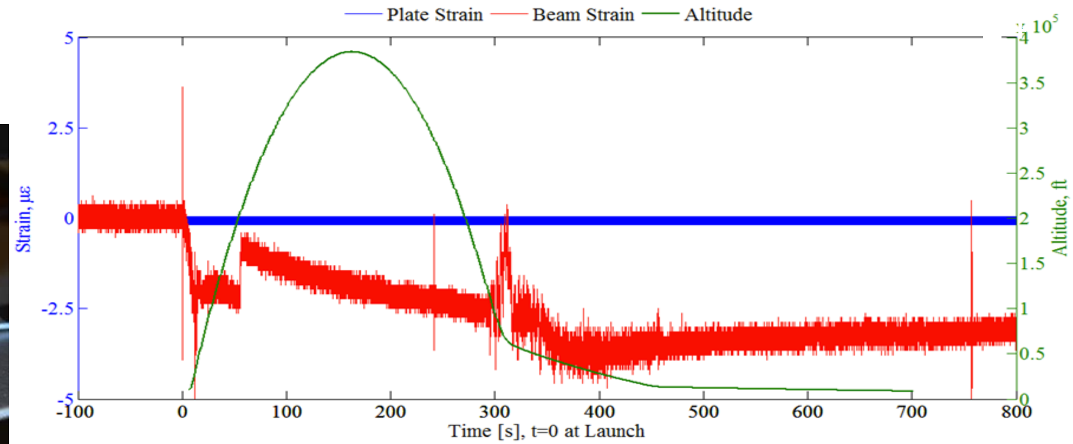


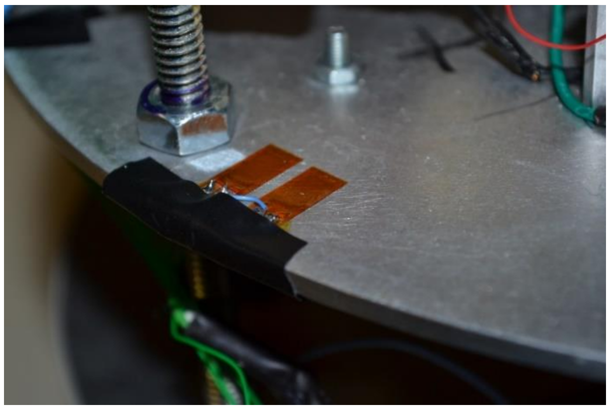
Sl8 Launch, November 12, 2013

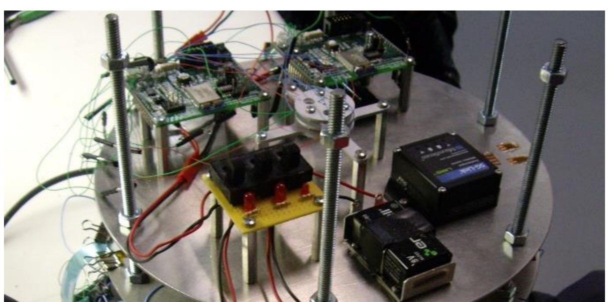


Wireless Test









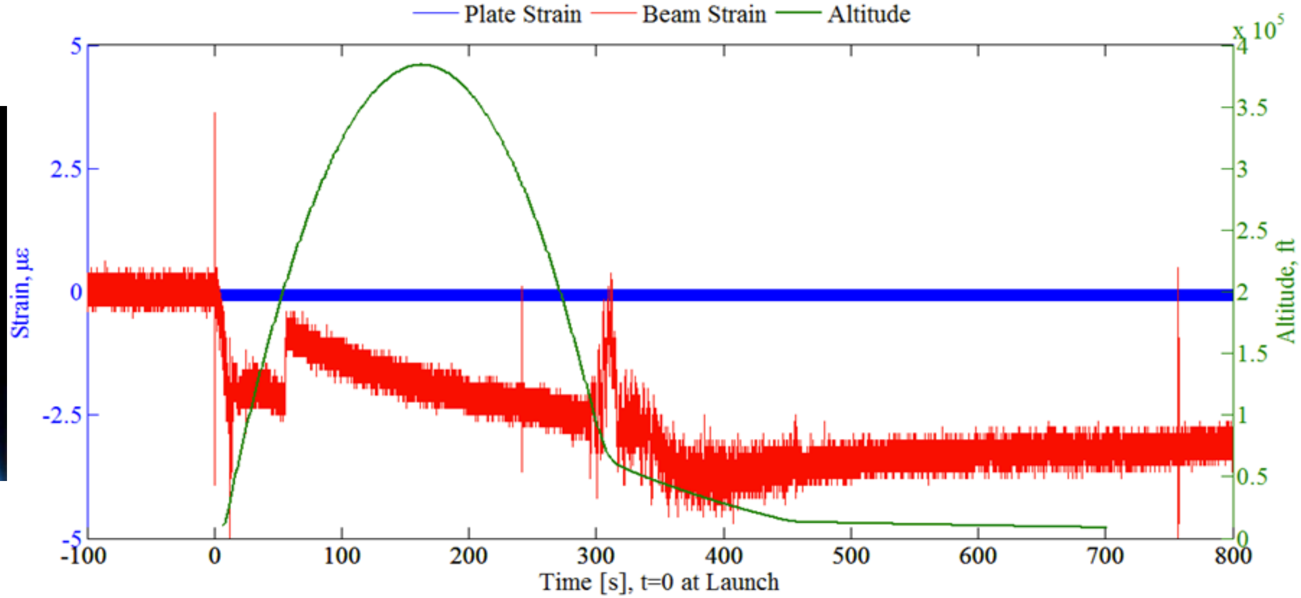
UP Aerospace Inc.
SpaceLoft-8
Launched November 12, 2013
NASA Flight Oportunities Program

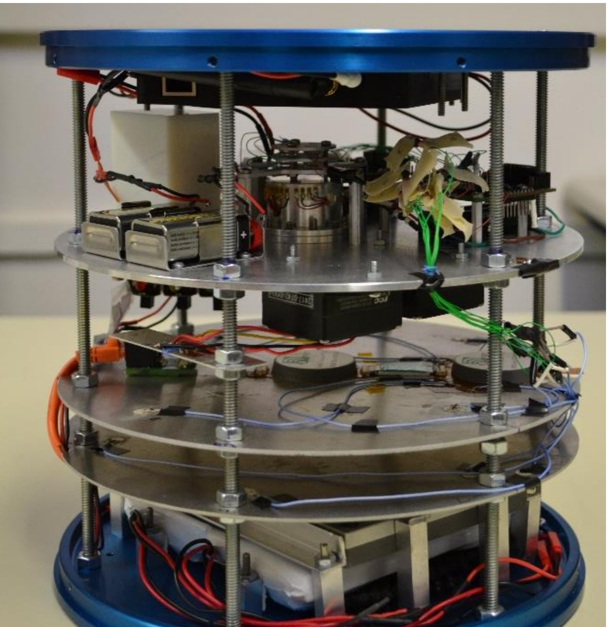
Two SG-Link -LXRS 3 Channel Wireless Analog Sensor Node (about 50 grams each)

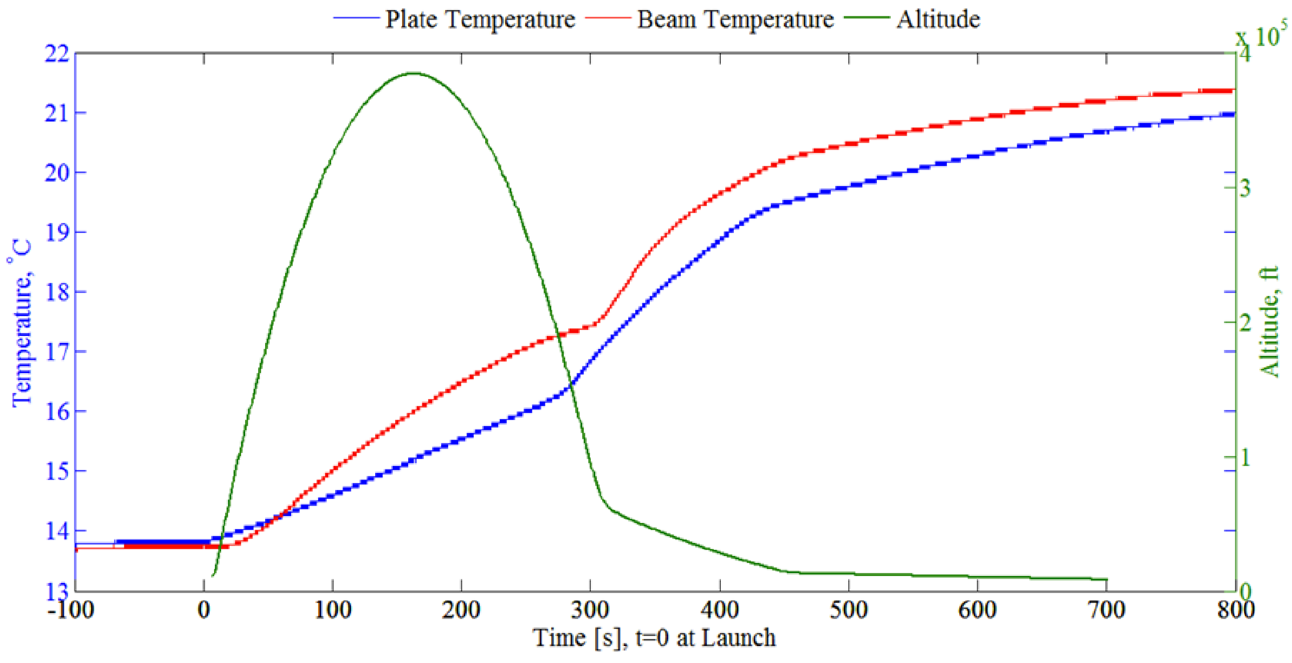
120Ω foil strain gauges connected in Full Wheatstone bridge configurations

256 Hz synchronous sampling

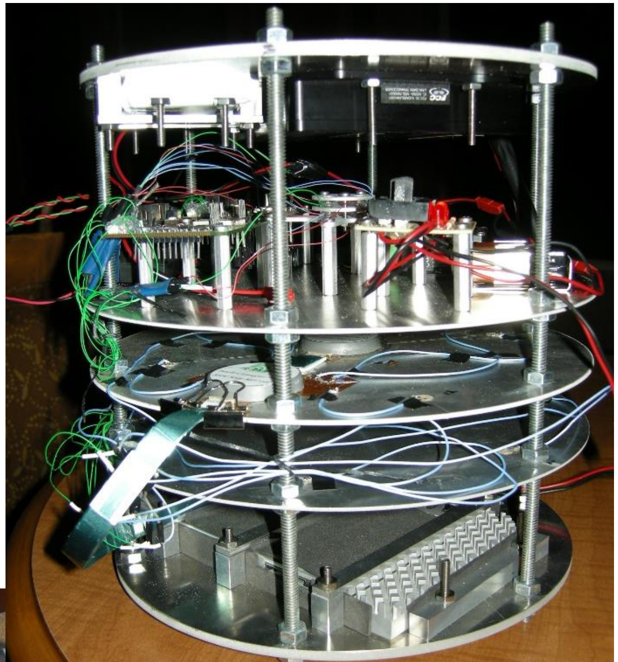
Wireless Strain and Temp. Sensing

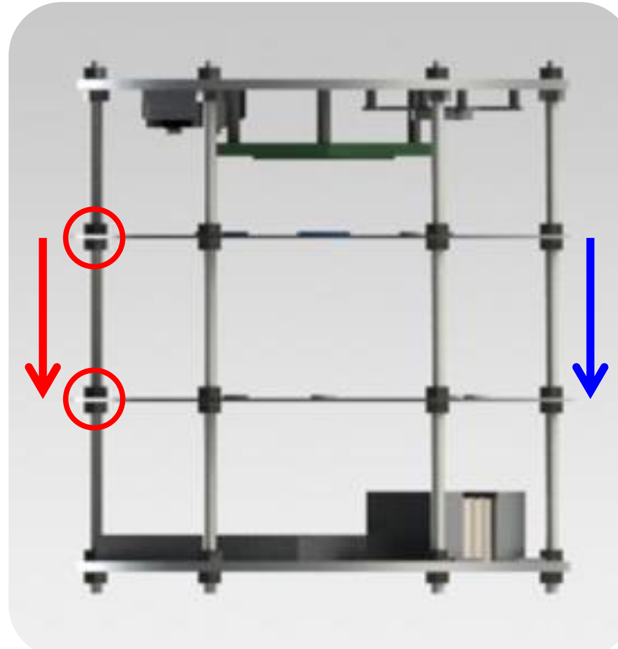


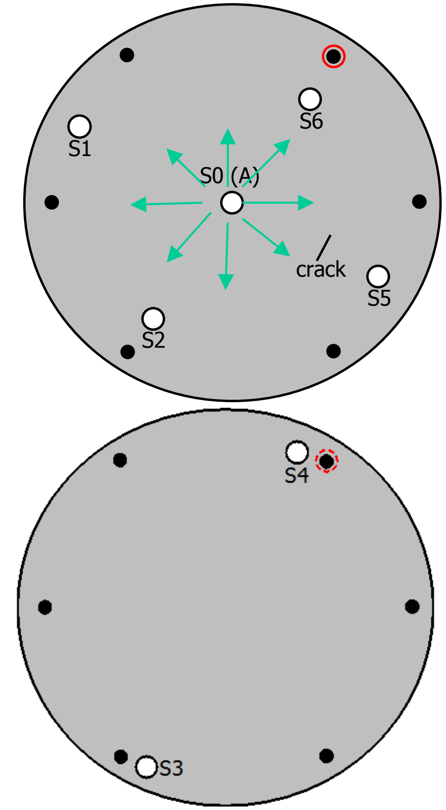




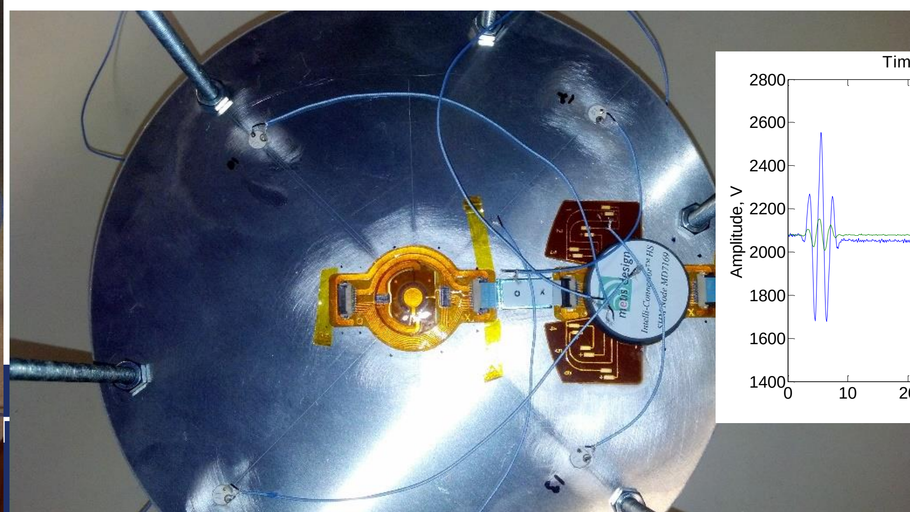
Wave Propagation (SHM & Sound Speed)

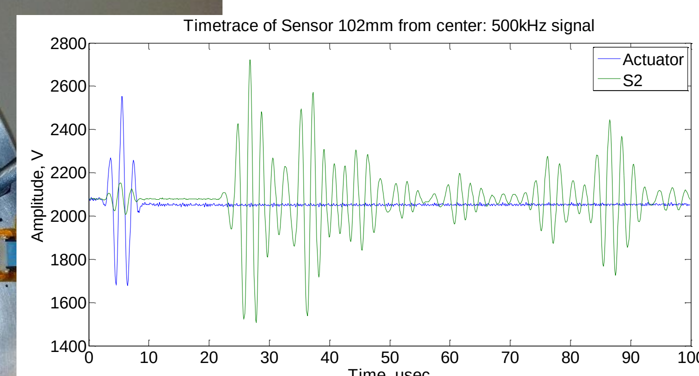




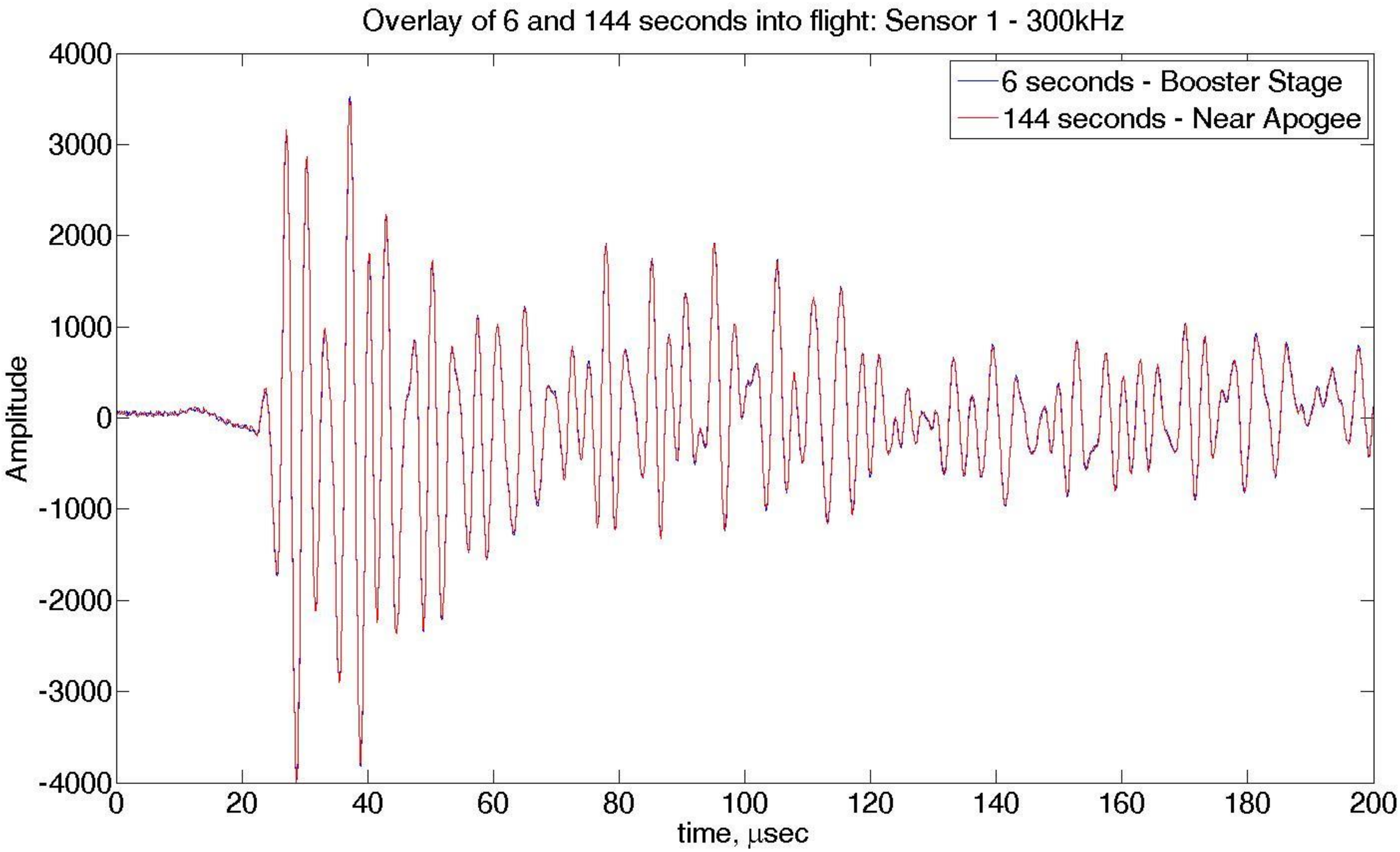


Metis Design hardware

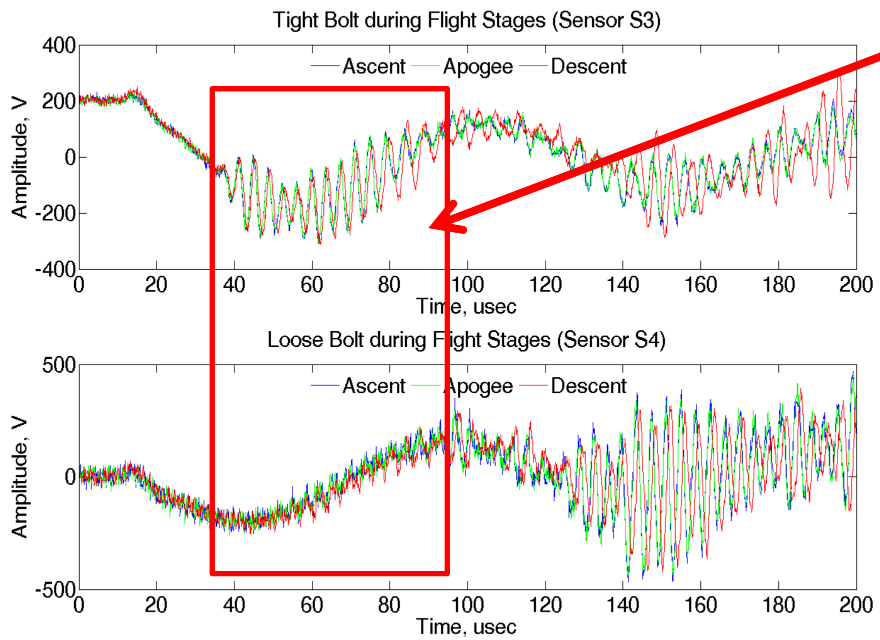




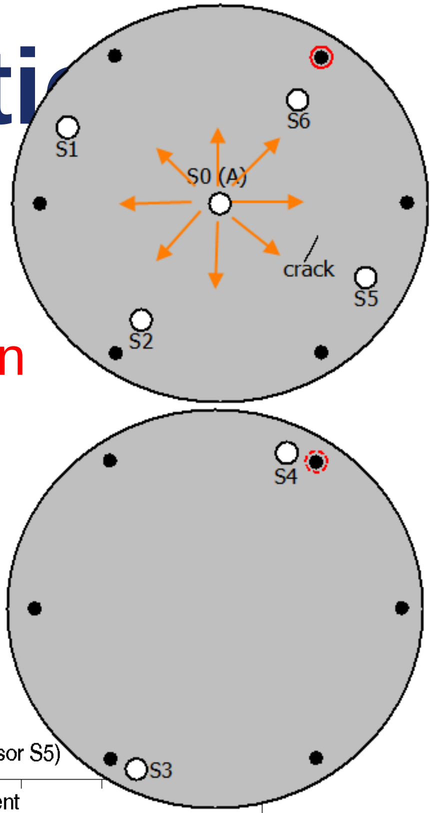
SL8 Flight Noise Effects

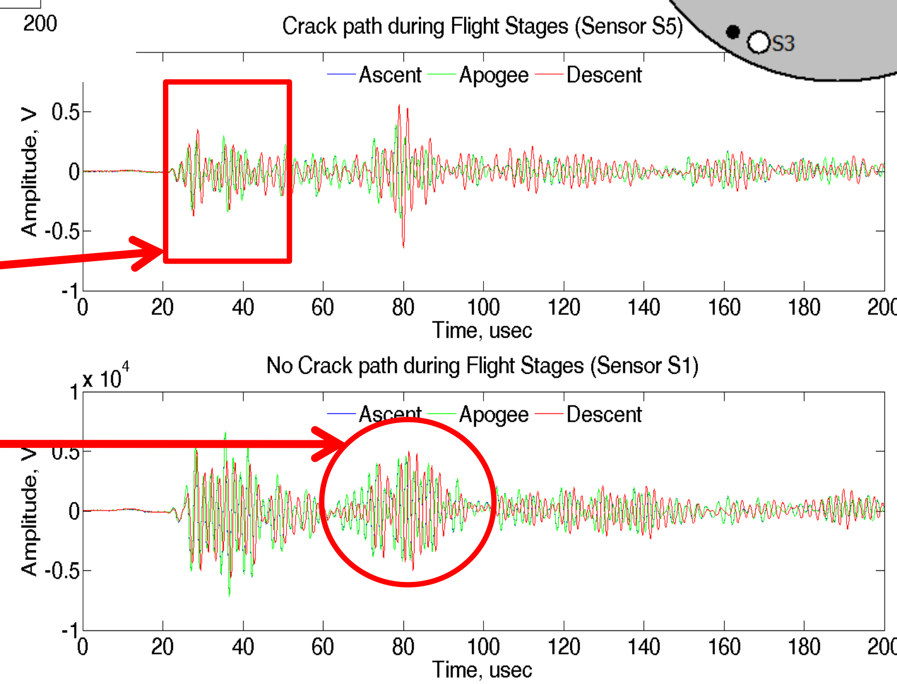


Loose Bolt and Crack Detecti



Loose Bolt Assessment: Amplitude reduced in loose bolt transmission

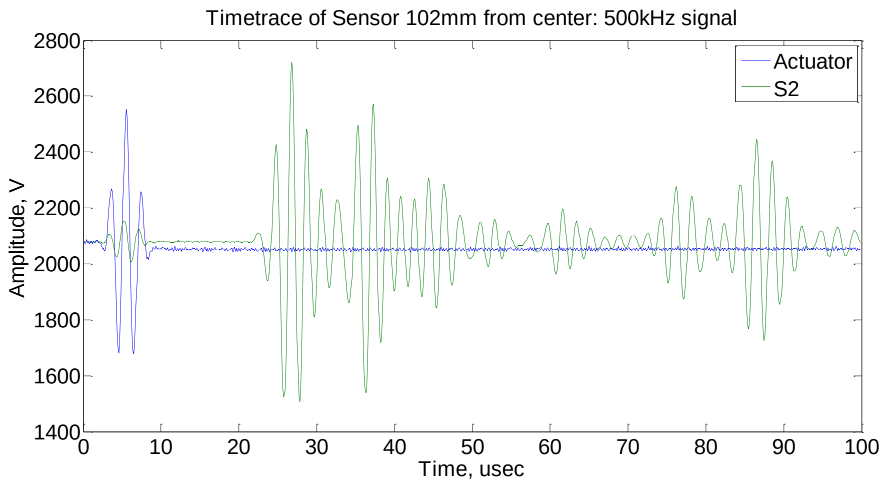


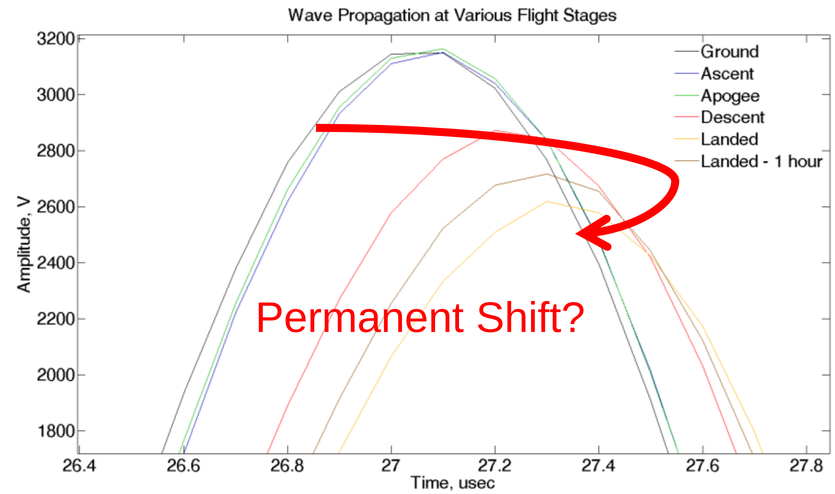


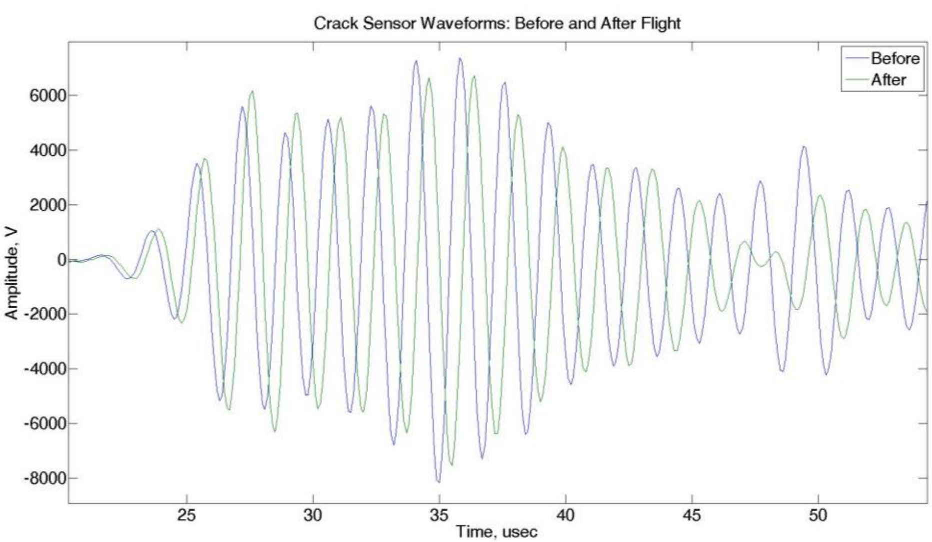
Crack Detection: Energy scattered by crack

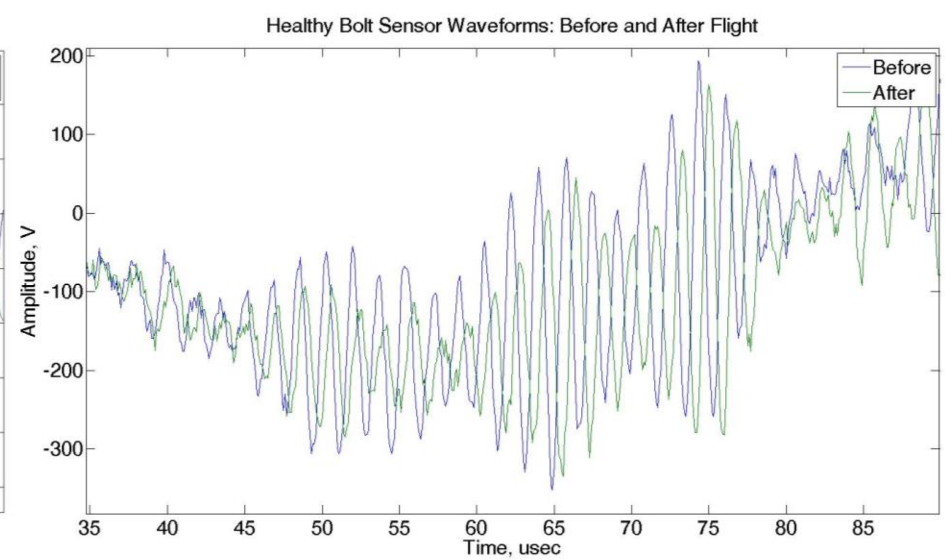
Pulse reflected by crack

SL8 – Suborbital Flight Temperature Effects

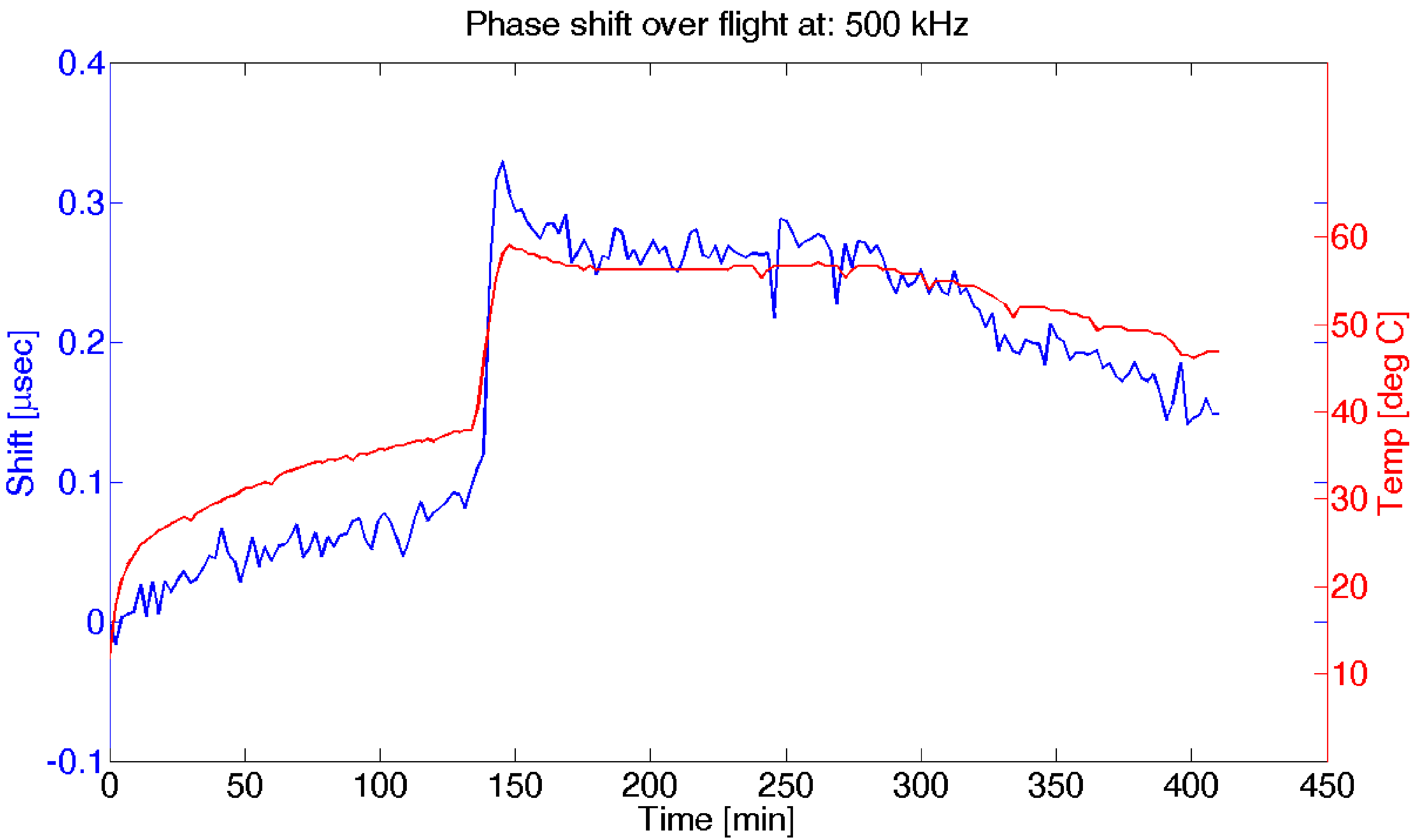




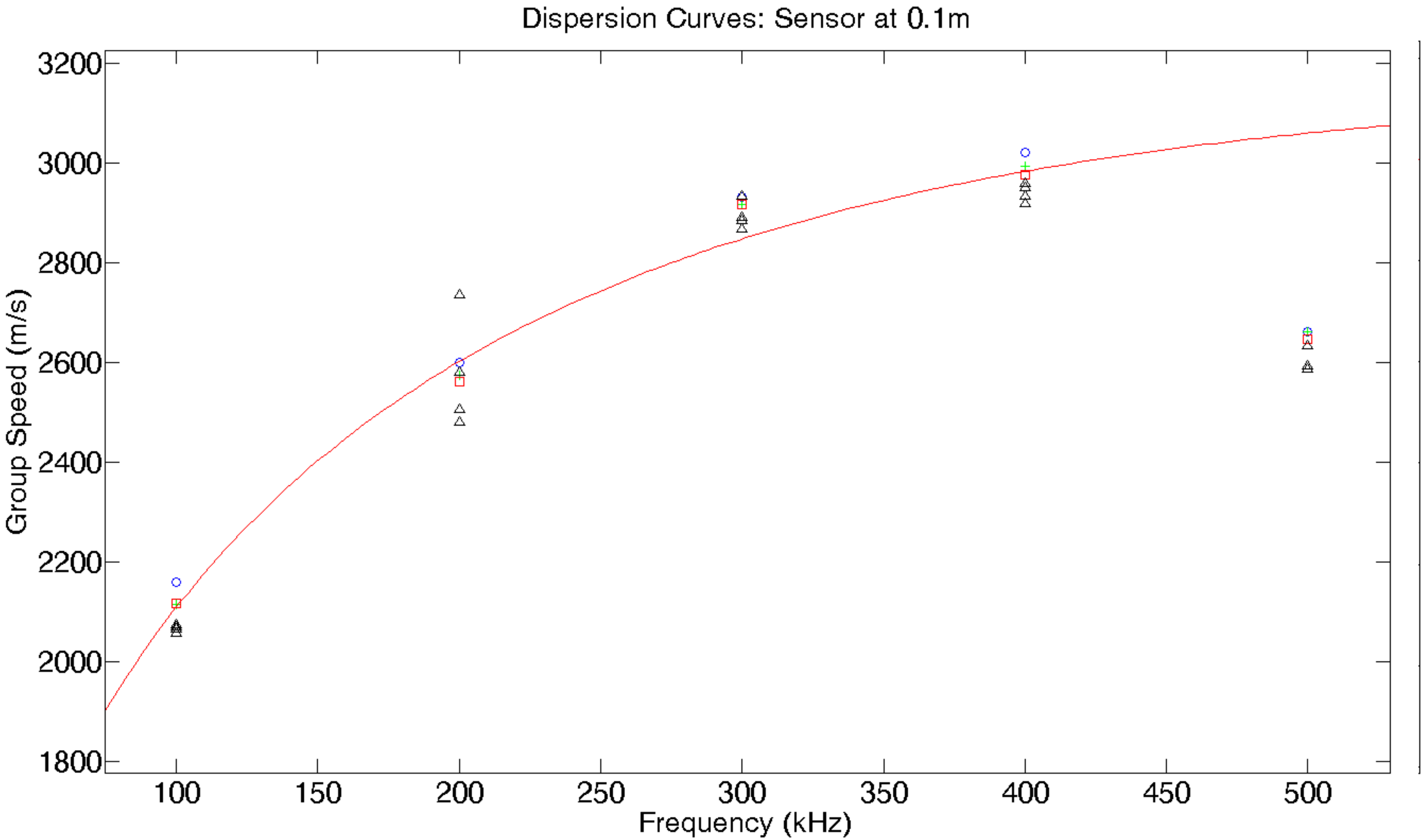




Phase Shift vs. Temperature



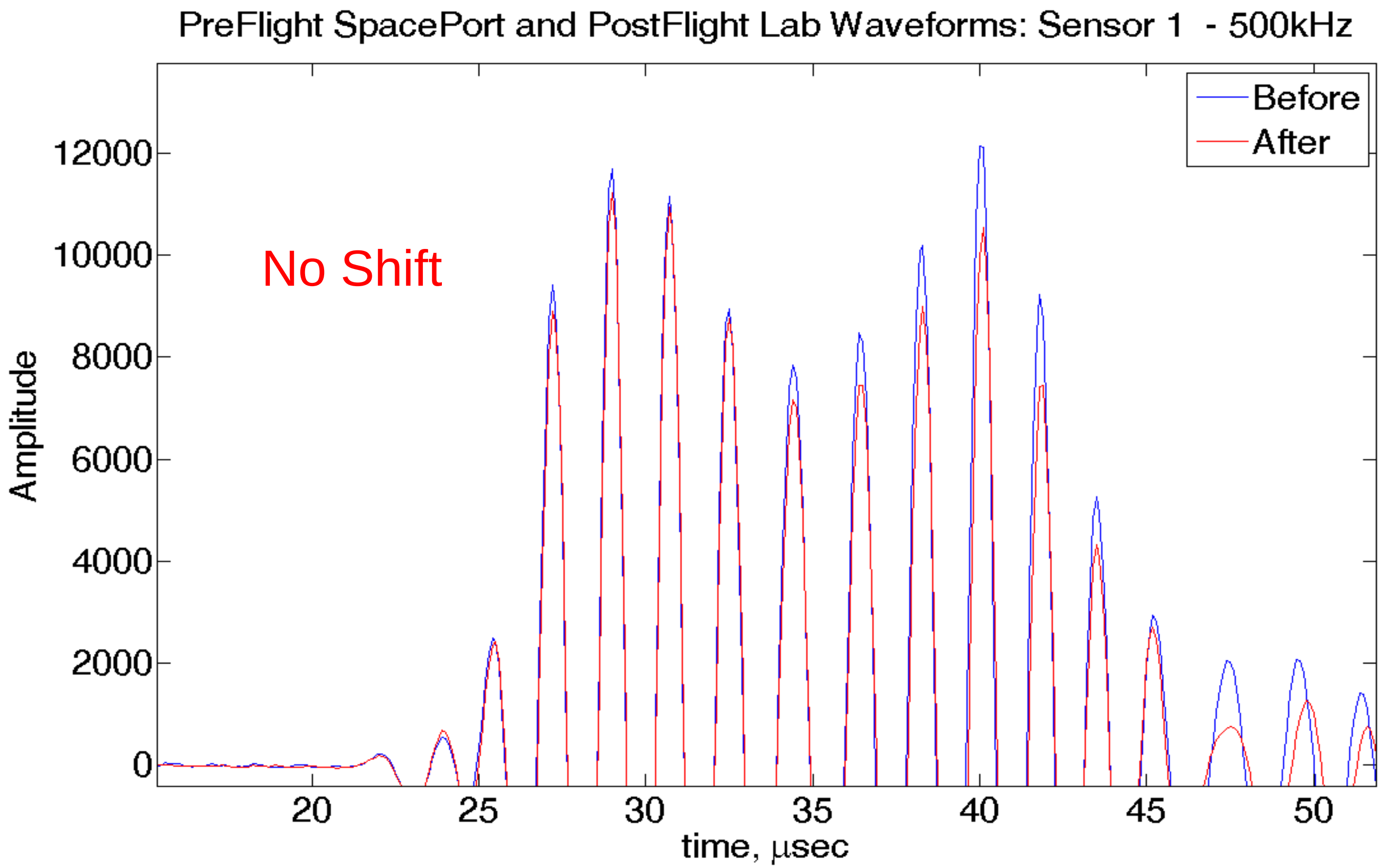
Phase Shift vs. Temperature



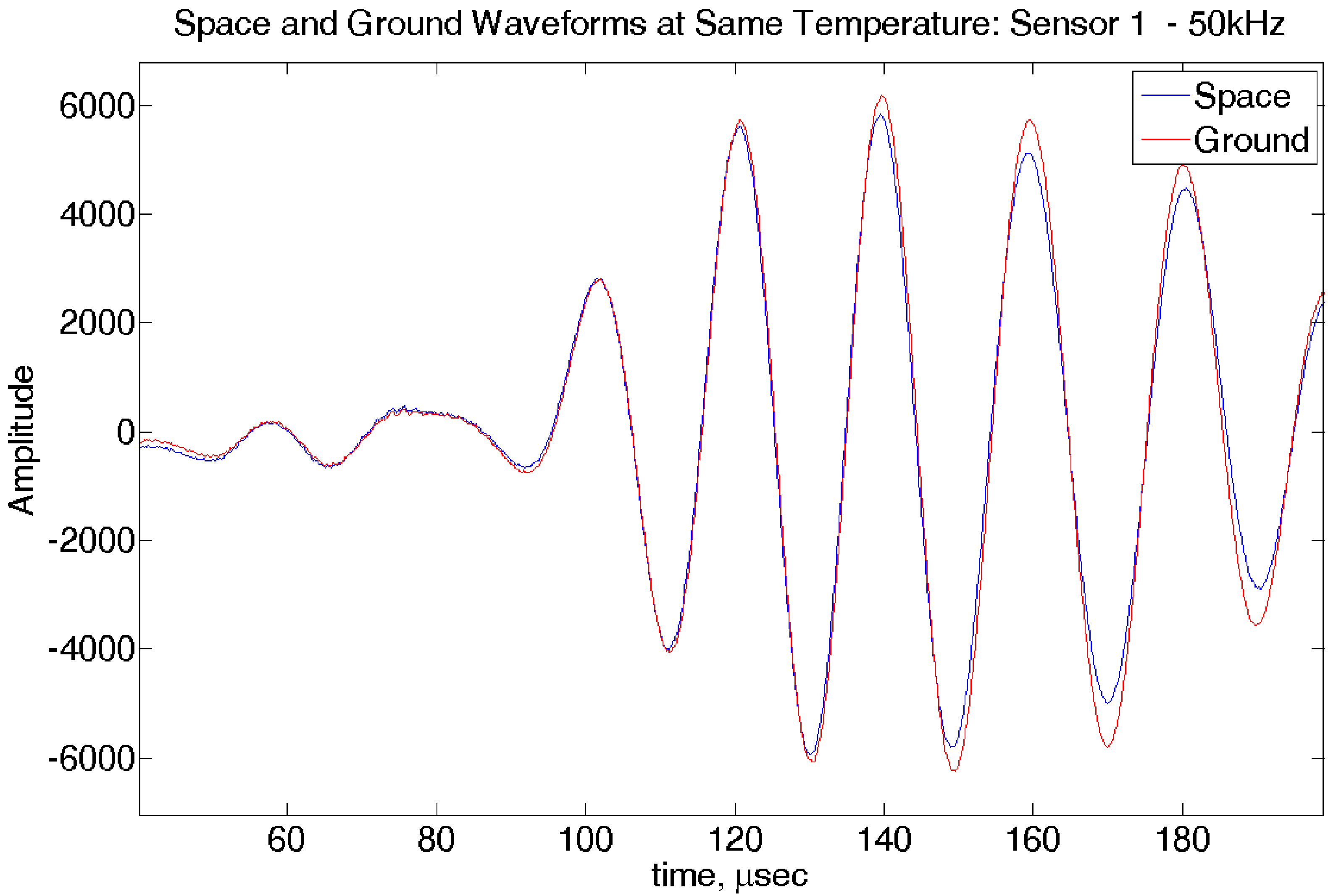
Center of Excellence for Commercial Space Transportation

PreFlight and PostFlight at Same Temp

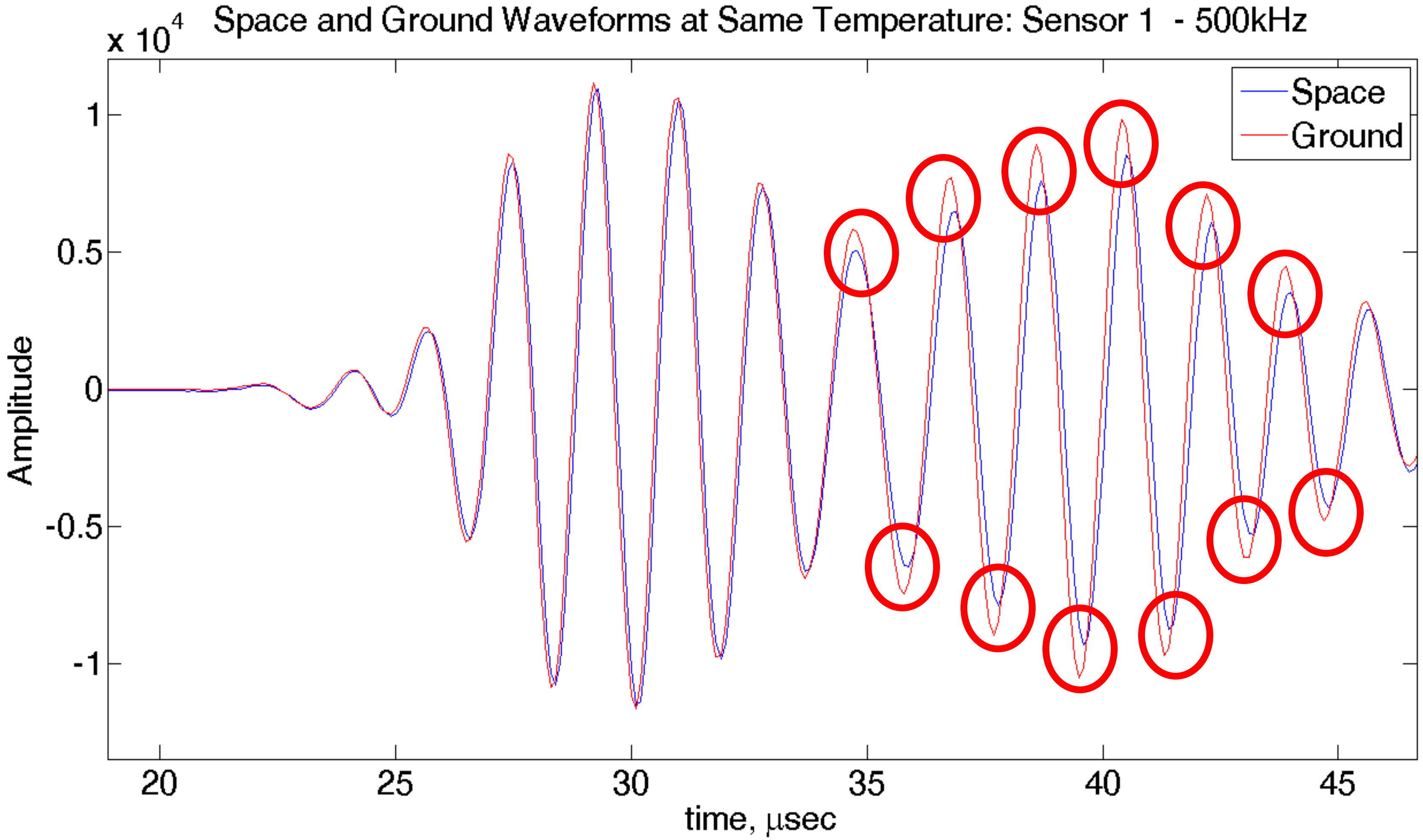
- Two records at 36.6°C, week before and week after space flight.
- Little, if any, permanent shift due to space environment is observed when temperature is accounted for.



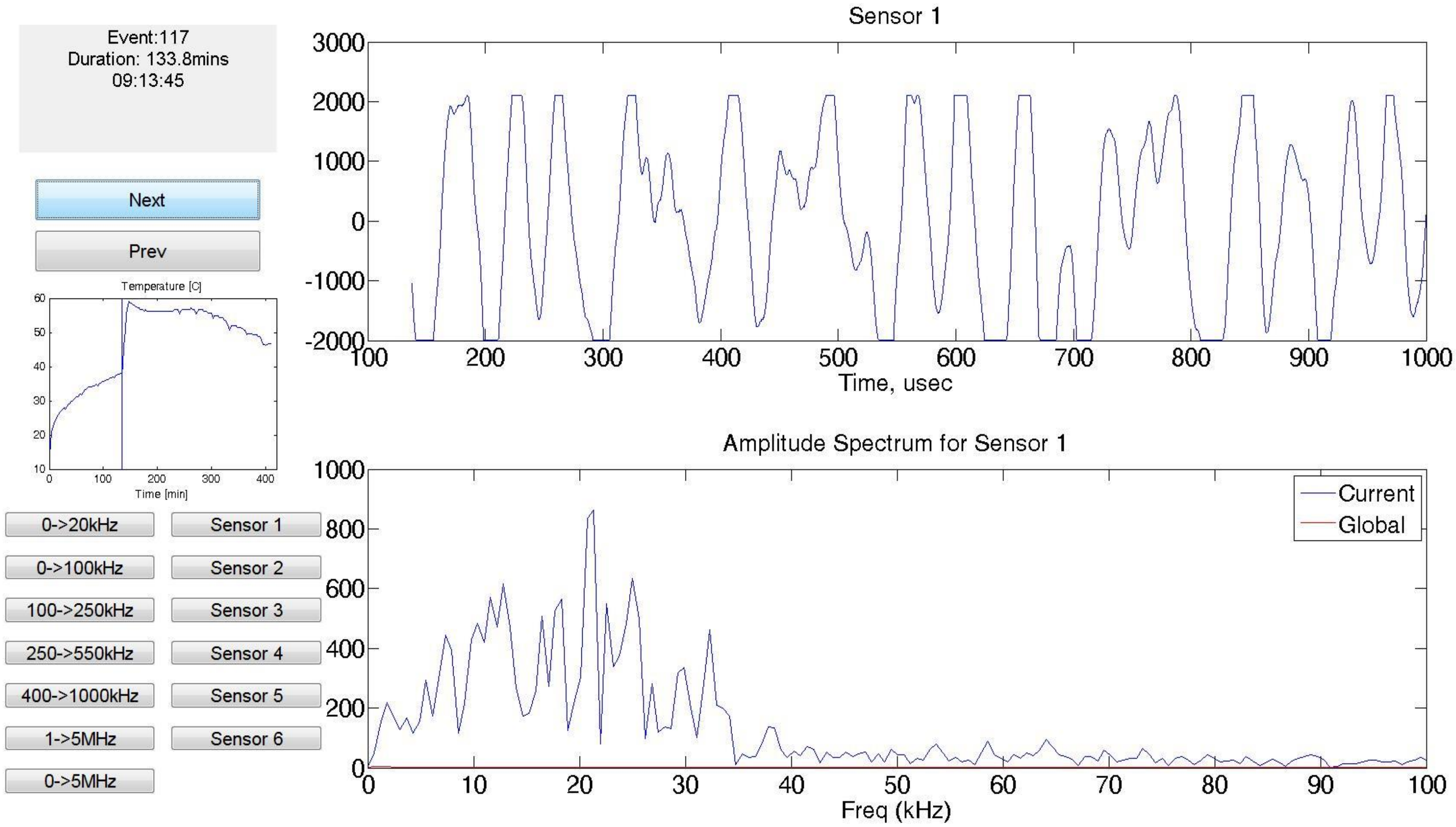
Same Temp 50.79^0 C : 500 kHz waveform



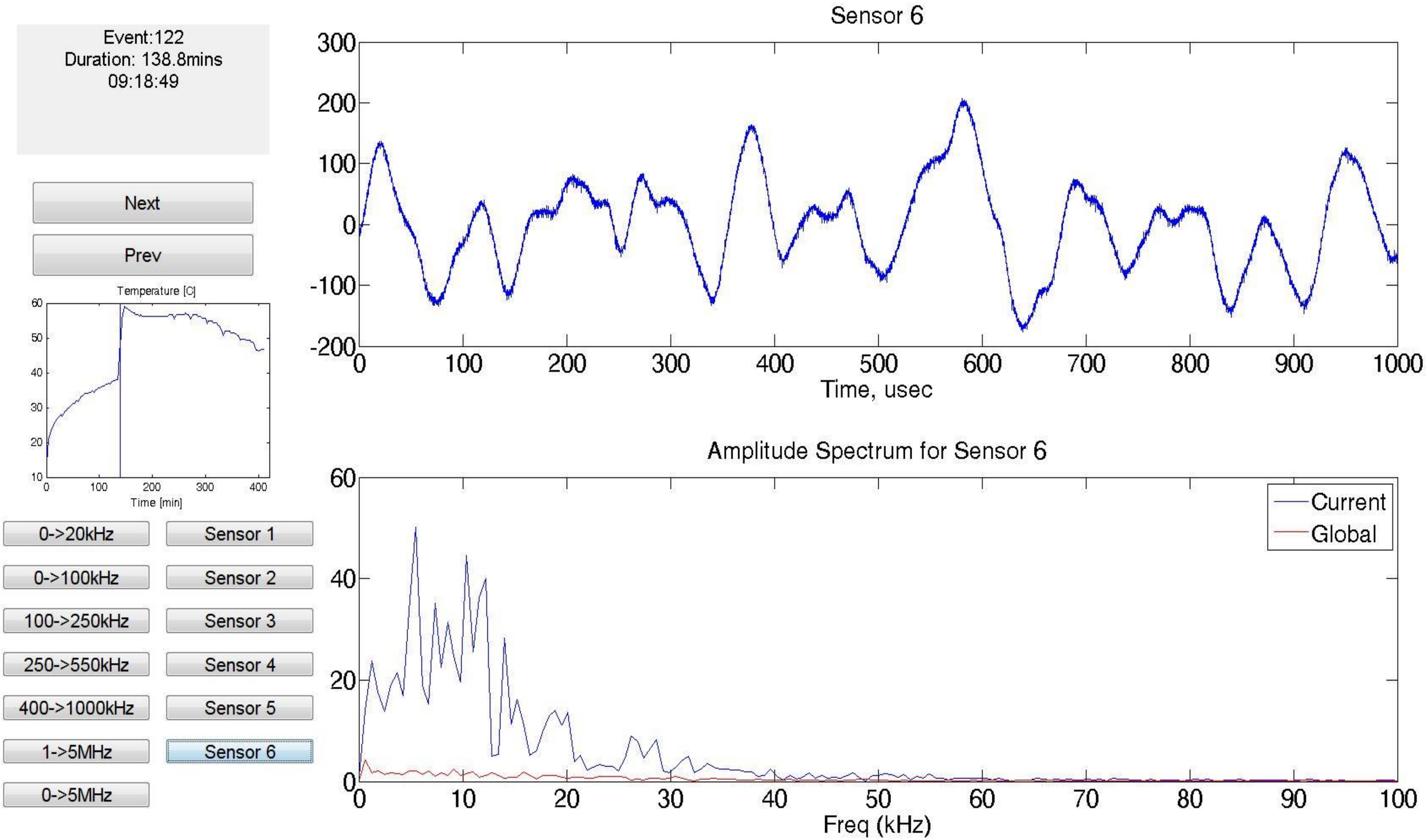
Same Temp 50.79^0 C : 500 kHz waveform



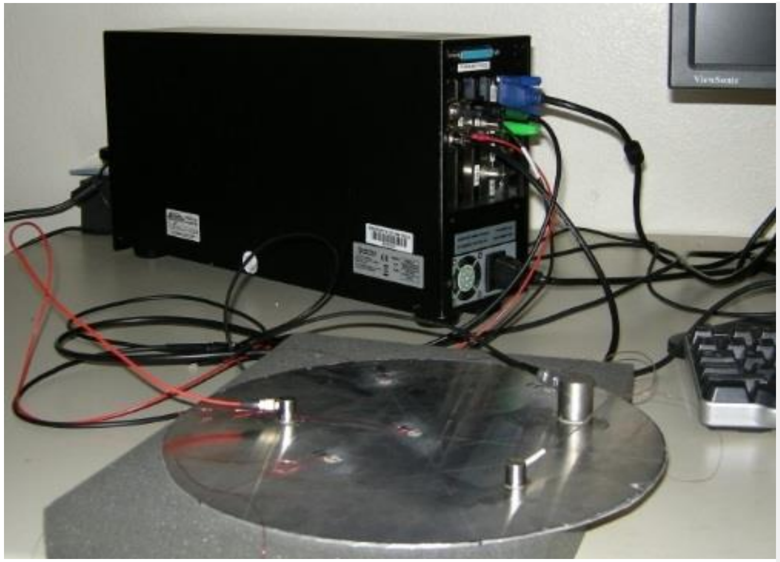
Passive Observations – Booster/Ascent

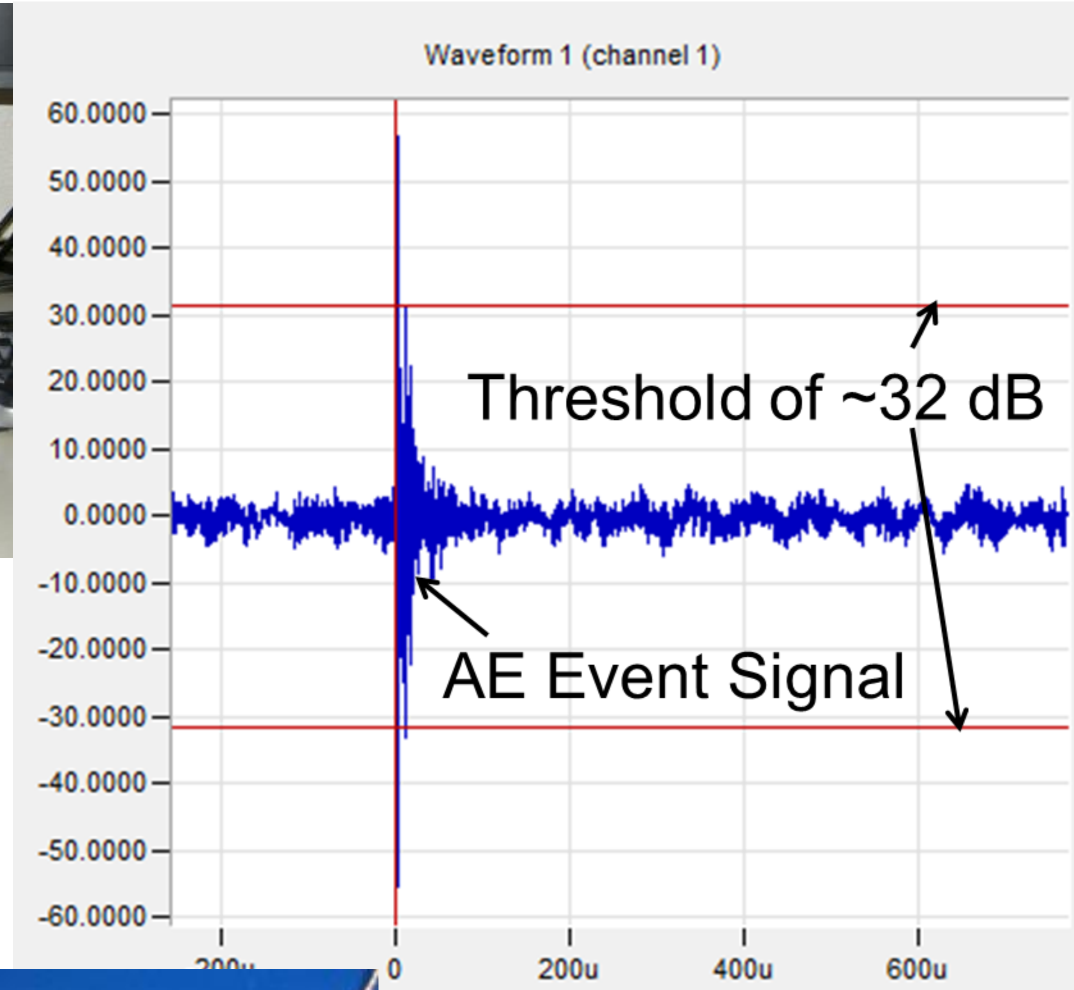


Passive – Drogue/Chute Deployment

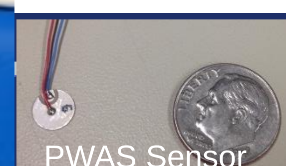


Acoustic Emission Investigations



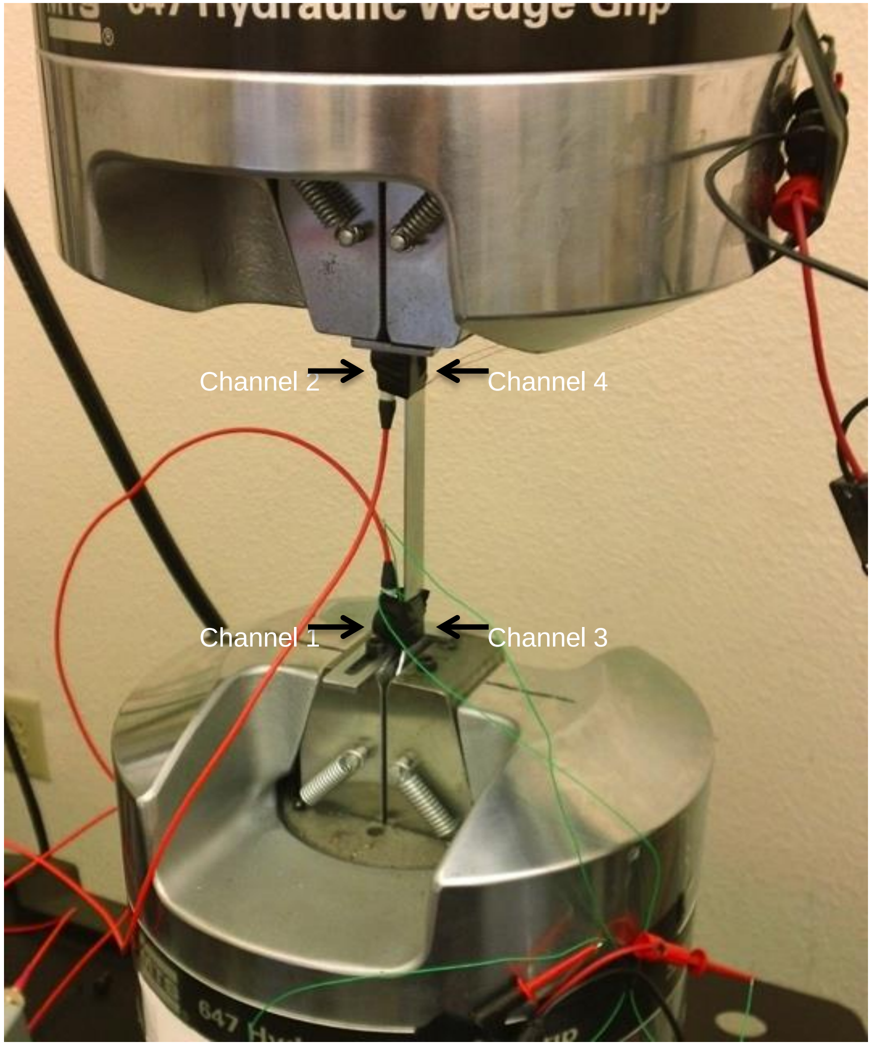


- PWAS and conventional AE sensors were were compared
- PWAS demonstrated utility in recording AE activity, but is more noisy
- New sensor design with shielding options is recommended.



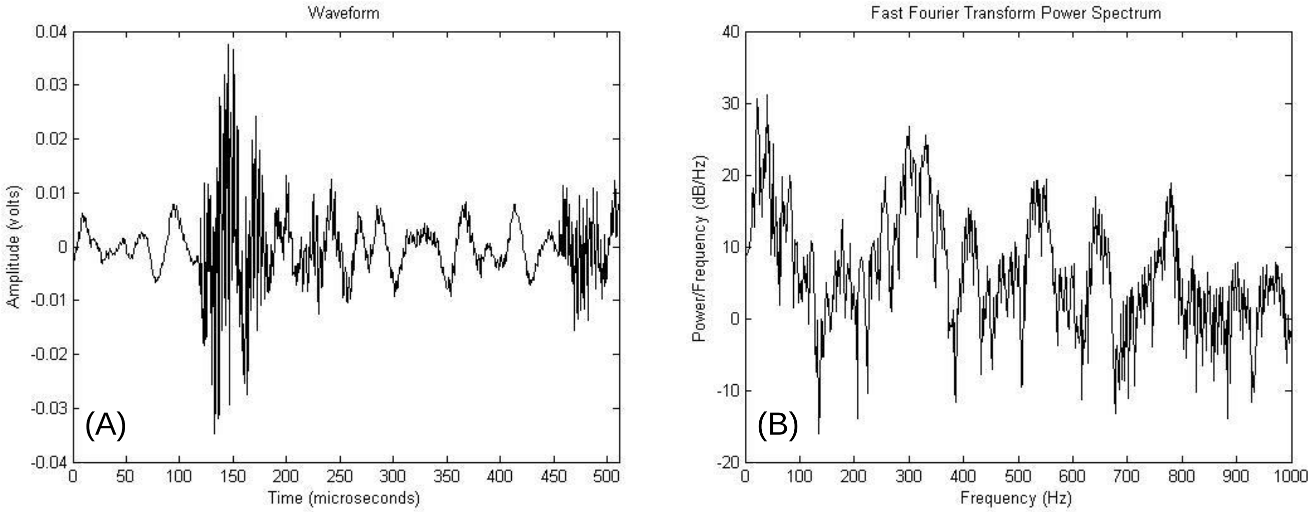
Fatigue Test Parameters

- ASTM Standard 557M-06 aluminum 6061 dog-bone specimens we used
- MTS 810 machine applied 10 Hz harmonic fatigue load
- 2 Micro-80 sensors (CH 1,2) and 2 PWAS (CH 3,4) were tested



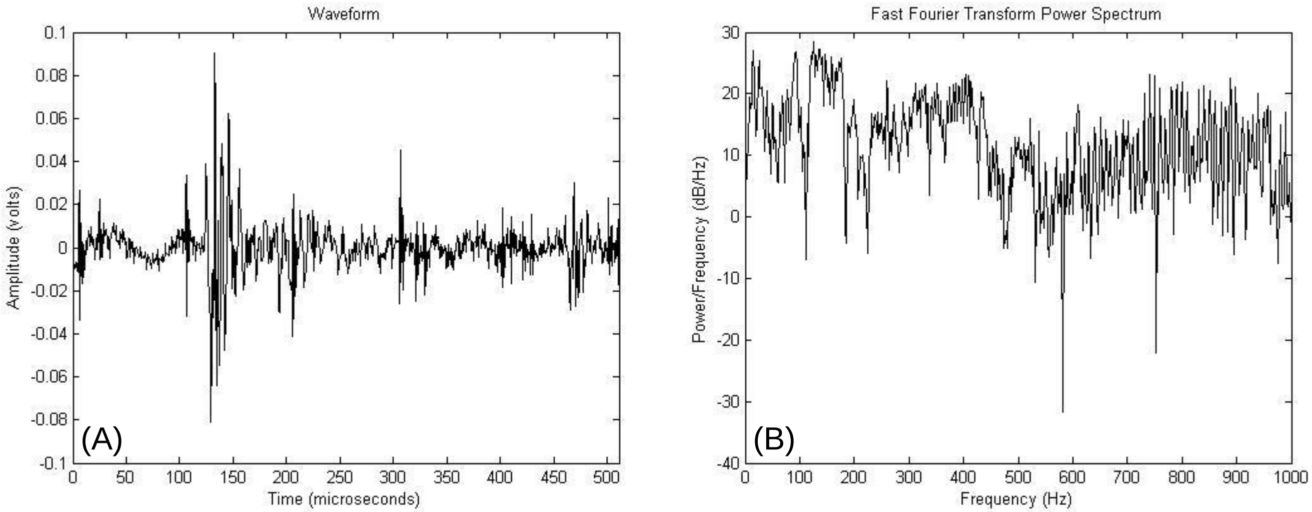
Fatigue Test Waveform Data

Micro-80 Sensor, Ch. 1,2



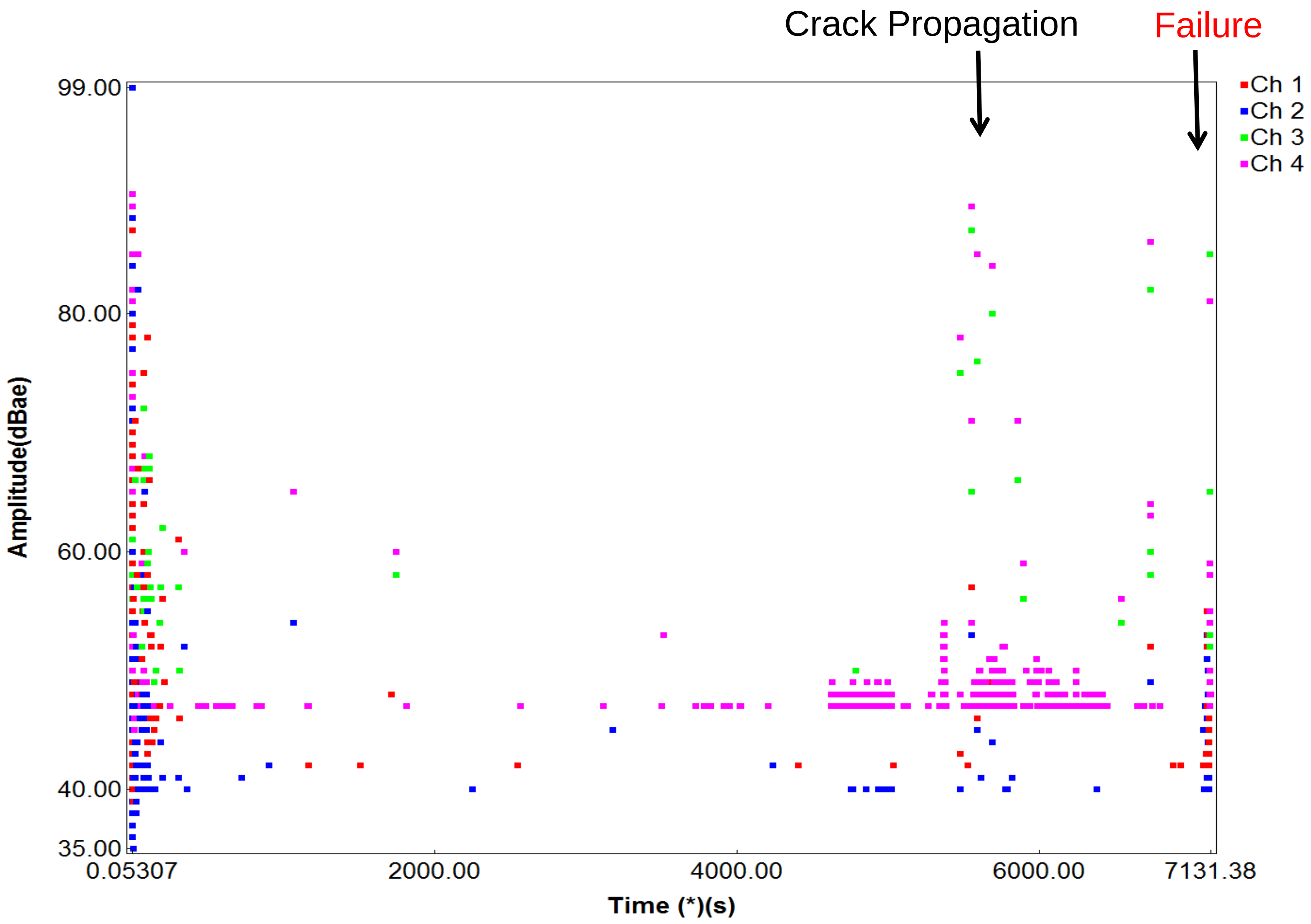
A) Captured Waveform, B) Fast-Fourier Power Spectrum

Piezoelectric Wafer Active Sensor, Ch 3,4



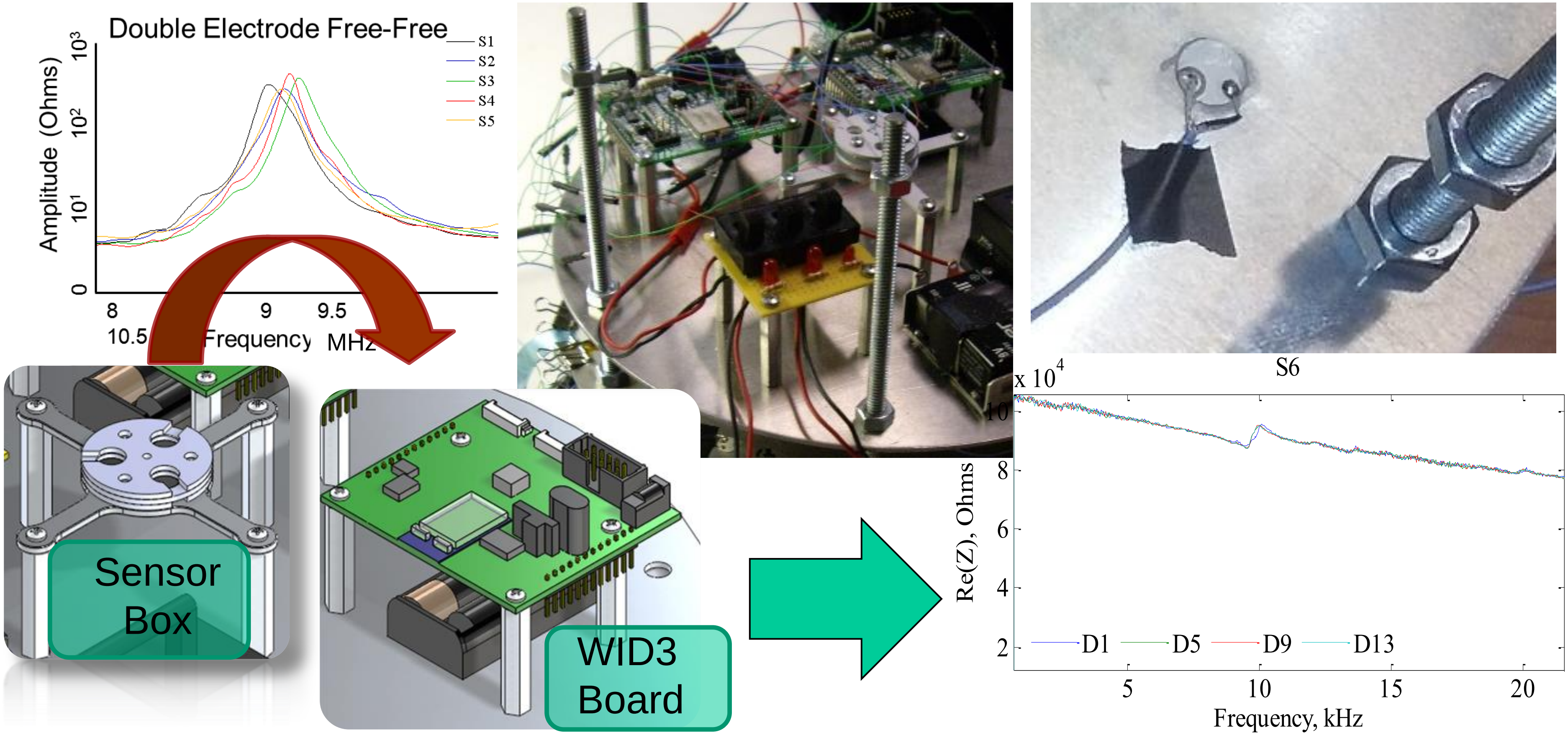
A) Captured Waveform, B) Fast-Fourier Power Spectrum

Fatigue Test Results



Impedance Measurements

- Electro-mechanical impedance measurements using LANL WID-3
  - Sensor characterization in near-space environment
  - Impedance-based SHM



Principles of EMI Method

Structural dynamics stiffness

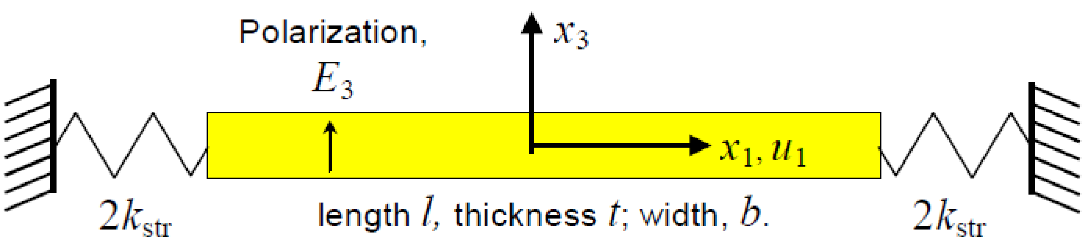
Giurgiutiu, 2000

$$Y(\omega) = \frac{I(\omega)}{V(\omega)} = i\omega \cdot C\left(1 - \kappa_{31}^{2}\left(1 - \frac{1}{\varphi \cot \varphi + r(\omega)}\right)\right) \qquad r(\omega) = \frac{k_{str}(\omega)}{k_{PWAS}^{b}}$$

Admittance

Sensor dynamics

Structural dynamics

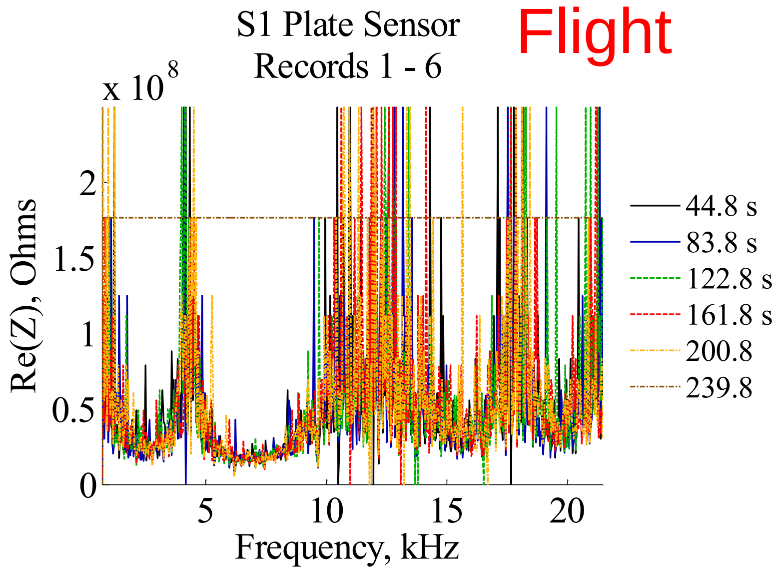


- Structural dynamic characteristics can be obtained through electro-mechanical impedance measurements
- Damage effects are reflected in the structural dynamic stiffness ratio
- Fatigue and other types of damage modify structural stiffness and thus impedance.

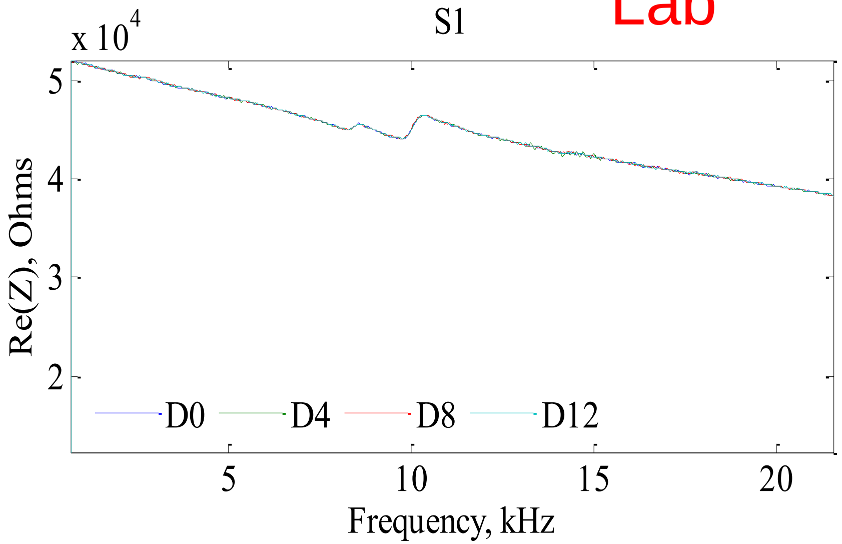
SL-8 Impedance Measurements

Structural Data

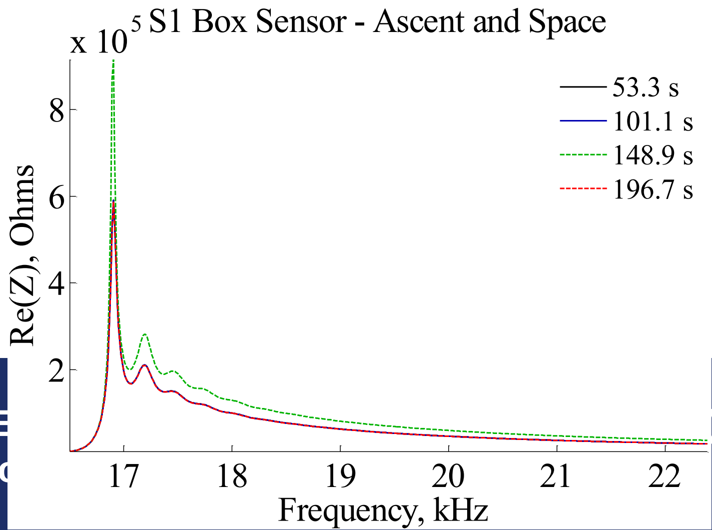
Flight

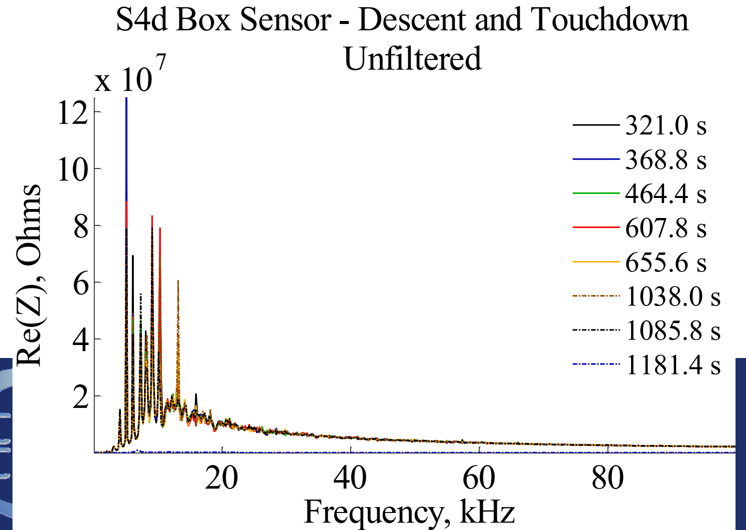


Lab



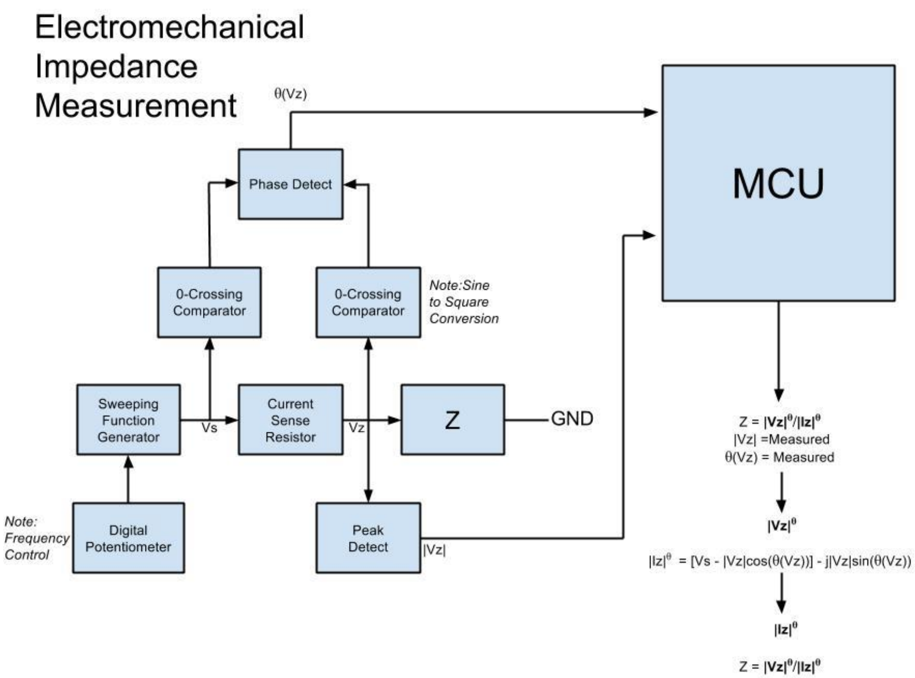
Sensor Data

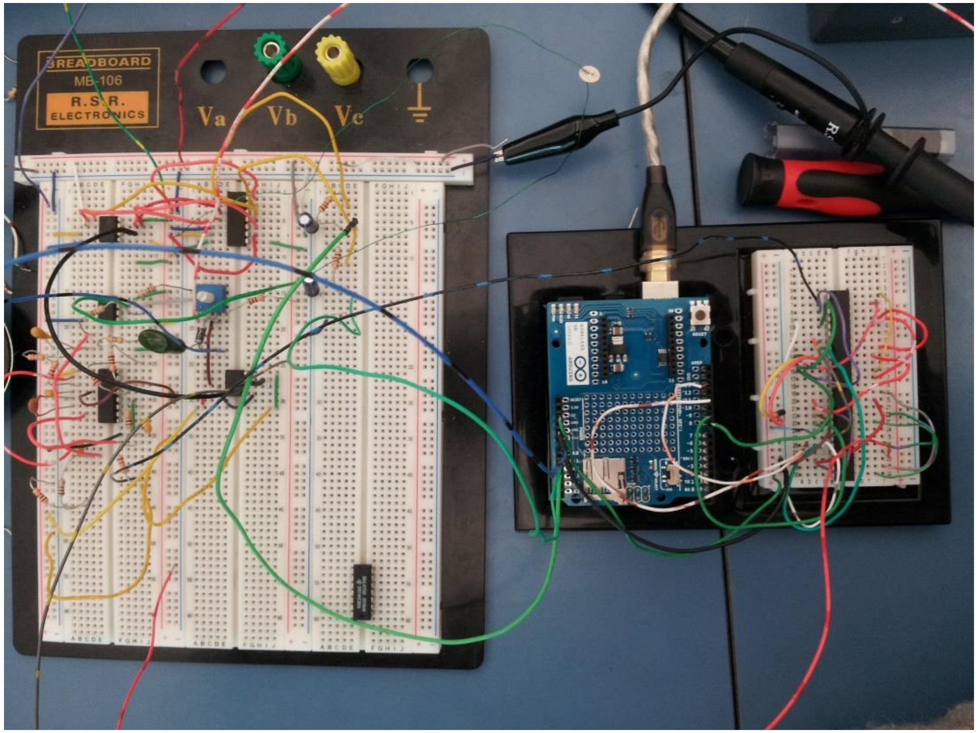




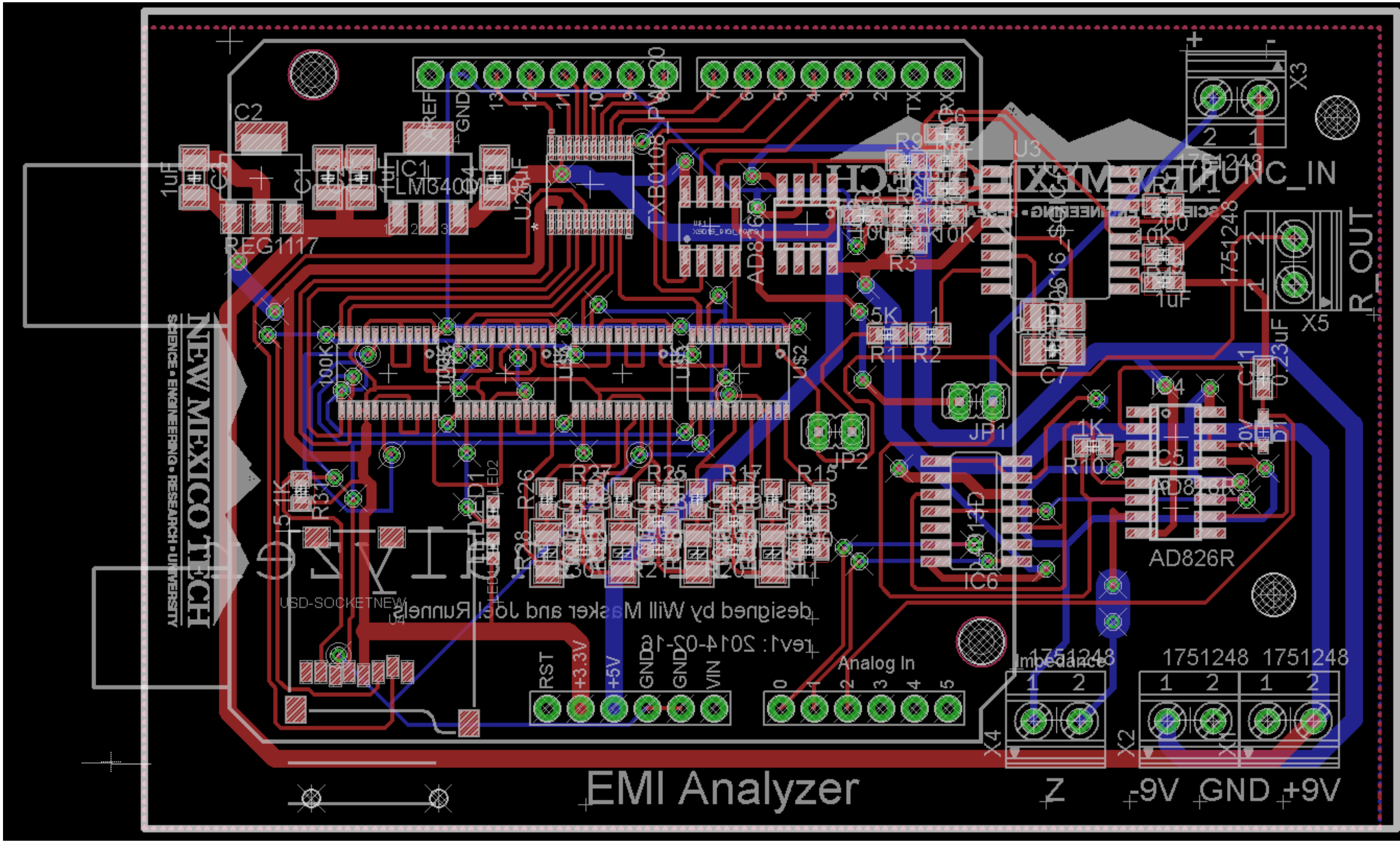
NMT Electro-mechanical Impedance Board

- Reliable impedance (amplitude and phase) measurements in high-altitude and space environments.
- Frequency band up to 0.5 MHz, at least 10 Hz sweep resolution.
- On-board impedance processing, frequency tracking
- Compact, light, and user friendly.



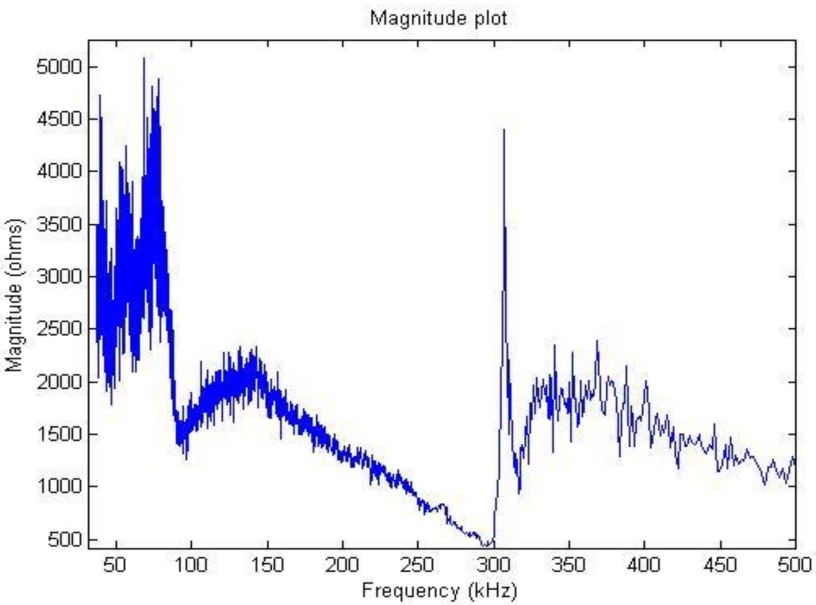


First Circuit Prototype



Piezoelectric Sensor Impedance Measurements

NMT EMI Board

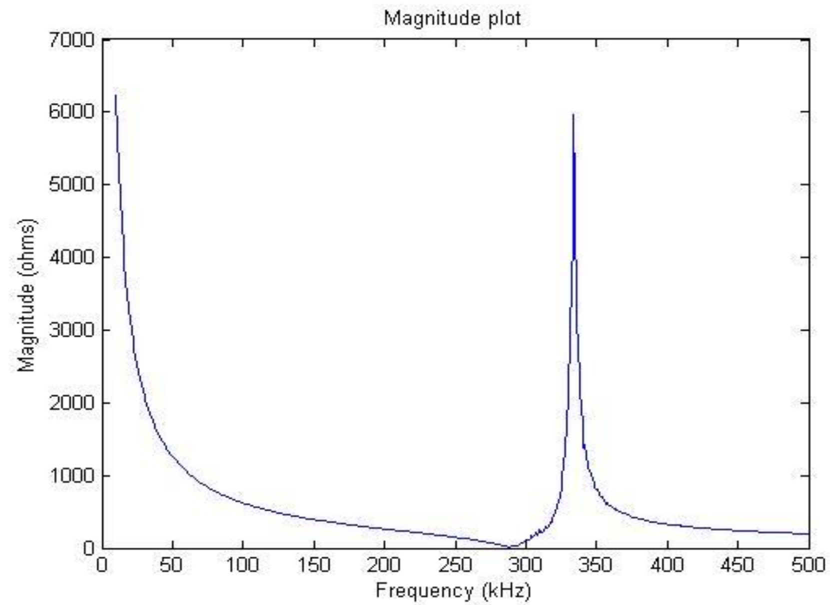


- Resonant Peak at 308 kHz

Potential response corrections:

- Measure Frequency (vs Calculate)
- Linearize Resolution

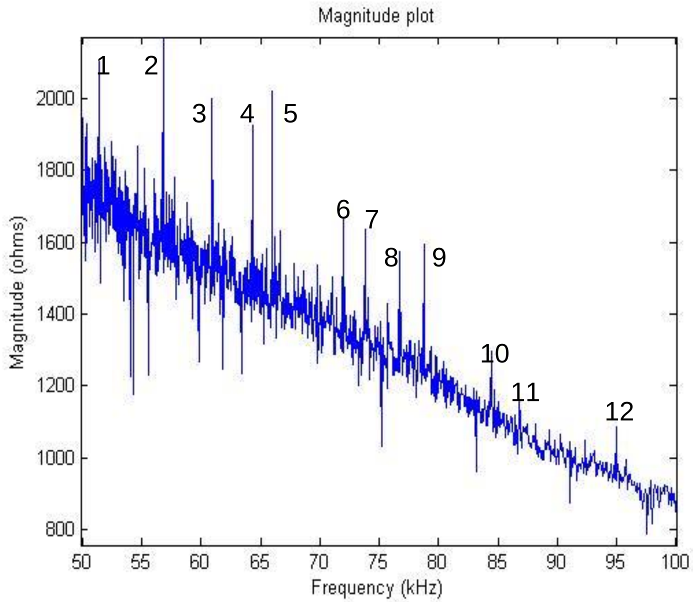
HP 4192A



- Resonant Peak at 334 kHz
- Industry Standard Impedance Analyzer (HP 4192A)

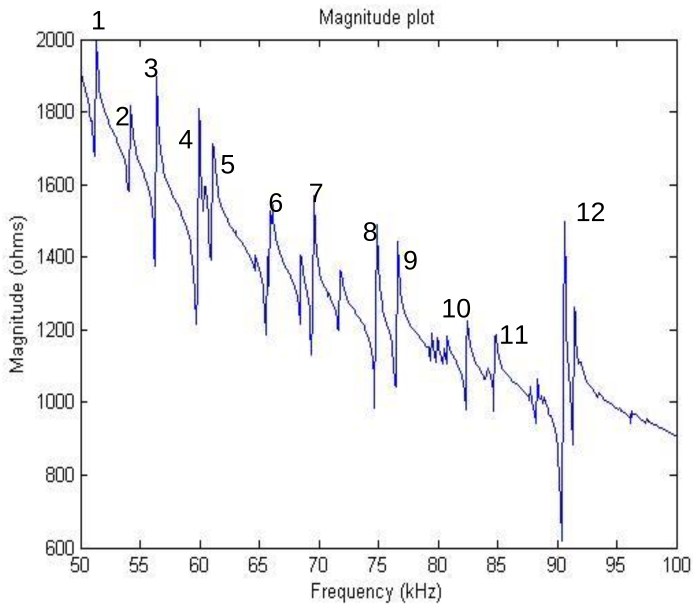
Structural Impedance Measurements

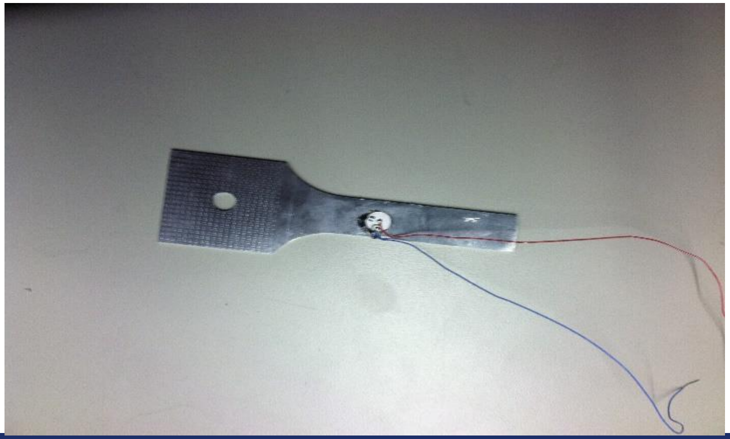
NMT EMI Board



- Points 1-12 show peaks
- Decreasing with freq. noise level
- Lower resolution at end of sweep

HP 4192A





+ and – of the NMT EMI Board

- Advantages
  - Low cost
  - Flexible bandwidth
  - Customizable programming
  - Expandable to provide wireless capabilities
- Disadvantages
  - Bandwidth limited to 500KHz
  - Currently no method to verify excitation frequency
  - Only one impedance measurement port (expandable in future)

Publications/Presentations

- Zagrai, A., (2013) “Structural Health Monitoring in Space and Near-Space Environments”, presentation at EI, EI-K Los Alamos National Laboratory Workshop,5 December 2013, Los Alamos, NM, USA
- Zagrai, A., (2013) “Embedded Ultrasonics – Path From Aircraft to Spacecraft Applications”, keynote presentation on First International Symposium on Aviation Maintenance and Management (ISAMM 2013) & Maintenance Equipment Exhibition, 25-28 November 2013, Xi’an, China.
- Zagrai, A., (2014) “High-frequency Sensor Technology”, presentation at AFOSR Workshop on Microsecond State Monitoring of Multicomponent Structures, 8 April 2014, Niceville, Florida 32578-1295
- Masker, W., Runnels, J., and Zagrai, A., (2014) “Small-factor Electromechanical Impedance Measurement Board for Space Applications”, presentation at SPIE's 21th Annual International Symposium on Smart Structures and Materials + NDE for Health Monitoring and Diagnostics, 9 - 13 March 2014, CA
- Trujillo, B. and Zagrai, A., (2014) “Monitoring of Acoustic Emission Activity using Thin Wafer Piezoelectric Sensors”, paper at SPIE's 21th Annual International Symposium on Smart Structures and Materials + NDE for Health Monitoring and Diagnostics, 9 -13 March 2014, CA
- Zagrai, A, Cooper, B., Schlavin, J., Clemens, R., White, C., Kessler, S., (2014) “Assessing structural condition during suborbital space flight,” Technical presentation at ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, September 9, 2014, Newport, RI, presentation: SMASIS2014-7726.

Conclusions

- Commercial hardware (wave propagation, wireless) ran entire suborbital flight. Impedance hardware malfunctioned. Camera batteries discharged.
- Passive acoustic emission correlated with mechanical events during flight.
- Damage (crack and loose bolt) was detectable at all stages of flight
- Temperature has major influence on wavespeed
- The **first anti-symmetric mode (A0) appears to be modified** between space and ground, even with matched temperature. Symmetric mode (S0) appears unchanged in both
- Fatigue studies demonstrated feasibility of using embeddable piezoelectric sensors for Acoustic Emission monitoring.
- Compact EMI measurement board is under development

Acknowledgements

- FAA, NASA, AFOSR for support
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- Metis Design and LORD Microstrain for collaboration on measurement hardware and assistance with tests.
- UPAerospace and Near Space Corporation for payload integration, launch and recovery.

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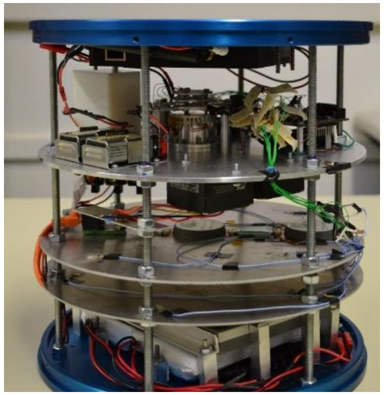
TASK 228: MAGNETO-ELASTIC SENSING FOR STRUCTURAL HEALTH MONITORING



PROJECT AT-A-GLANCE

- UNIVERSITY: New Mexico Tech
- PRINCIPAL INVESTIGATOR:
  Dr. Andrei Zagrai and Dr. Warren Ostergren.
- STUDENTS: Blaine Trujillo (MS),
  Joel Runnels (UG) and William Masker (UG)

RELEVANCE TO COMMERCIAL SPACE INDUSTRY

The benefits of SHM for space vehicles include: pre-launch diagnostic, monitoring during launch and/or re-entry, in-orbit structural verification and structural assessment for rapid re-launch.

STATEMENT OF WORK

- Demonstrate utility of various SHM strategies during suborbital space flight
- Investigate potential of magneto-elastic active sensors and embeddable thin wafer piezoelectric sensors to record acoustic emission activity due to structural fatigue and thermal damage
- Develop portable hardware for electro-mechanical impedance measurements in space environment.

STATUS

- 038S NASA FOP Flight completed & analyzed
- Acoustic emission measurements of fatigue damage is explored. PWAS AE validated.
- Development of portable EMI board started

FUTURE WORK

- Electro-mechanical impedance manifestation of dynamic behavior of bolted joints
- Modeling of temperature effects on electro-mechanical impedance