COE CST Third Annual Technical Meeting:

Task 228: Magneto-Elastic Sensing for Structural Health Monitoring

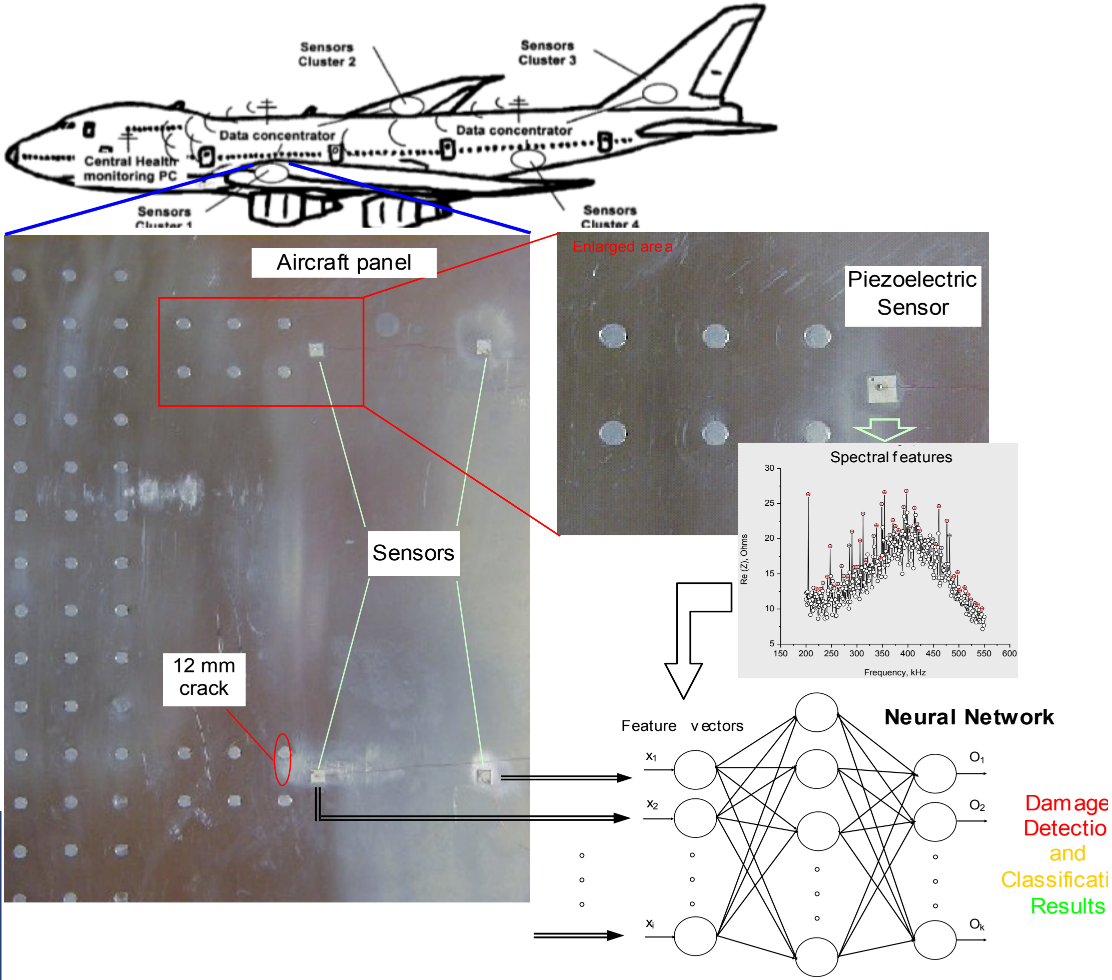
Andrei Zagrai and Warren Ostergren

29 October 2013

COE CST

Center of Excellence for Commercial Space Transportation

Aircraft Structural Condition Assessment

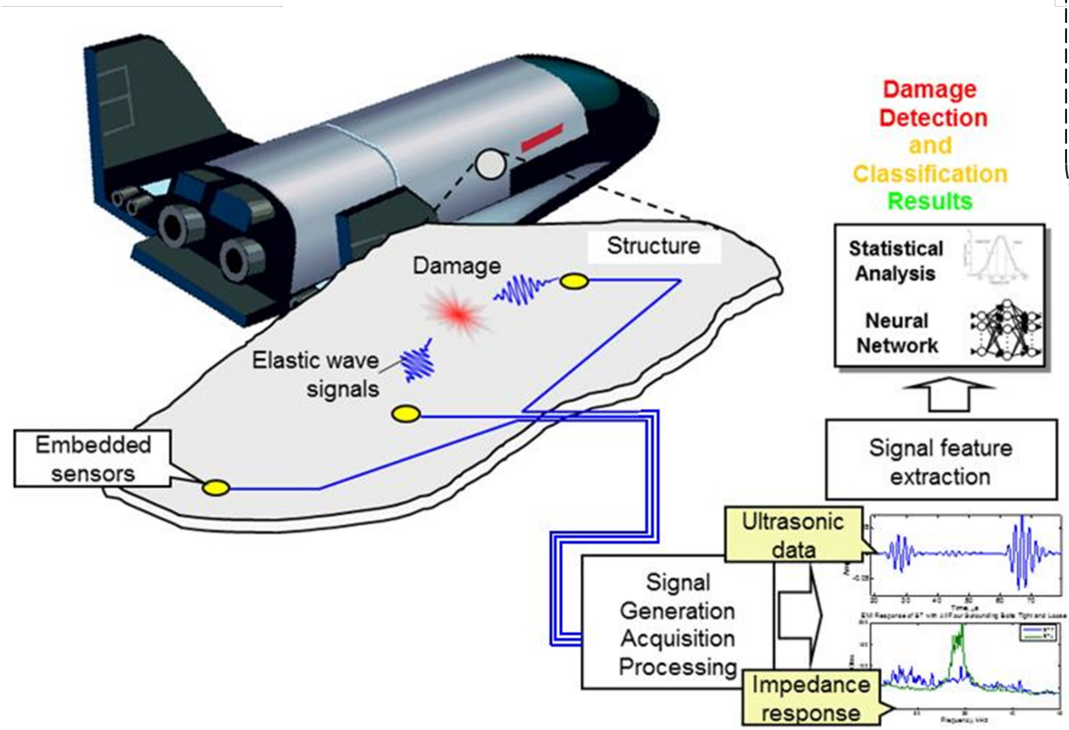


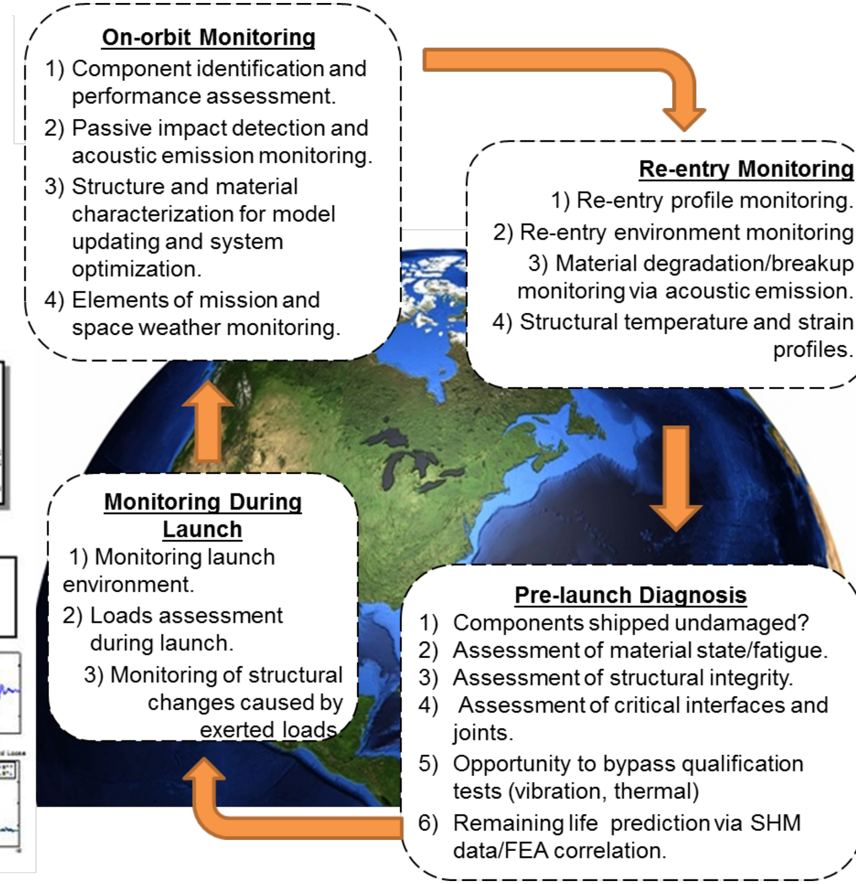
- PAST/CURRENT
  - Pre-flight critical components assessment
  - In-flight data (control, voice, communication, altitude, etc.) recording in "black box"
  - Mandatory periodic inspections (often manual) of structural elements (downtime!)
- +CURRENT/FUTURE
  - In-flight video
  - Improved inspections (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?

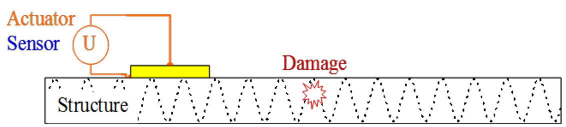
Flight Safety: Certification/anomaly detection



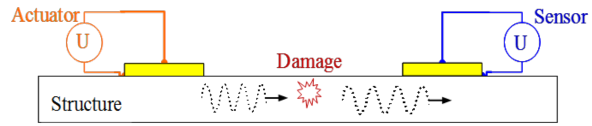


SHM Strategies for Commercial Space Vehicles

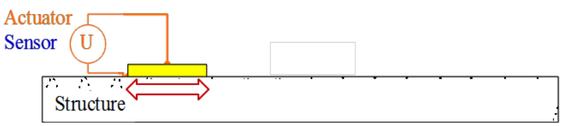
Electro- mechanical impedance



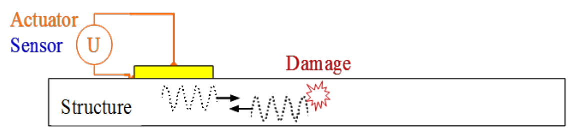
Wave propagation: Pitch-catch method



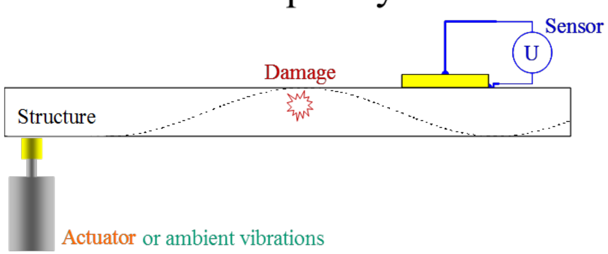
Dynamic strain measurement



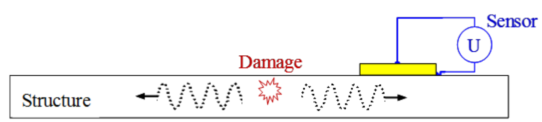
Wave propagation: Pulse-echo method



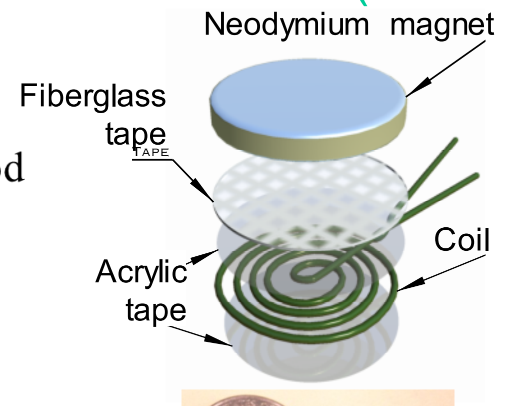
Low frequency vibrations



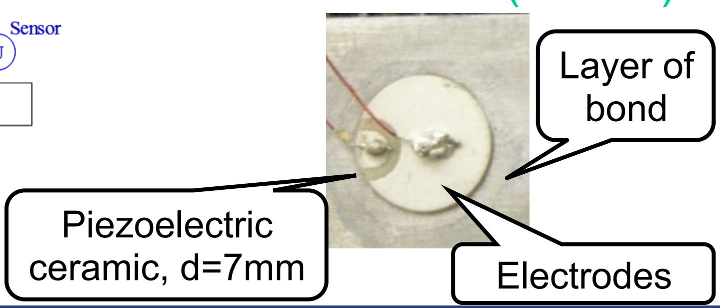
Acoustic emission



Magneto-elastic Active Sensor (MEAS)



Piezoelectric Wafer Active Sensor (PWAS)



Focus on appropriate sensors + off-the-shelf hardware

Purpose of Task

- Demonstrate utility of various SHM strategies during high altitude stratospheric balloon 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 guidelines for sensor installation and measurement procedures in acoustic emission SHM of space vehicles.

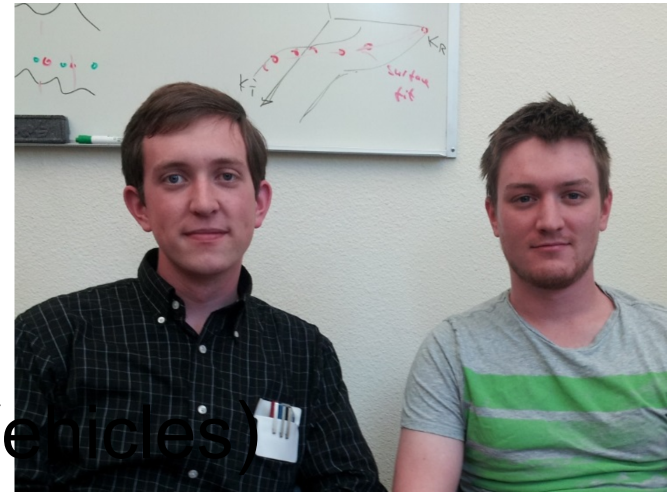
Team Members

Task 228 NMT Team

- Jaclene Gutierrez (UG ME)(Graduated)
- Daniel Meisner (GR ME) (Graduated)
- David Conrad (GR ME) (Graduated)
- Joel Runnels & William Masker (UG ME/EE)
- 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)

News & Features

- News Topics
- News Releases
- Media Resources
- Speeches
- Budgets & Plans
- Reports

Feature

Text Size Tweet 9 Like 8 Pin it

NSC High-Altitude Balloon Lofts Multi-Agency Space-Technology Payload 02.19.13

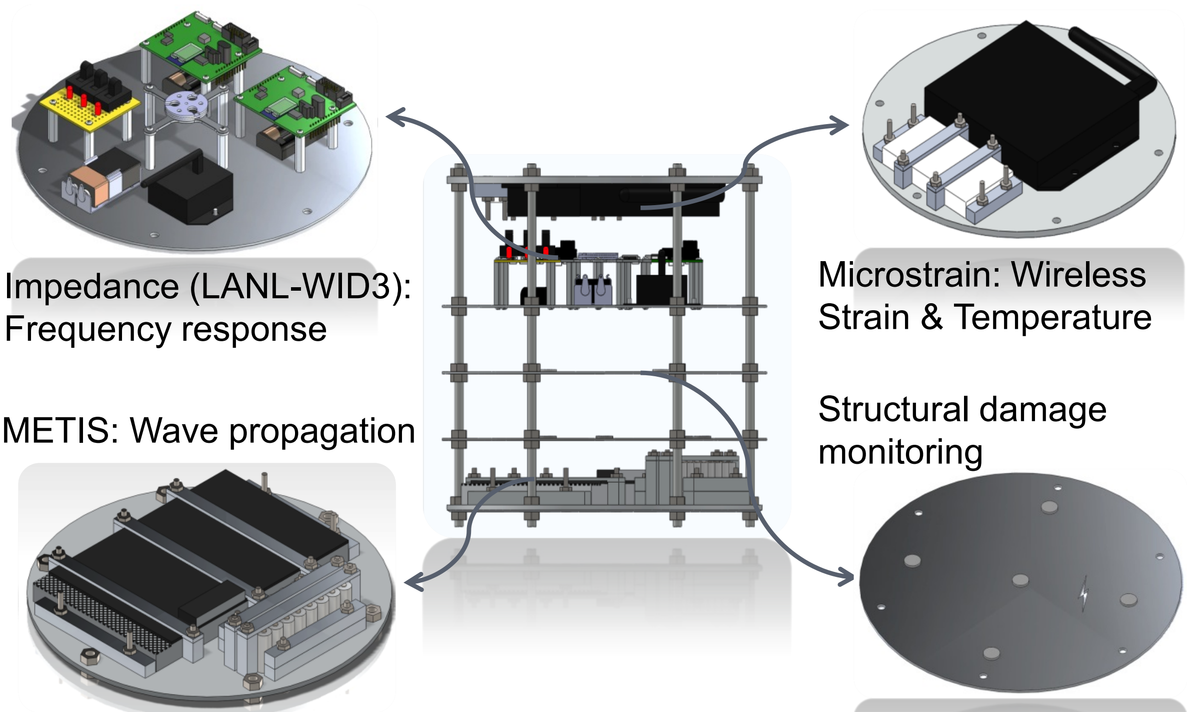
With snow-capped Mt. Jefferson in the Cascade Range providing the backdrop, the NSC balloon carrying the NMT prototype data acquisition payload begins its ascent from the Madras, Ore., airport. (NASA / Bruce Webbon) › View Larger Image

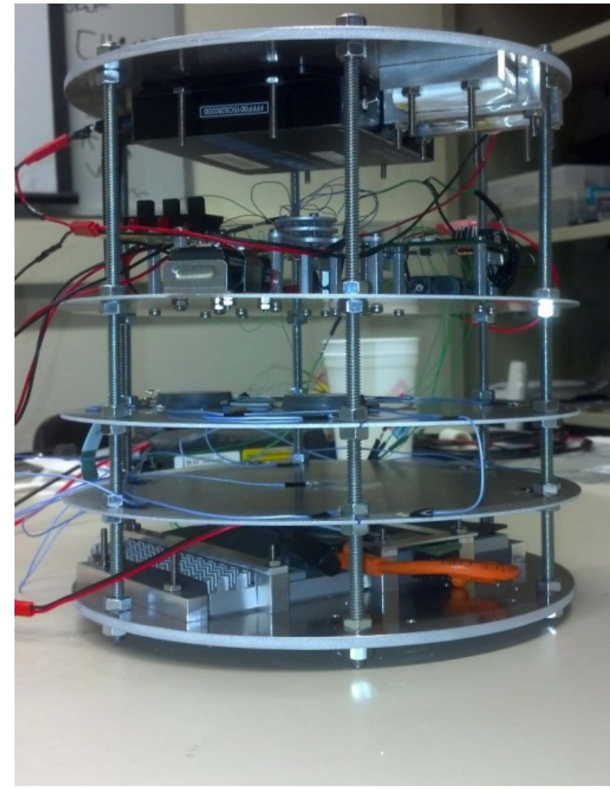
NASA's Flight Opportunities Program marked its first high-altitude balloon payload flight recently when one of the program's flight providers, Near Space Corporation (NSC) of Tillamook, Ore., launched a developmental

Structural Condition Assessment Payload

EXP 5: Electro-mechanical impedance structural dynamic measurements

EXP 6: Wireless strain and temperature sensing

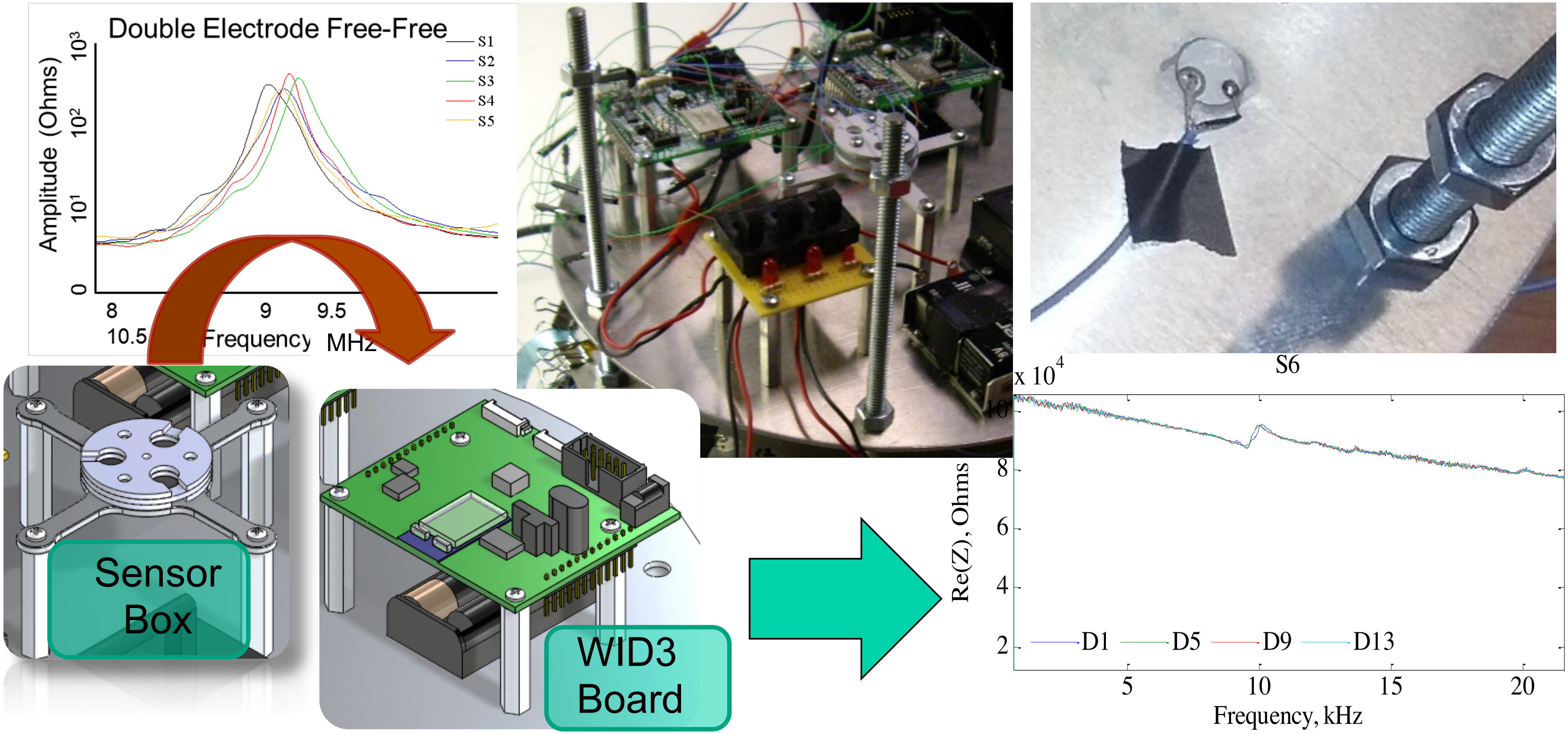




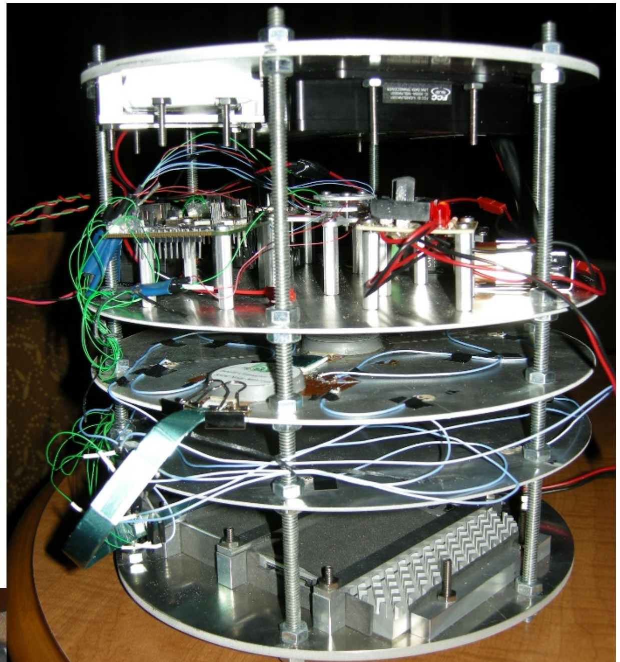
EXP 1: Structural sound speed measurements
EXP 2: Crack detection
EXP 3: Loose bolt detection
EXP 4: Acoustic emission (AE) measurements

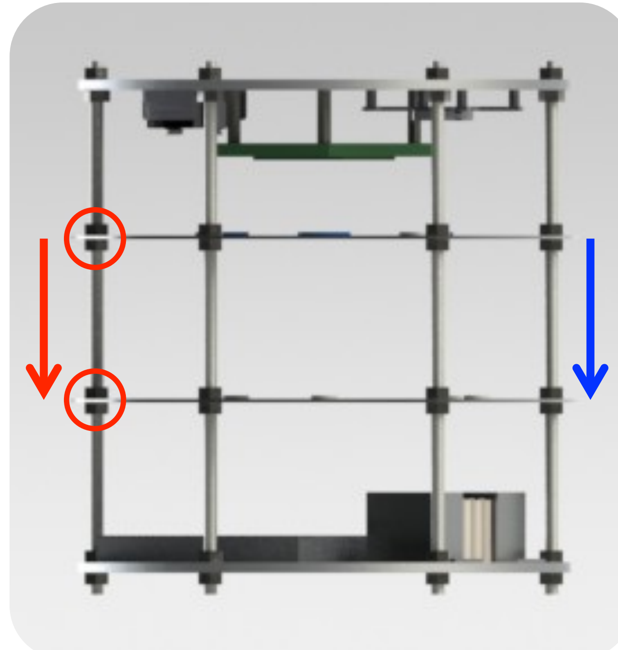
Impedance Measurements

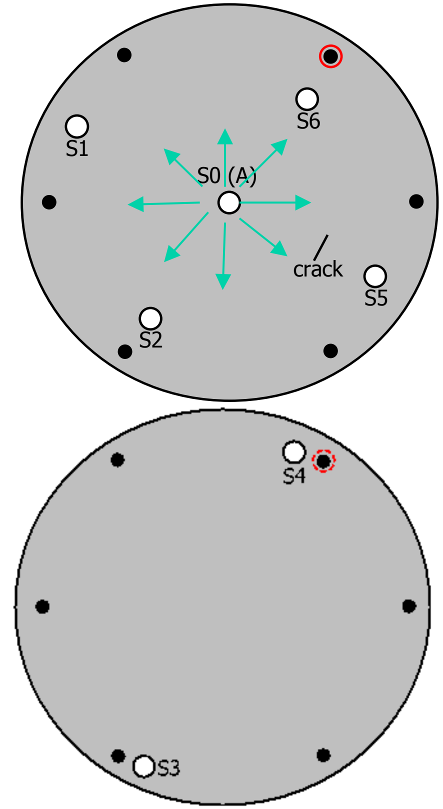
- Electro-mechanical impedance measurements using LANL WID-3
  - Sensor characterization in near-space environment
  - Impedance-based SHM



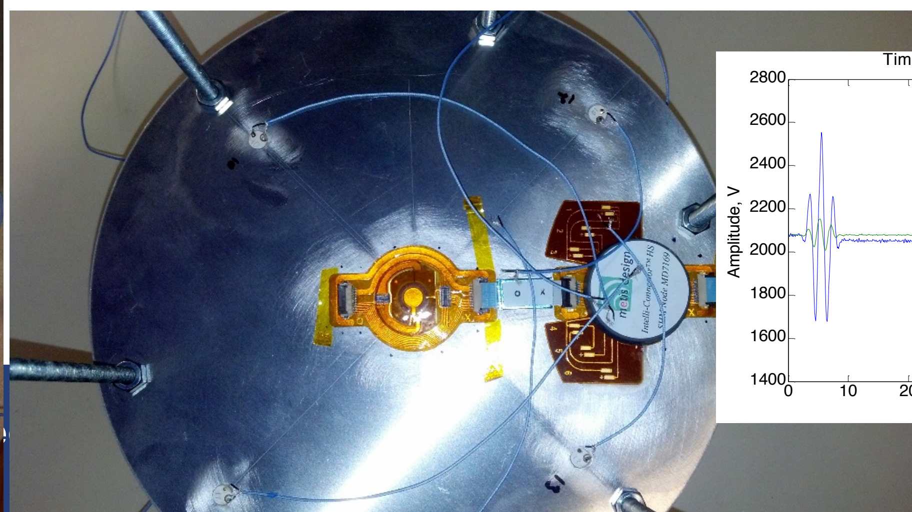
Wave Propagation (SHM & Sound Speed)

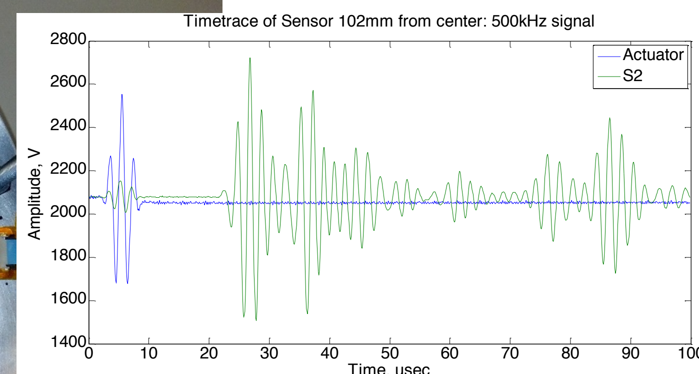






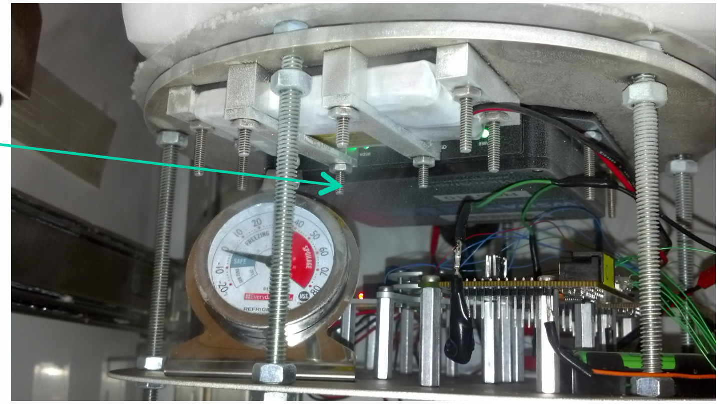
Metis Design hardware

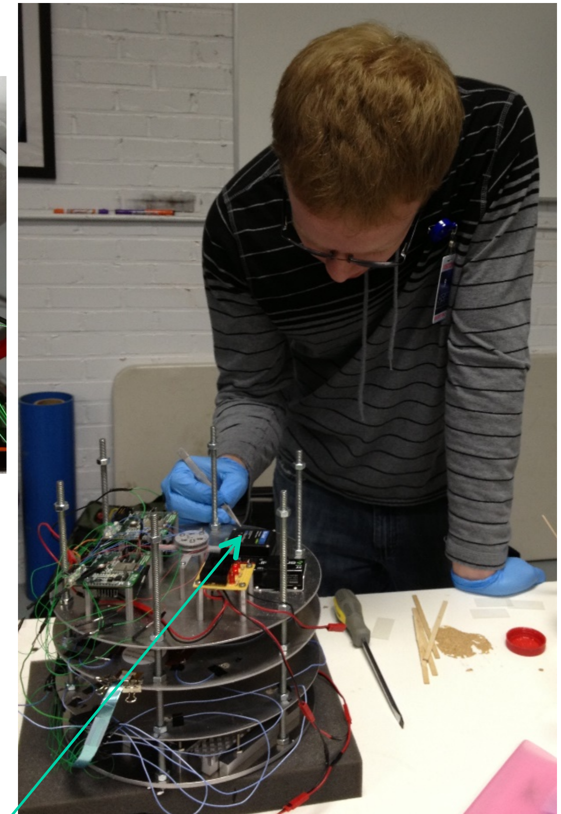


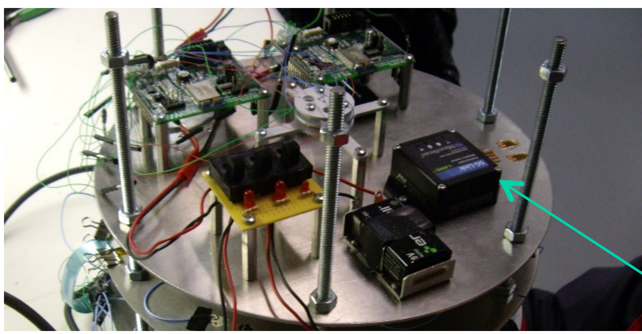


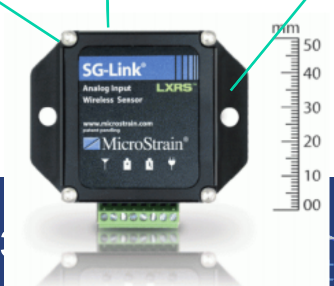
ce for
Transportation

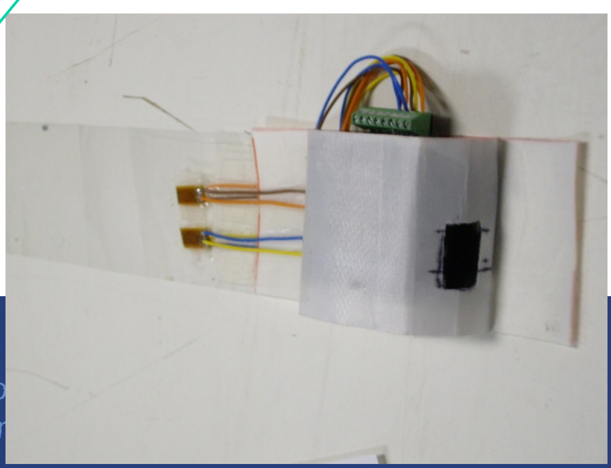
Wireless Hardware (Strain & Temperature)





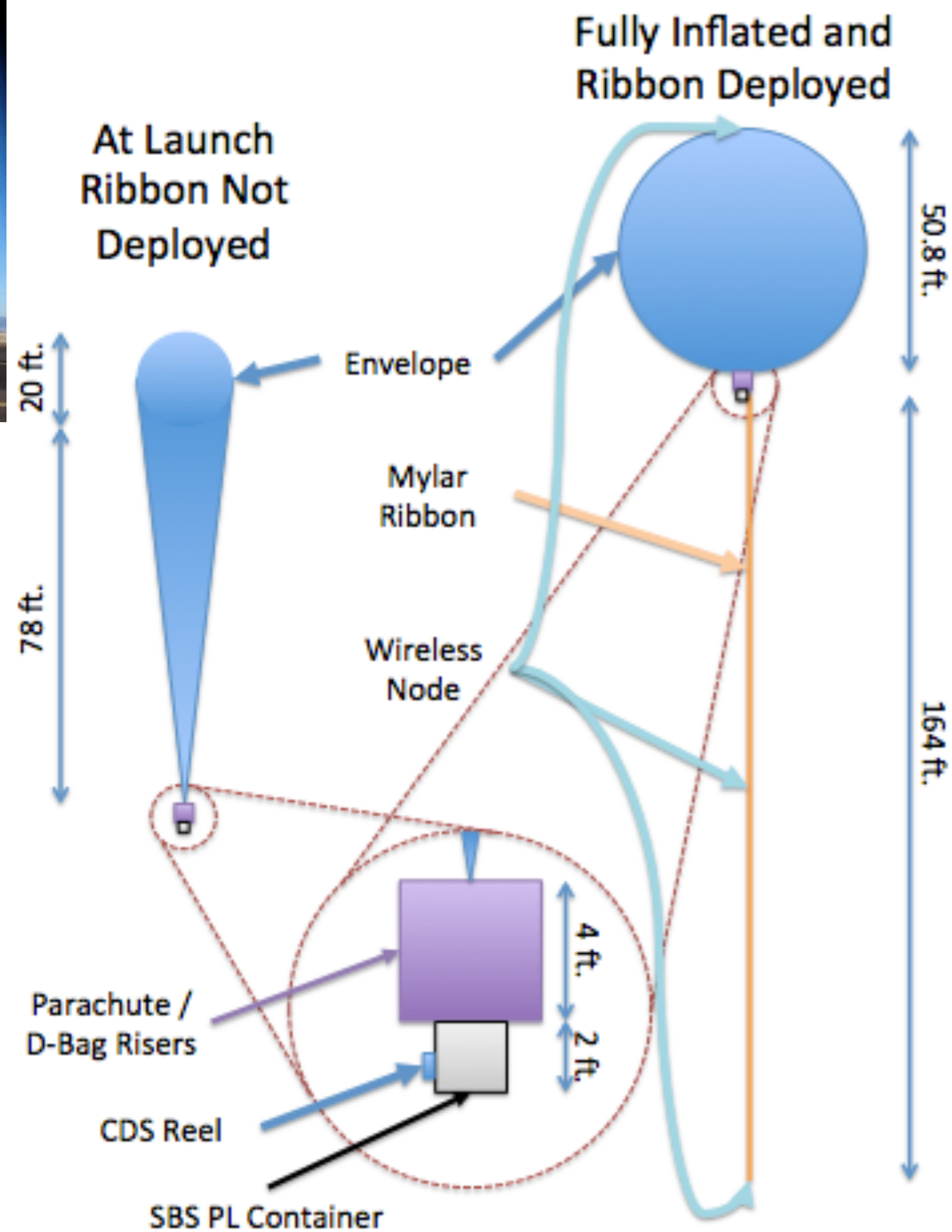






LORD MicroStrain® Wireless Sensor Data Aggregator (WSDA)
Four SG-Link -LXRS 3 Channel Wireless Analog Sensor Node (about 50 grams each)
120Ω foil strain gauges connected in Full Wheatstone bridge configurations
256 Hz synchronous sampling

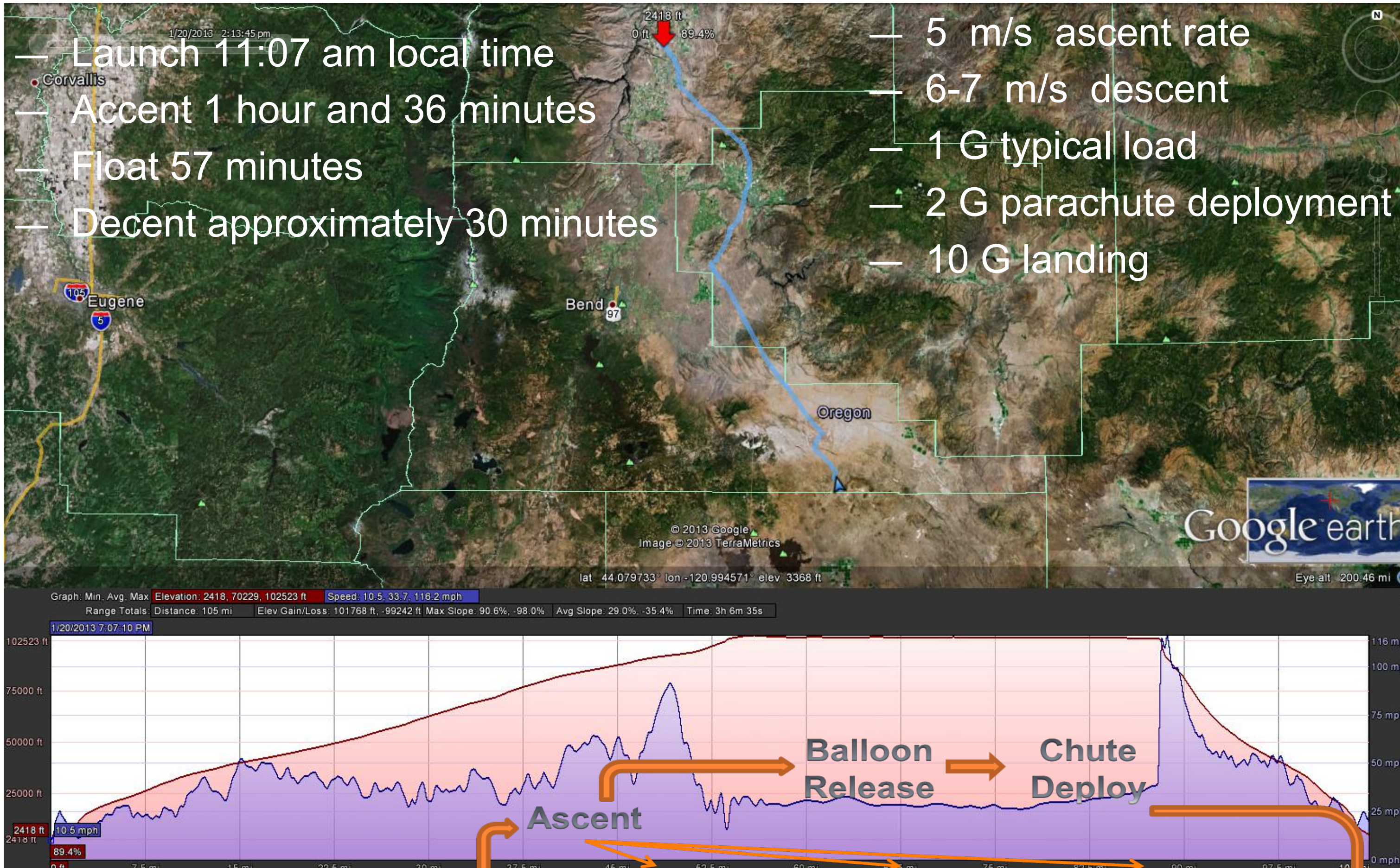
Balloon / Payload / Ribbon



Flight Profile

- Launch 11:07 am local time
- Accent 1 hour and 36 minutes
- Float 57 minutes
- Decent approximately 30 minutes

- 5 m/s ascent rate
- 6-7 m/s descent
- 1 G typical load
- 2 G parachute deployment
- 10 G landing



Troposphere
- 0 -> 11 km
- 15ºC -> -55ºC

Tropopause
- 11 -> 20 km
- -55ºC

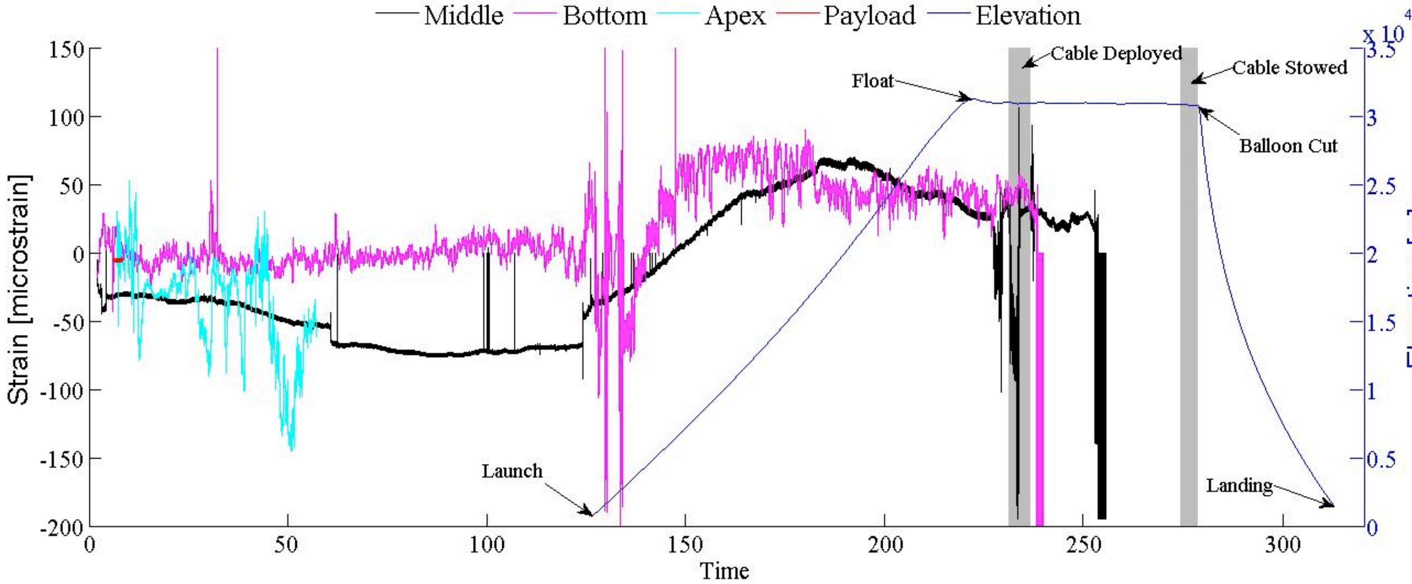
Stratosphere
- 20km & up
- -55ºC -> -46ºC

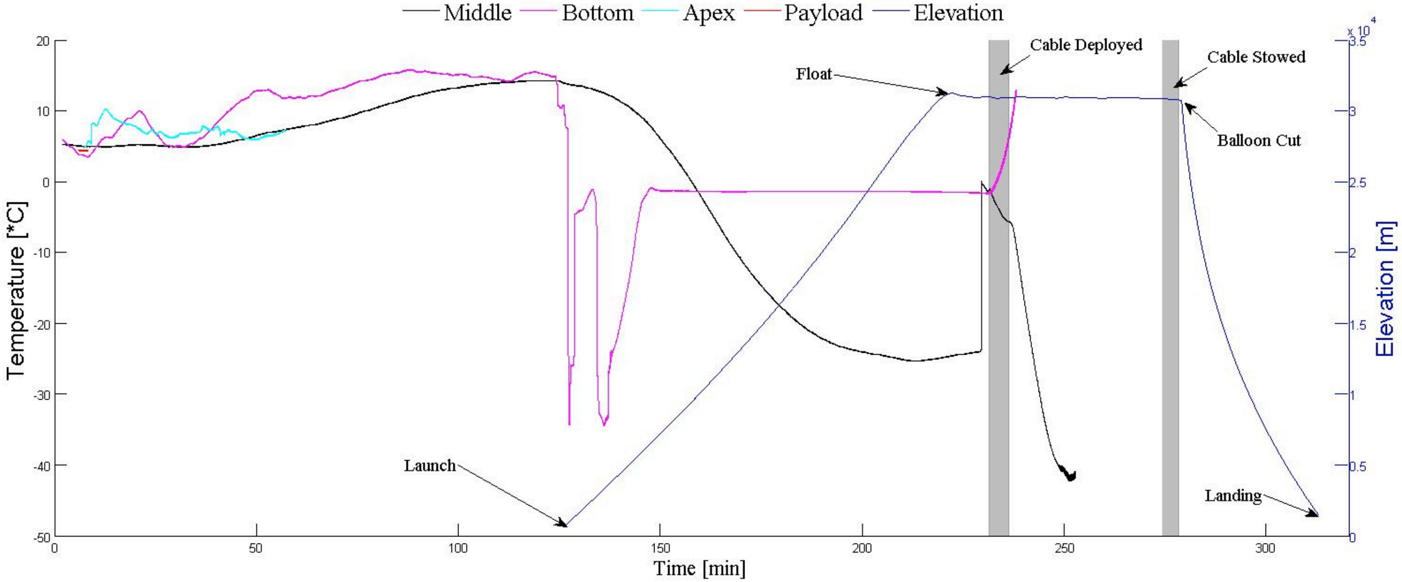
Descent

Release

Landing

Wireless Sensing Results

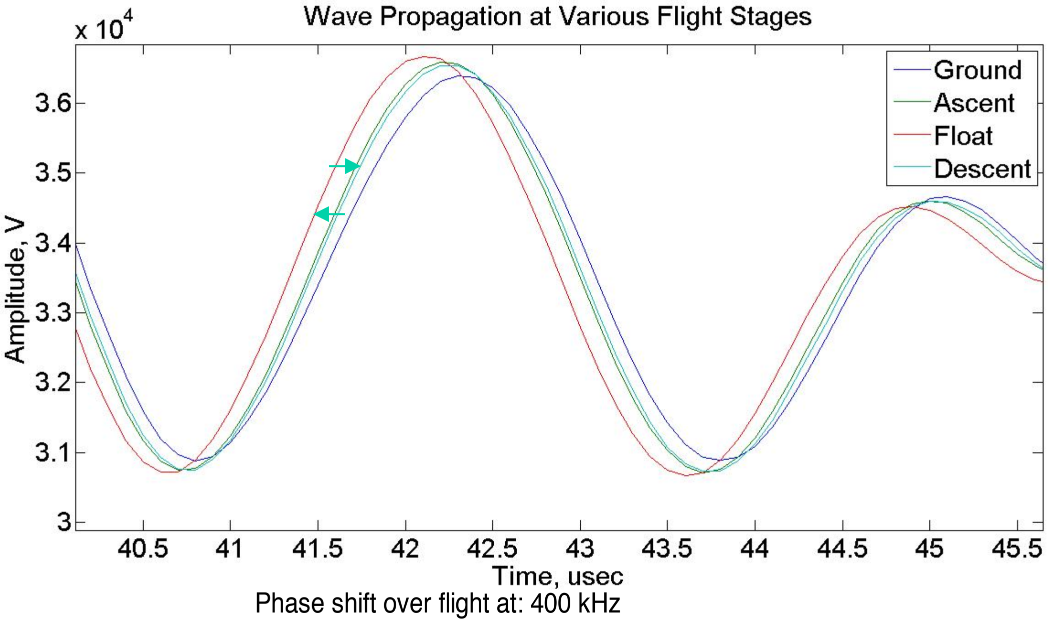


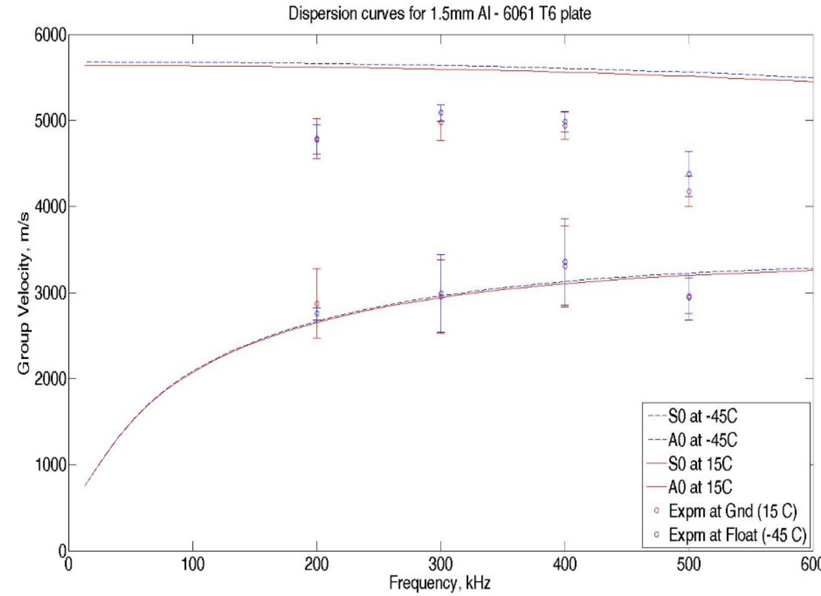


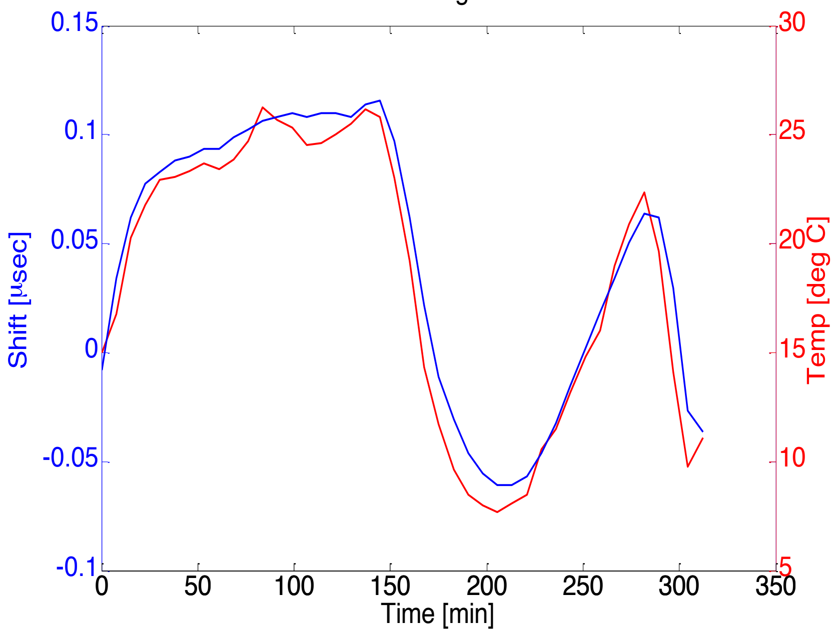
- High-rate dynamic events were detected !
- Temperatures were measured !
- Strain variation generally correlates with temperature variation
- Electromagnetic interference and shielding may be an issue
- Payload geometry and EM wave propagation may be an issue
- Hardware survivability may be an issue.

Structural Sound Speed Measurements

High altitude - first time

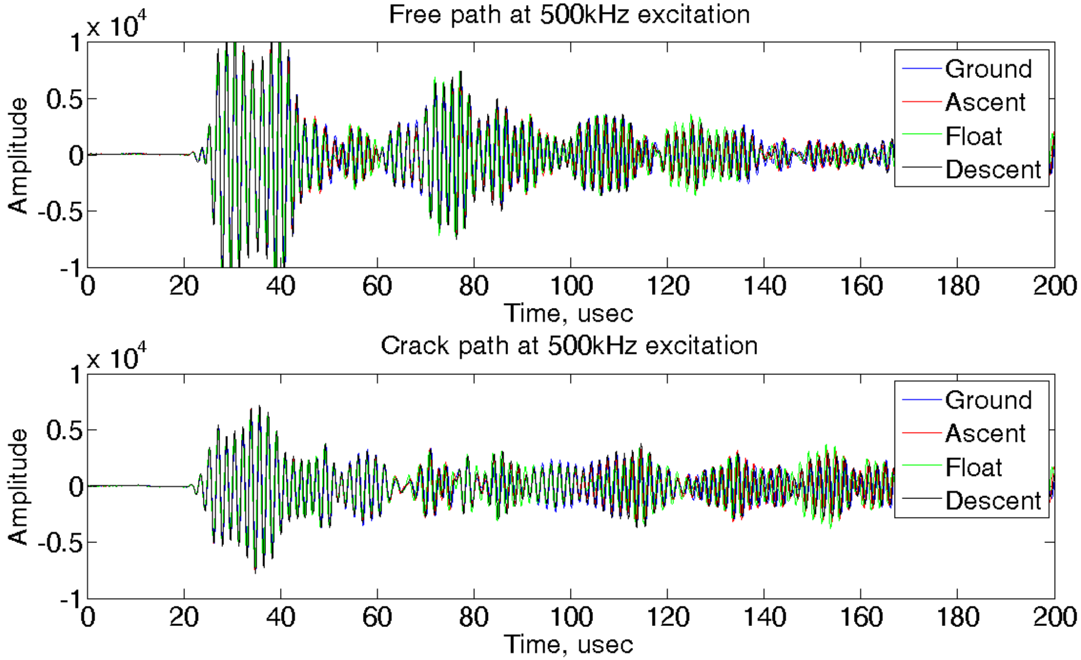


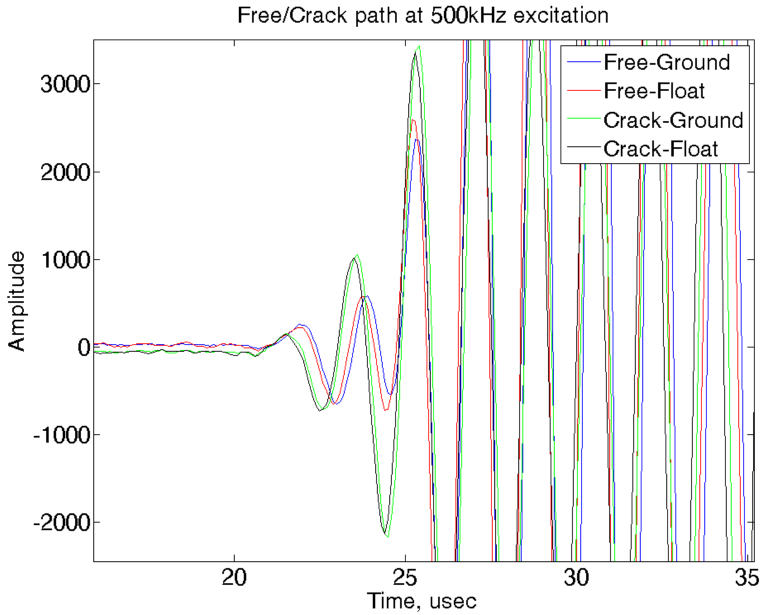




- Amplitude and phase of elastic wave changes depending on flight stage
- Structural sound speed depends on flight stage and strongly correlates with temperature
- Advances in analysis methods are needed to investigate additional effects.

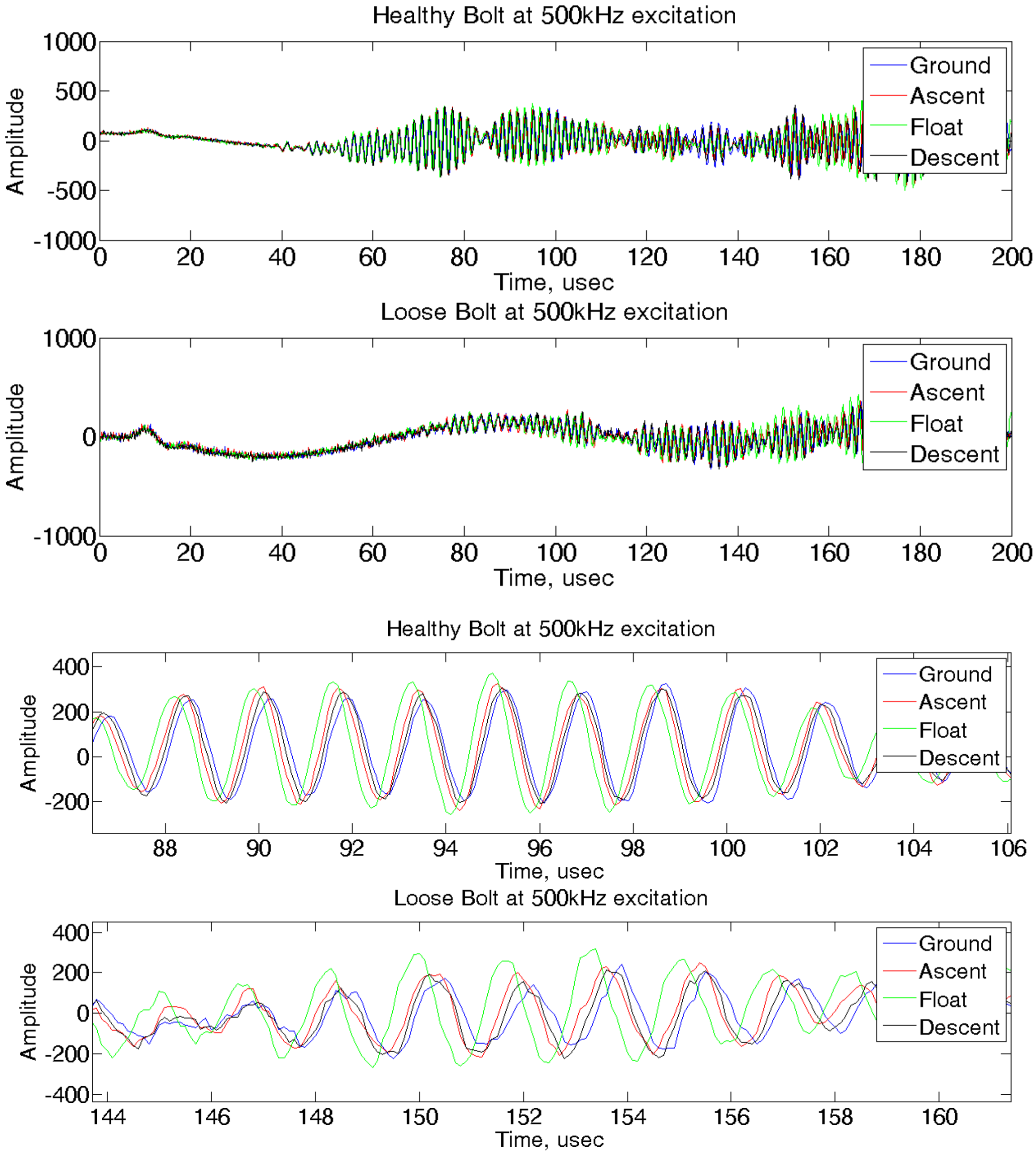
Crack Detection **High altitude - first time**





- Through transmission crack detection is demonstrated
- Amplitudes and phases of elastic wave depend on flight stage, but clearly distinguishable
- Changes are noticeable in the first and subsequent pulses.

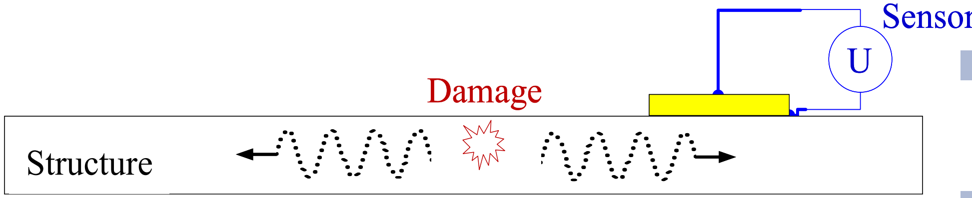
Loose Bolt Detection **High altitude - first time**

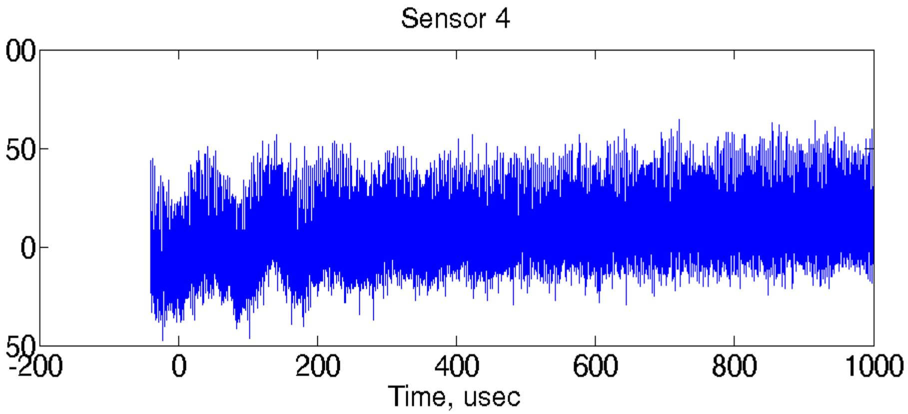


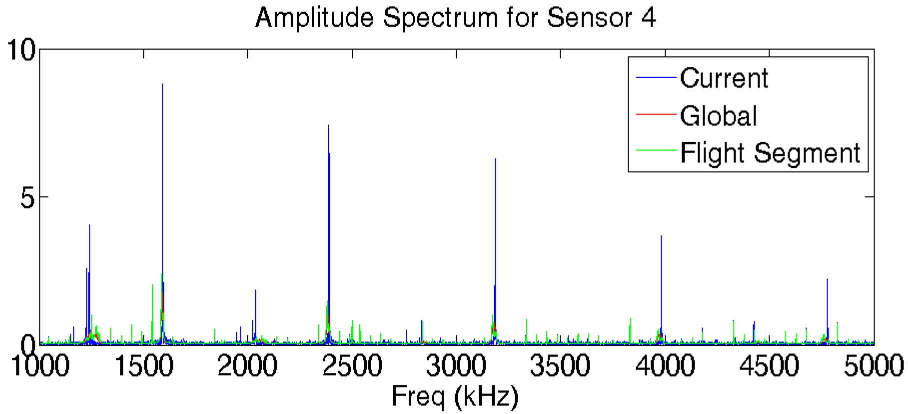
- More elastic energy passes through properly tight bolt as is evident in higher amplitude of elastic wave
- Loose bolt case exhibits low amplitude and higher nonlinearity of the through transmitted elastic wave
- Phase shift (temperature influence?) is also more pronounced in the case of loose bolt.

Acoustic Emission

High altitude - first time

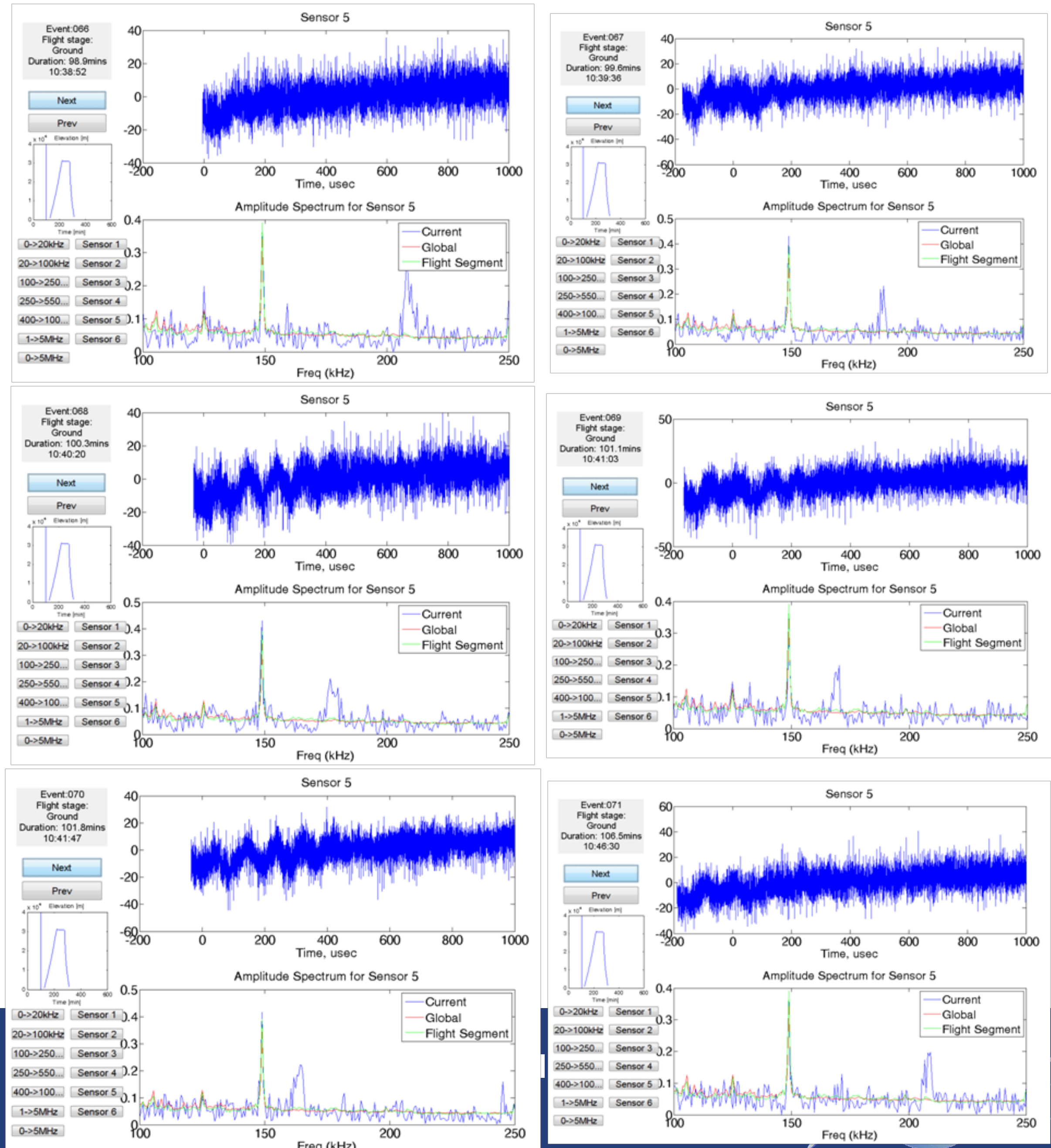


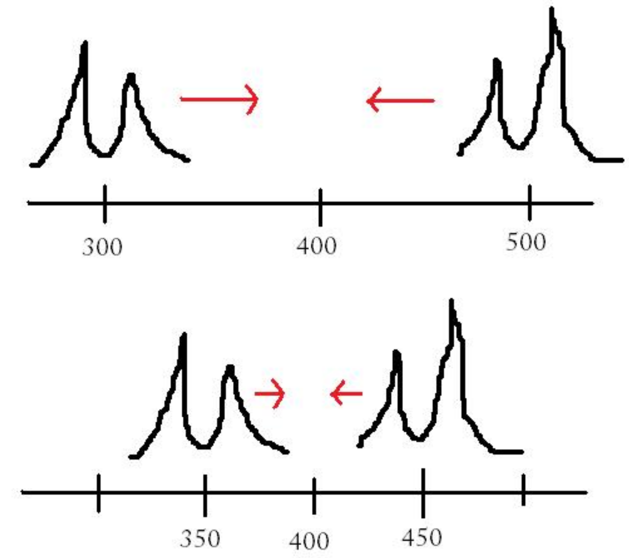




- Sensors are in passive mode listening for acoustic event.
- Acoustic emission spans broad frequency range from several kHz to hundreds of kHz
- Material degradation, crack development, friction, fracture and other mechanical activities result in acoustic emission
- Acoustic emission is seen as primary detection technology for re-entry breakup and unexpected events during flight.
- Acoustic emission data was collected every 10 seconds during 3 hours of stratospheric flight.

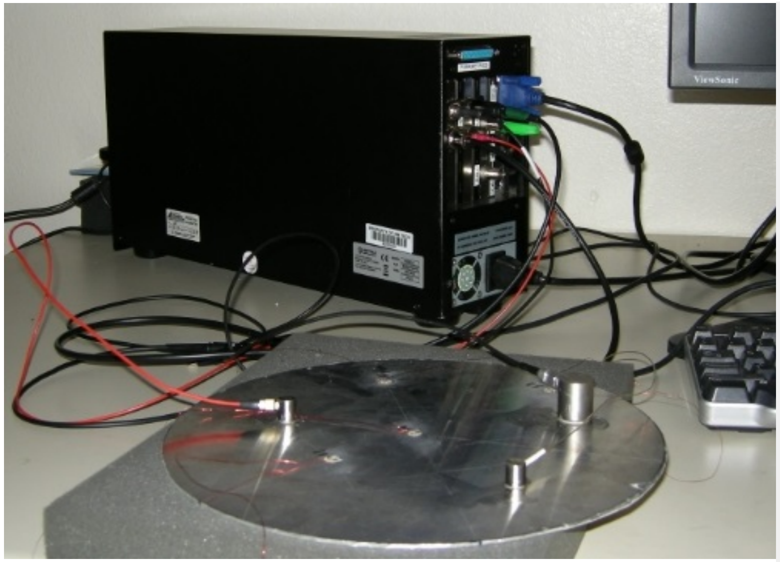
Acoustic Emission





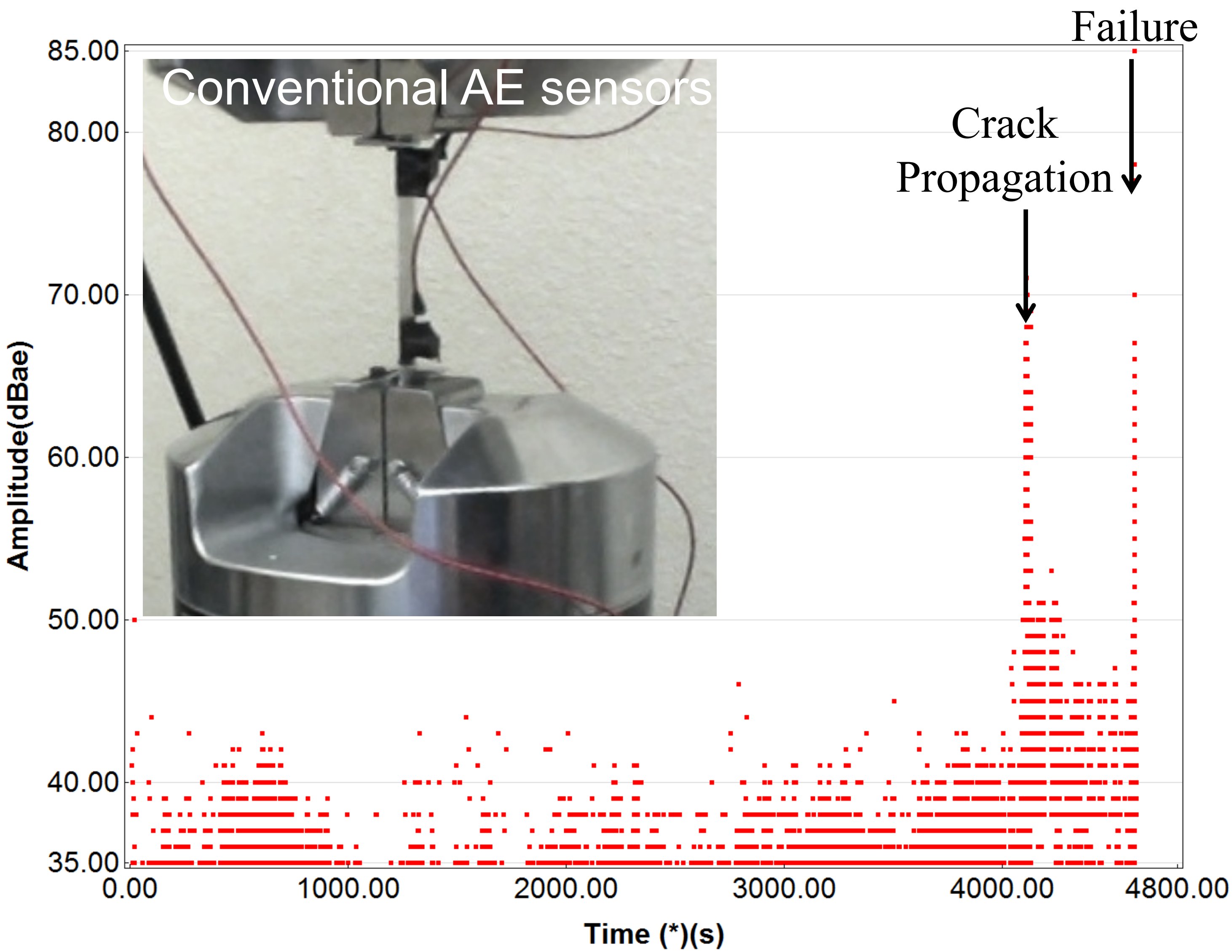
- Multiple frequency peaks were notices in spectrum of AE signal, some with repeatable dynamics every 7 minutes of flight
- Ribbon deployment was detected
- Most of acoustic emission data collected was associated with electrical interference.

Acoustic Emission Investigations

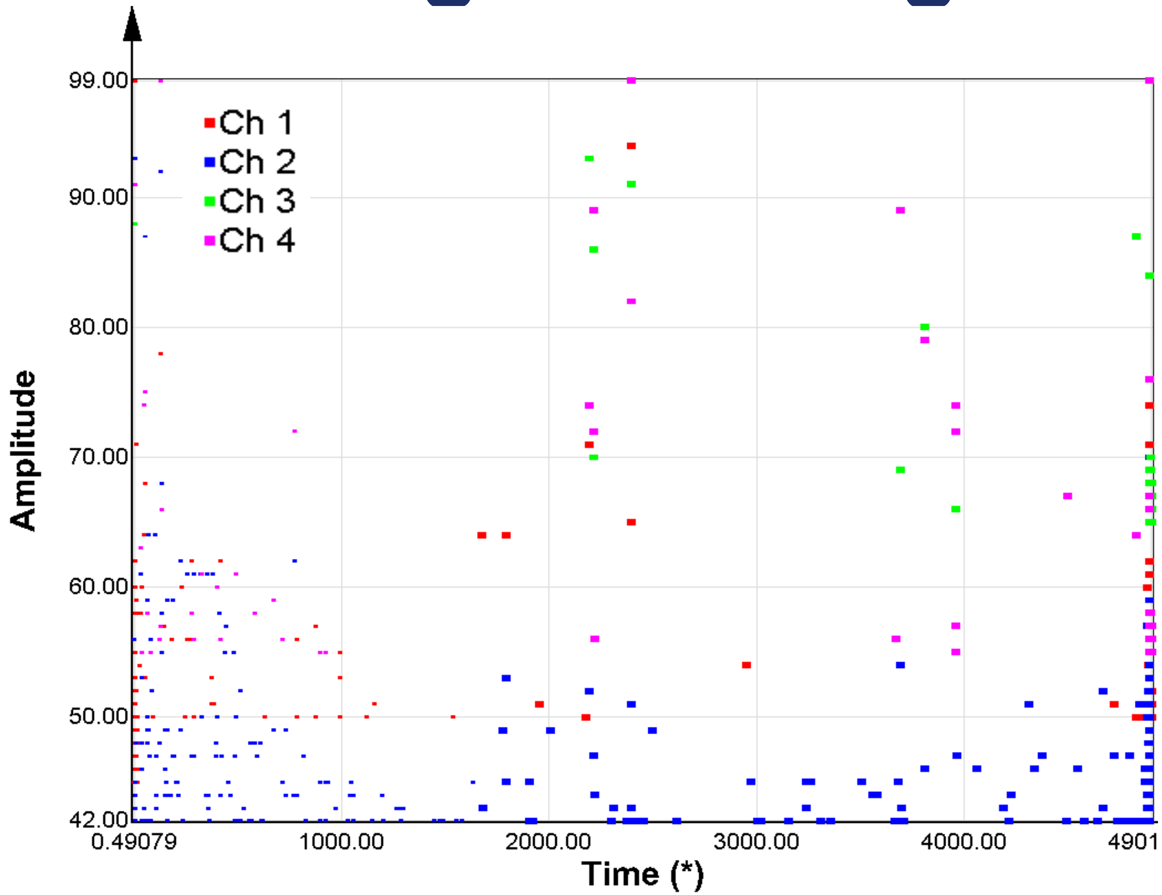


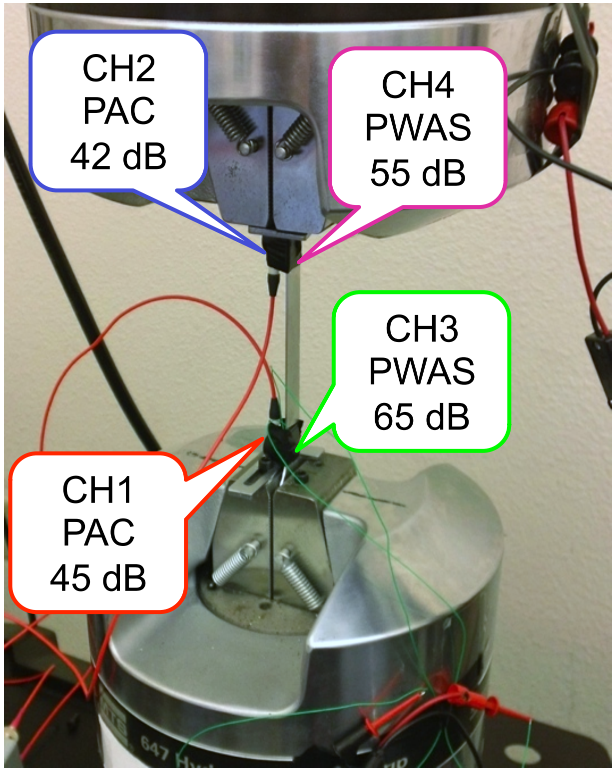
- PWAS and conventional AE sensors were were compared
- PWAS demonstrated utility in recording AE activity, but is more noisy
- New sensor design with shielding options is recommended.

Acoustic Emission During Fatigue Testing



AE & Fatigue Testing: PWAS + Conventional

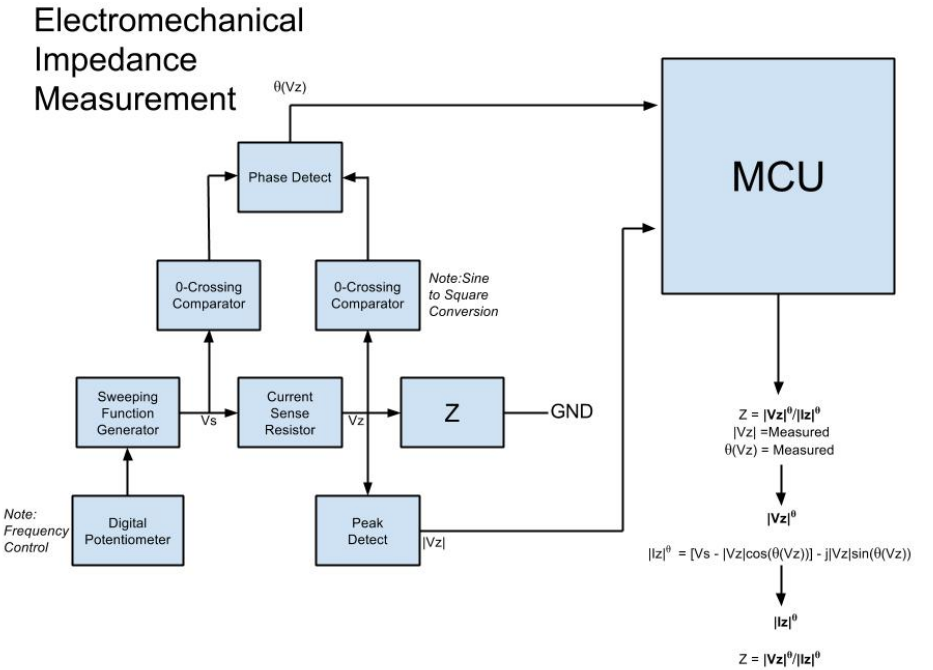


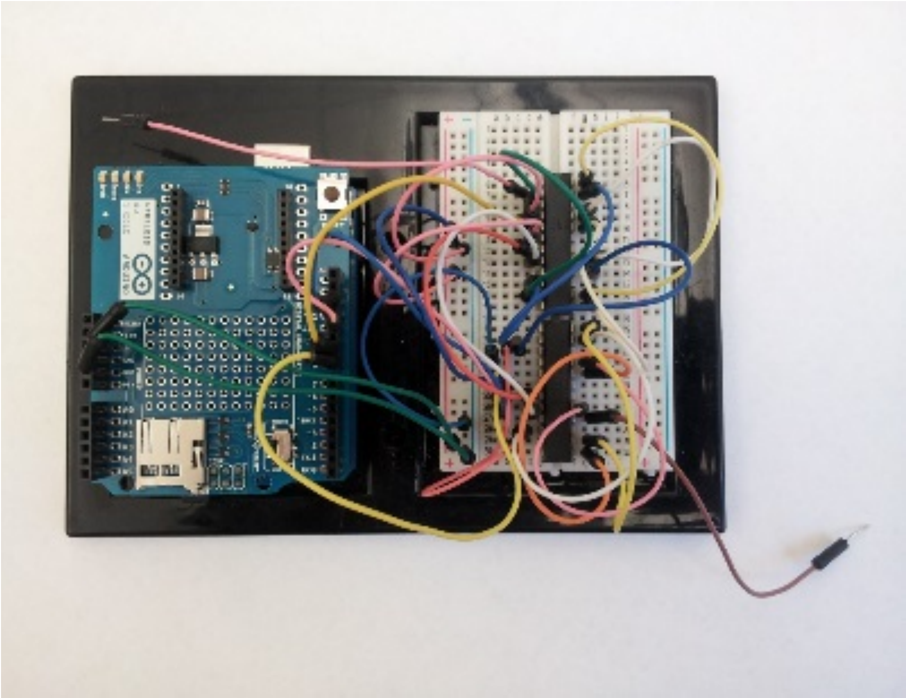


- PWAS are able to detect fatigue damage
- It is possible that PWAS detects fatigue damage at earlier stage
- Electro-magnetic shielding is an issue.

NMT Electro-mechanical Impedance Board

- Reliable impedance measurements in high-altitude and space environments.
- Frequency band up to 0.5 MHz to investigate sensor properties
- Compact, light, and user friendly.



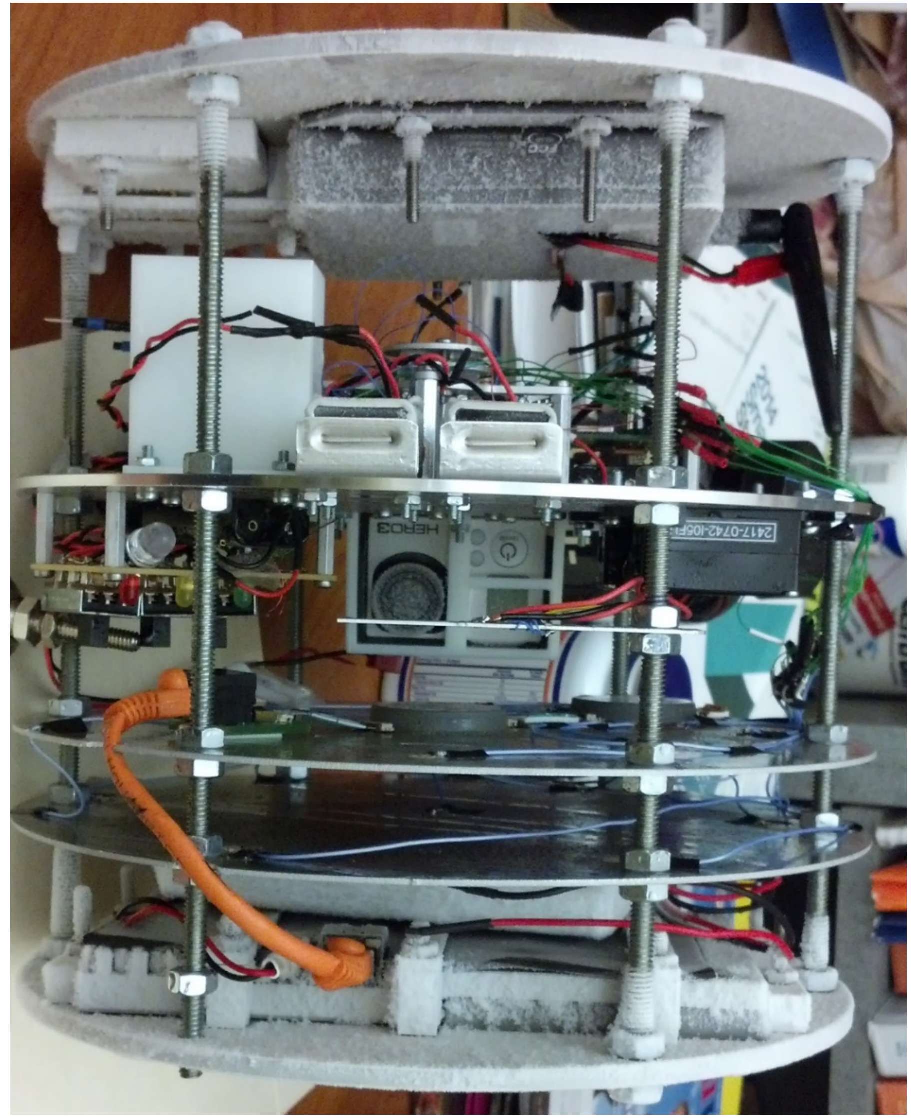


S38 Power On Sequence

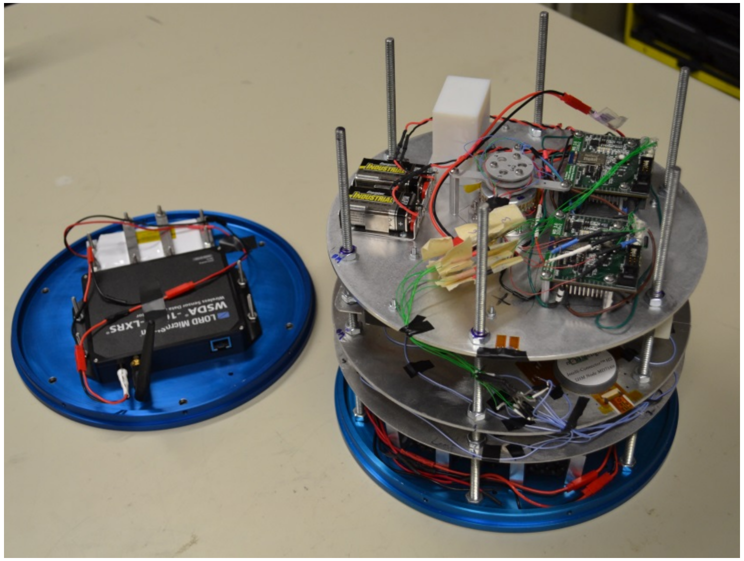
40 minutes before launch

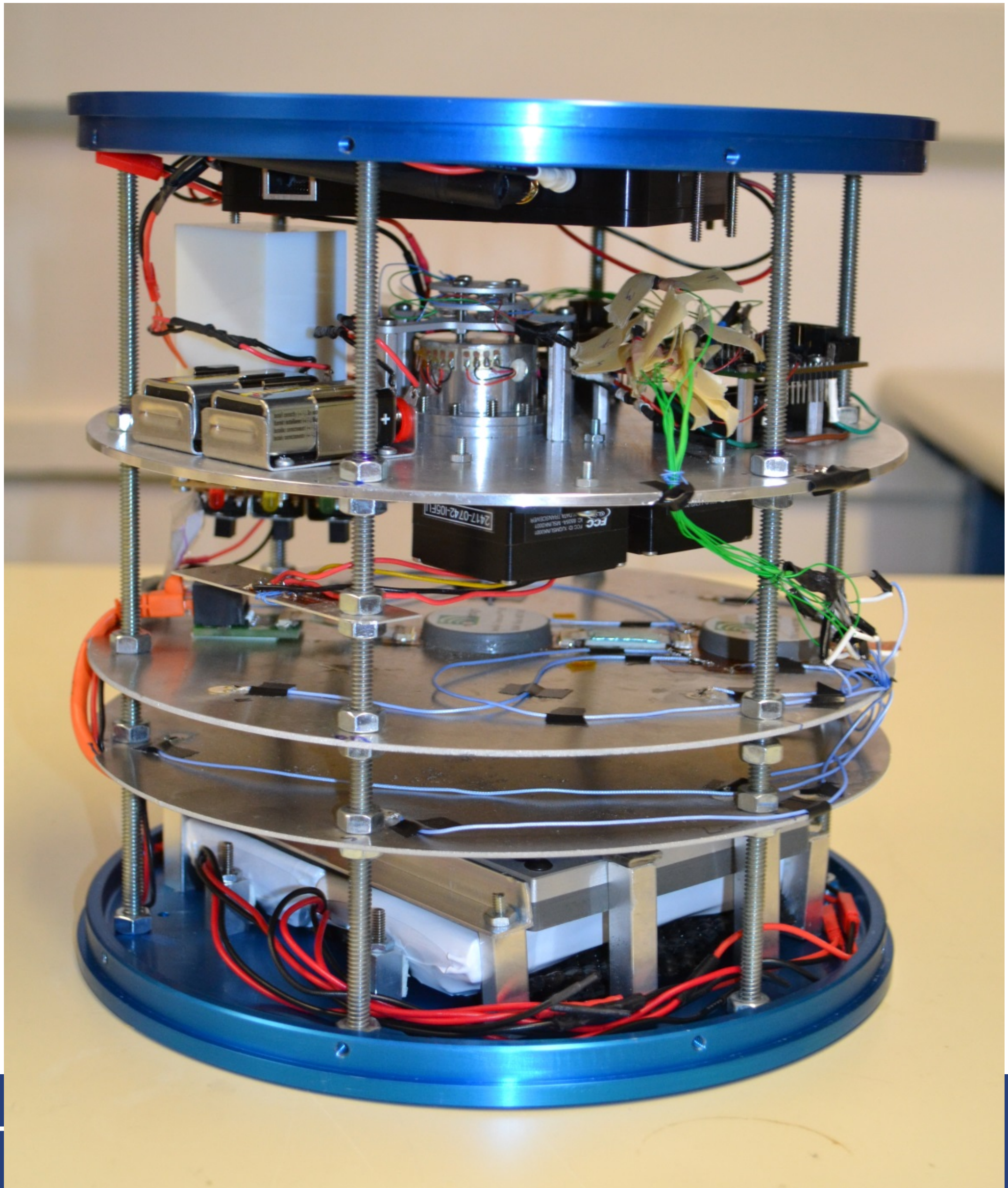
UP Aerospace Suborbital SL-8

- Flip 3 switches to activate WID3 impedance tests (will be triggered by signal from accelerometer during launch) , WSDA wireless base, Metis hardware. LED will light up indicating power on.
- Press power button on GoPro camera
- Flip a switch on each of two wireless nodes (opposite switch box).
- Flip a switch on each of two wireless nodes distributed on a vehicle



S38 Payload





Publications/Presentations

- Zagrai, A., Demidovich, N., Cooper, B., Schlavin, J., White, C., Kessler, S., MacGillivray, J., Chesebrough, S., Magnuson, L., Puckett, L., Tena, K., Gutierrez, J., Trujillo, B., Gonzales, T., (2013) "Structural Condition Assessment during High Altitude Stratospheric Balloon Flight," Presentation at *Next-Generation Suborbital Researchers Conference 2013,* June 3-5, 2013, Broomfield, Colorado.
- Zagrai, A., Demidovich, N., Cooper, B., Schlavin, J., White, C., Kessler, S., MacGillivray, J., Chesebrough, S., Magnuson, L., Puckett, L., Tena, K., Gutierrez, J., Trujillo, B., Gonzales, T., (2013) "Structural Health Monitoring using COTS Equipment during High Altitude Stratospheric Balloon Flight," Presentation at *Commercial and Government Responsive Access to Space Technology Exchange,* Bellevue, Washington, June 26, 2013.
- Zagrai, A., Cooper, B., Schlavin, J., White, C., Kessler, S., (2013) "Structural Health Monitoring in Near-Space Environment, a High Altitude Balloon Test," *Proceedings of International Workshop on Structural Health Monitoring,* Stanford University, September 10, 2013.
- Cooper, B., Zagrai, A., Kessler, S., (2013) "Effects of Altitude on Active Structural Health Monitoring," *Proceedings of SMASIS-13, ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, September 16 – 18, 2013, Snowbird, Utah, paper: SMASIS2013-3269.

Conclusions

- 038B high altitude balloon flight was successful and yielded considerable volume of data for the embedded ultrasonics structural health monitoring approach and wireless sensing.
- The experiment demonstrated basic proof-of-concept spacecraft ultrasonic SHM and wireless sensing through metallic spacecraft materials over considerable distances.
- Structural sound speed exhibited variation depending on flight stage. This variation correlates with temperature changes.
- In-flight loose bolt and crack detection has been demonstrated
- Acoustic emission recorded in-flight was mostly attributed to electronic interference, but also demonstrated ability to detect low frequency dynamics
- Further acoustic emission studies in laboratory (fatigue) and field conditions (shock wave) are underway.

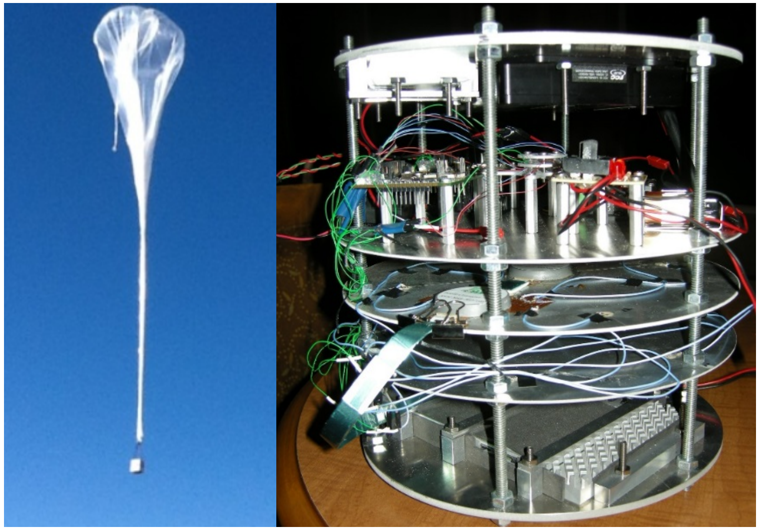
Acknowledgements

- Nickolas Demidovich (Federal Aviation Administration)
- The flight opportunity was provided by the NASA Flight Opportunities Program http://flightopportunities.nasa.gov , flight 38 BS.
- Bruce Webbon (NASA) for helpful discussions and assistance.
- Federal Aviation Administration (FAA) through Center of Excellence for Commercial Space Transportation, AFRL Space Vehicles Directorate, and NMT Department of Mechanical Engineering are acknowledged for financial support.
- Los Alamos National Laboratory Engineering Institute for providing WID3 impedance measurements boards (Charles Farrar, Stuart Taylor, Gyuhae Park).
- Metis Design and LORD Microstrain for collaboration on measurement hardware and assistance with tests.
- Near Space Corporation (Tim Lachenmeier and the team) for payload integration, launch and recovery.

Contact Information

- Andrei Zagrai
- Department of Mechanical Engineering
- New Mexico Institute of Mining and Technology
- 801 Leroy Pl., Weir Hall, Room 124, Socorro, NM
- Ph: 575-835-5636;
- Fax: 575-835-5209;
- E-mail: azagrai@nmt.edu

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 high altitude stratospheric balloon 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 guidelines for sensor installation and measurement procedures in acoustic emission SHM of space vehicles.

STATUS

- 038B NASA FOP Flight completed
- Acoustic emission measurements of fatigue damage is conducted
- Utility of PWAS for AE testing is investigated

FUTURE WORK

- Sound speed data analysis
- 038S Suborbital SL-8 flight
- PWAS design for AE testing
- Thermal damage assessment