National Aeronautics and Space Administration

NASA Applications of Structural Health Monitoring Technology

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NASA Engineering and Safety Center, Hampton, Virginia
NASA Johnson Space Center, Houston, Texas

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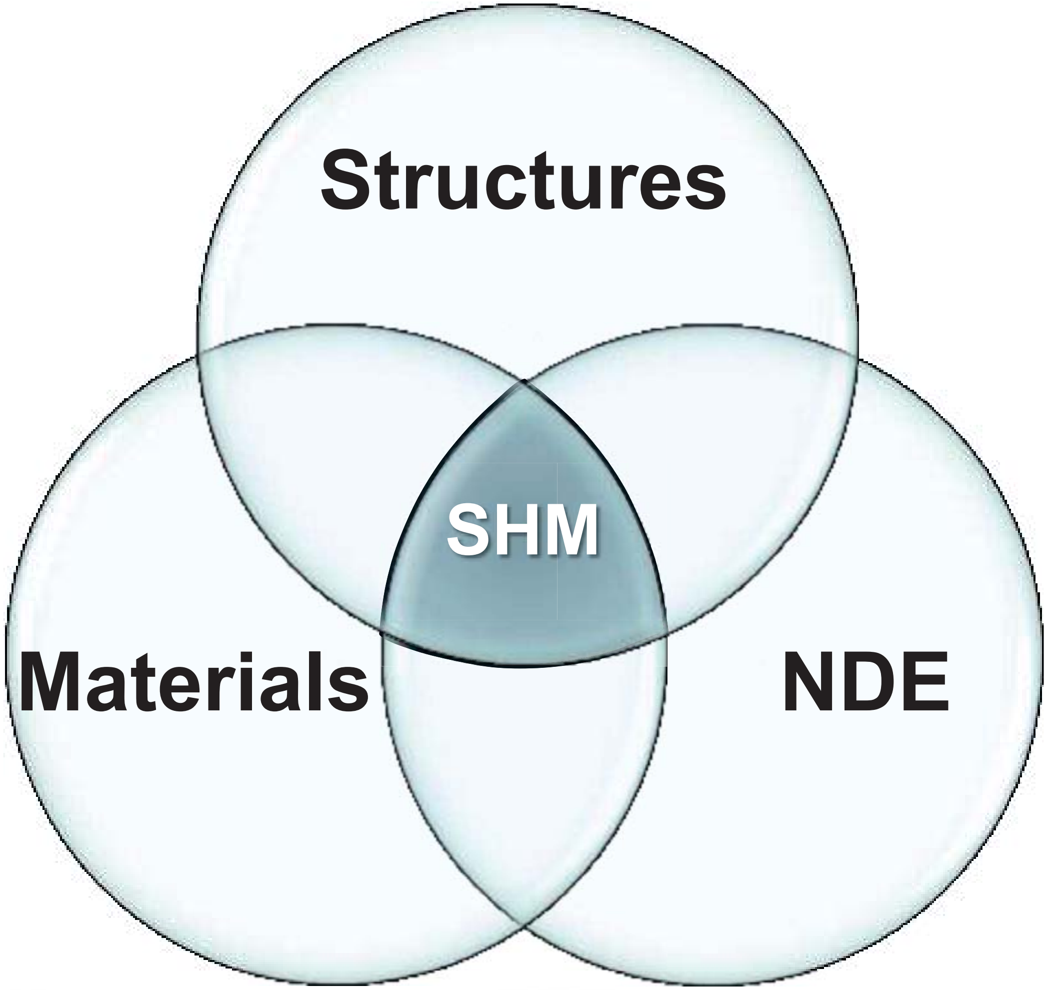
NASA Focused Structural Health Monitoring

Key Drivers

Vehicle-focused
Real-time,
decision-making
Online processing
Onboard systems
Lightweight,
Small size,
Low power,
System solutions



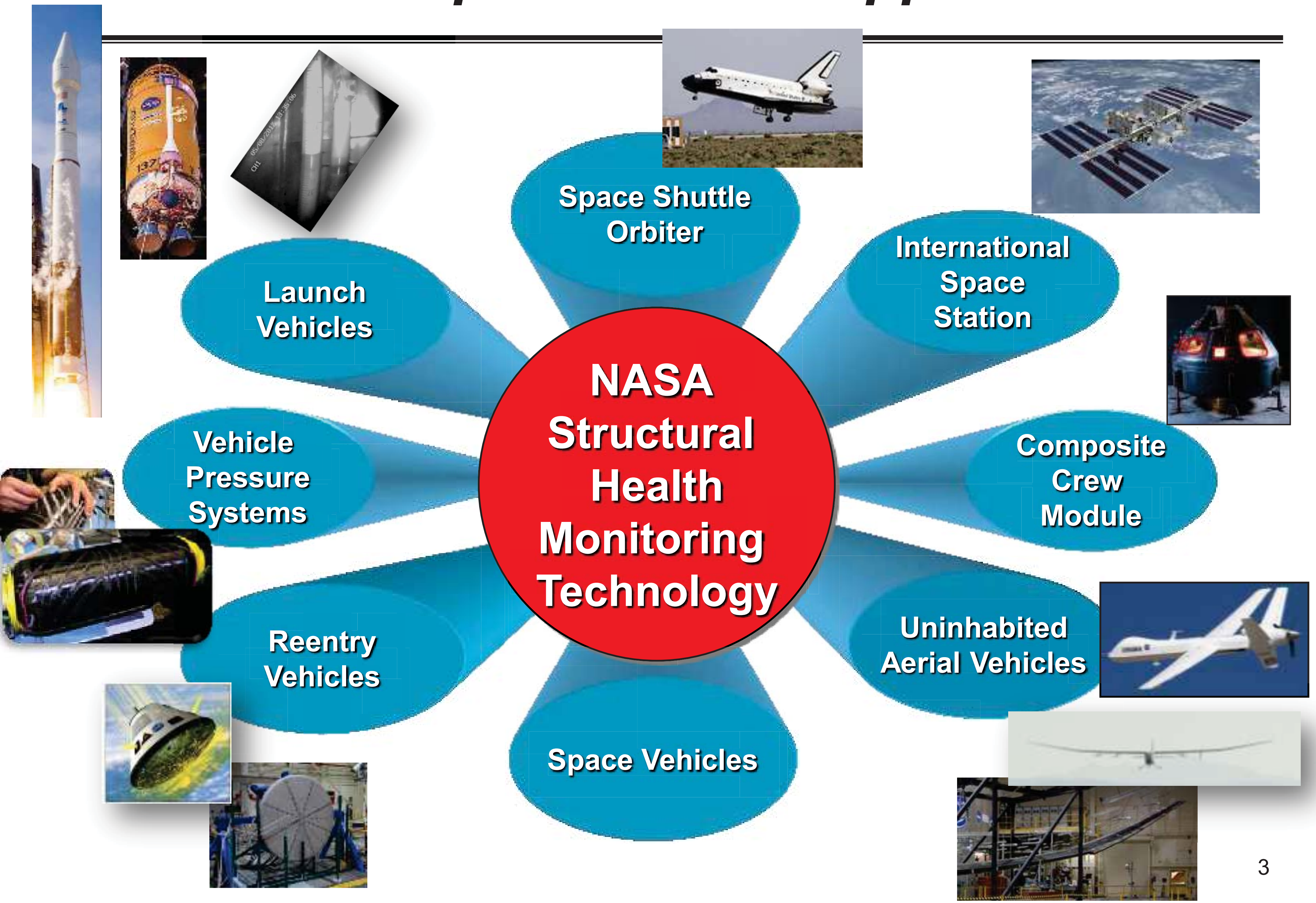
Enabling Technologies

Advanced Sensing
- Multi-parameter
- Sensor arrays

Advanced Systems and Processing
- Solid state
- Rugged
- High Speed

Ultra-Efficient Algorithms

SHM Aerospace Vehicle Applications



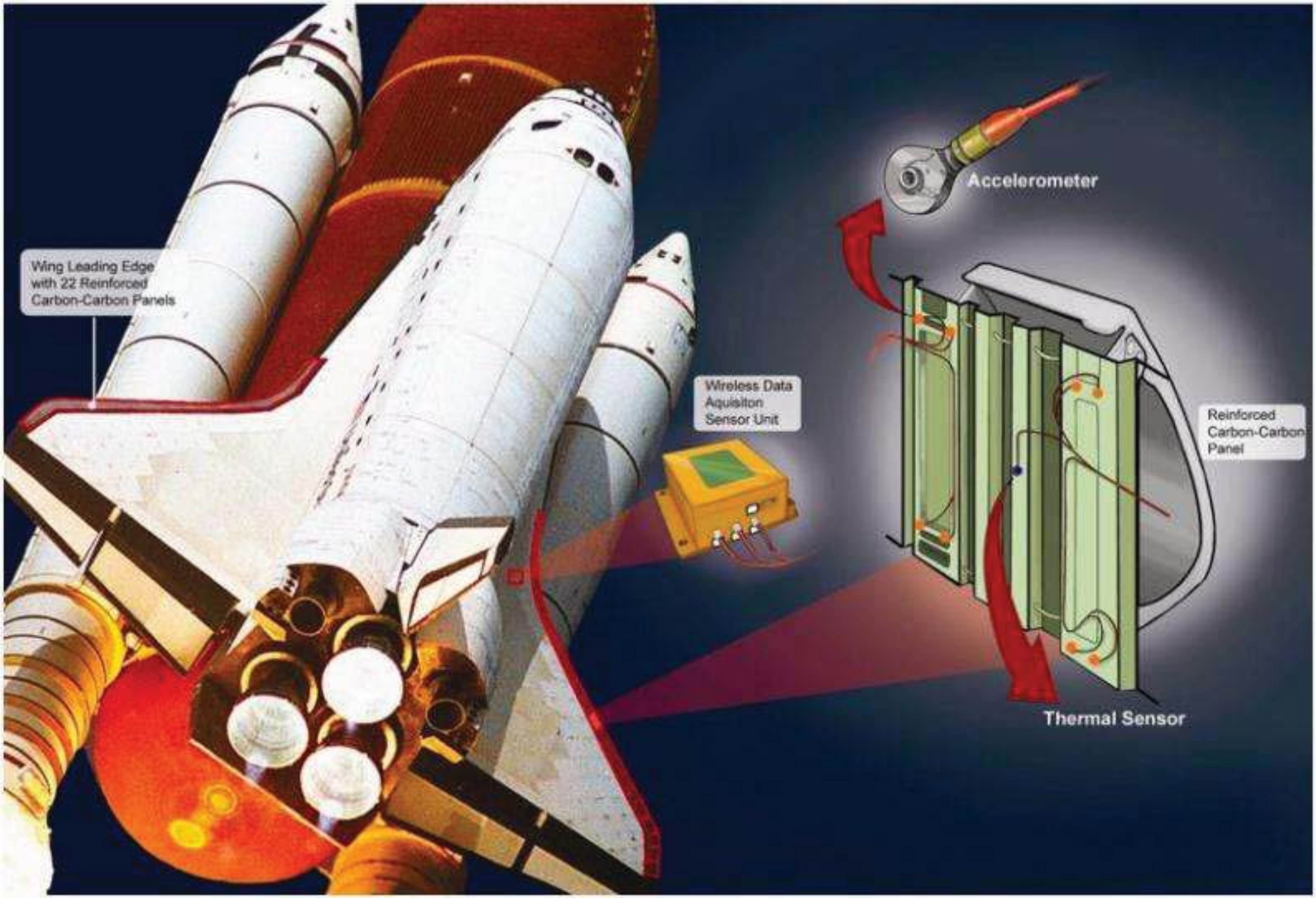
Topics

National Aeronautics and Space Administration

- **Structural Health Monitoring**
  - Definition
  - SHM vs NDE
- **Agency Overview of SHM Activities**
  - **Accel & Acoustic-based SHM on STS (Prosser, NESC)**
  - Wireless-based SHM on ISS / STS (Studor, JSC)
  - Piezo-based SHM on ISS (Madaras, LaRC)
  - Fiber-optic-based SHM on Aerospace Vehicles (Richards, DFRC)
    - Uninhabited Aerial Vehicles
    - Composite Crew Module
    - Reentry Vehicles
    - Space Vehicles
    - Vehicle Pressure Systems
    - Expendable Launch Vehicles

Space Shuttle Orbiter

Wing Leading Edge Impact Detection System (WLEIDS)

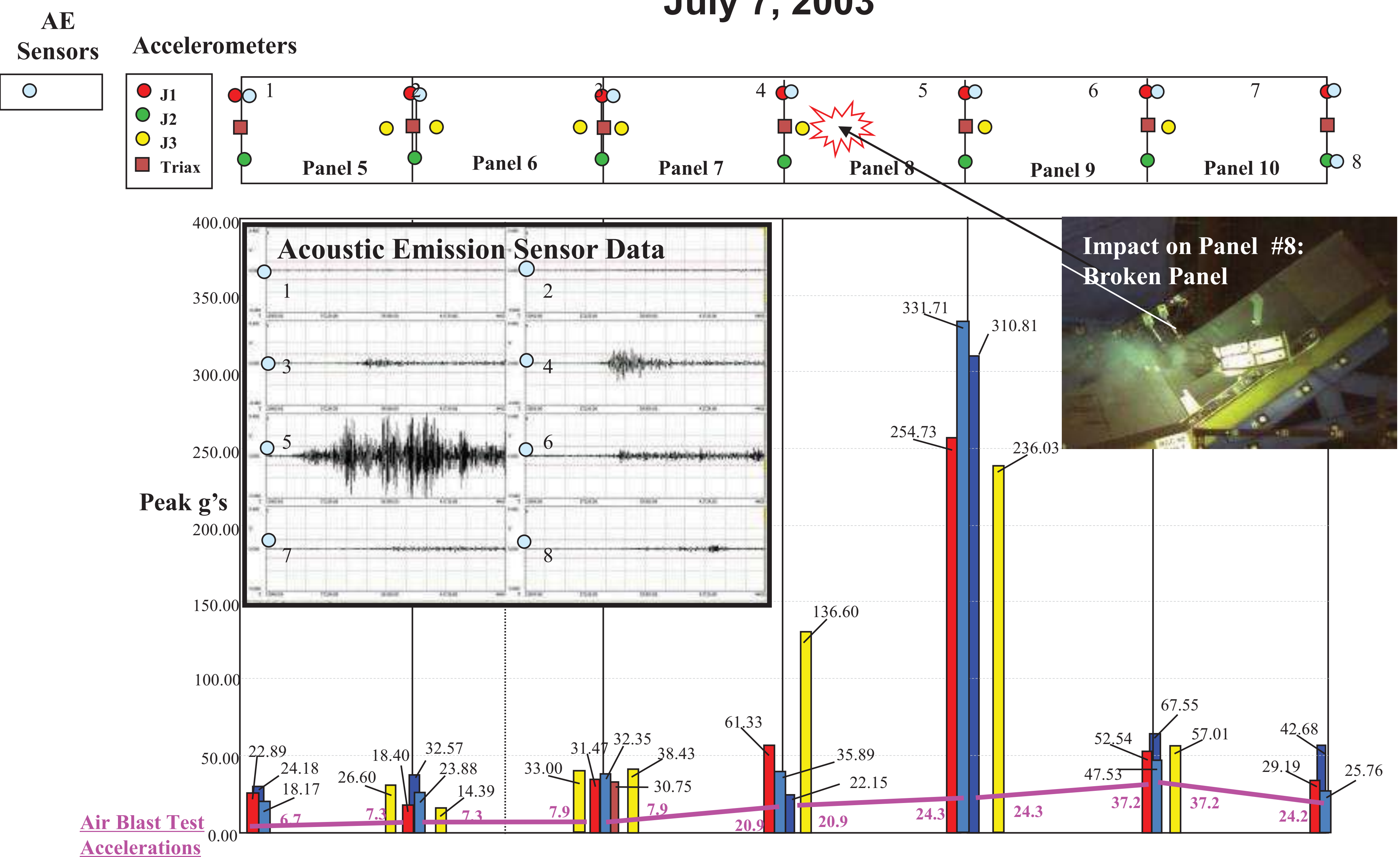


Wing Leading Edge Impact Detection System (WLEIDS) Development

- Columbia accident investigation testing
  - Recovery of DFI sensor data on MADS focused impact testing on RCC
- Additional impact testing
  - Ascent impacts
  - MMOD impacts
- Vehicle testing
- System development and implementation
- Flight results

Columbia Accident Investigation
Catastrophic Impact Damage Test on RCC Panel 8

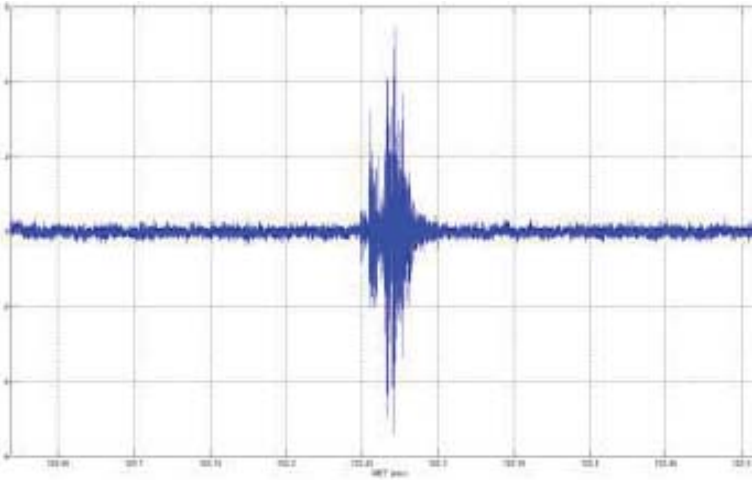
July 7, 2003



WLEIDS Operations

- **Installed on all Shuttles**
- **Successfully flown on all flights since *Columbia***
- **Detected small impacts during ascent**
  - Small amplitude, nondamaging
  - Likely popcorn foam
- **Detected several small MMOD impacts**

Sensors and Data Recorder in Wing



WLEIDS probable impact signal

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  - Fiber-optic-based SHM on Aerospace Vehicles (Richards, DFRC)
    - Sensor Development
    - Strain-based Parameter Development
      - Shape, Loads, Liquid Level, Magnetic Field
    - Sensor Attachment / Characterization
    - System Development
    - Ground / Flight Applications

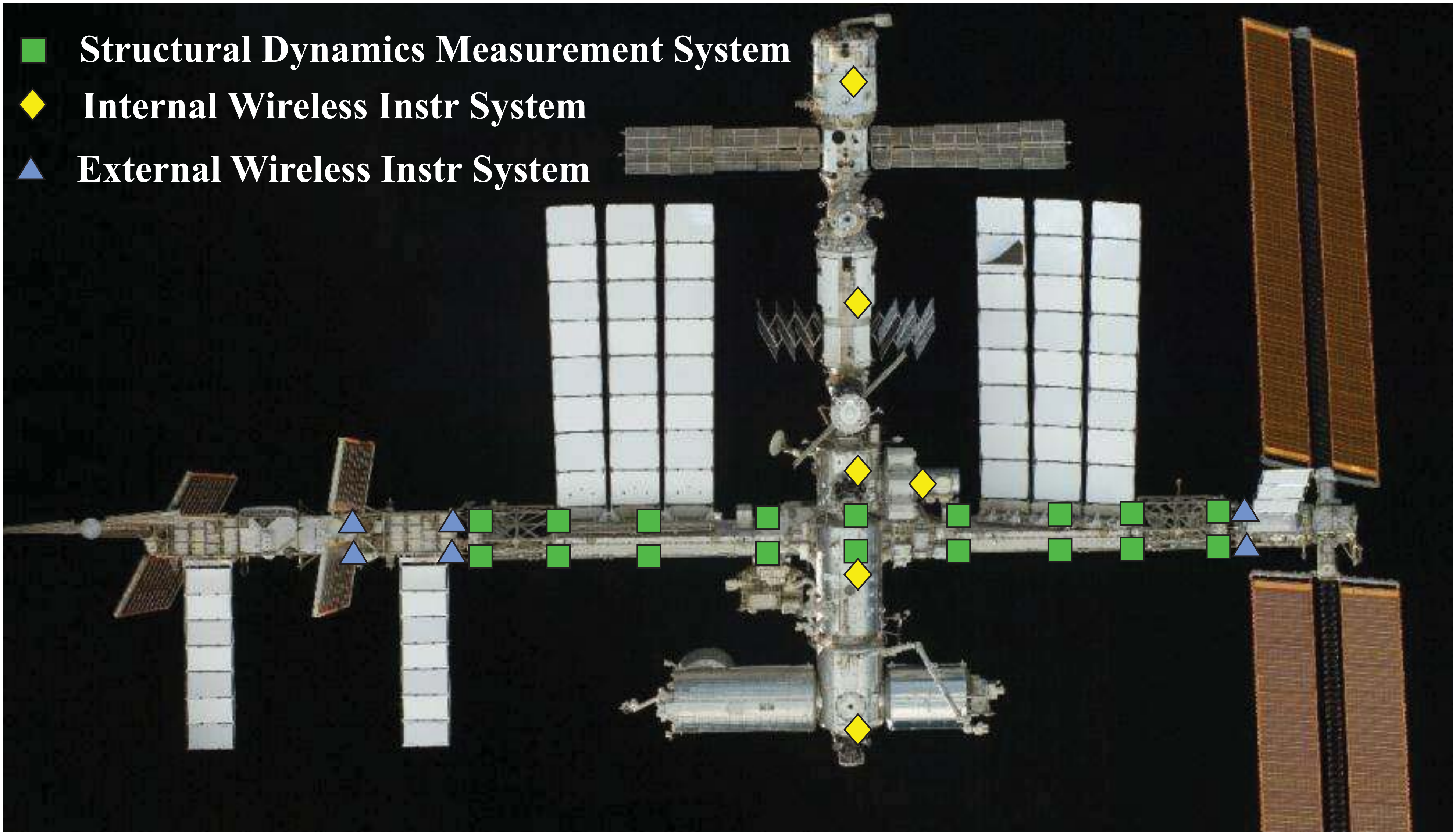
Space Shuttle / ISS
Evolution of Micro-WIS Systems

System	MicroWIS (SBIR)	Extended Life MicroWIS	MicroSGU / MicroTAU	Wideband MicroTAU	Enhanced WB MicroTAU	Ultra-sonic WIS (new Ph2 SBIR)
Date Certified	1997	2001	2000/2001	2002	2005	2007
Purpose	IVHM	Thermal Models	Cargo Loads Cert Life Extension	MPS Feedline Dynamics	Wing Leading Edge Impacts	ISS Impact/Leak Monitoring
Dimensions	1.7” dia. x 0.5”	2.7”x2.2”x1.2”	2.7”x 2.2” x 1.2”	3.0”x 2.5” x 1.5”	3.25”x2.75”x1.5	3.4” x2.5”x 1.1”
Sample Rate	Up to 1Hz	Up to 1Hz	Up to 500Hz (3 channels)	Up to 20KHz (3 channels)	Up to 20KHz (3 channels)	Up to 100KHz (10 channels)
Data Storage	None	2Mbytes	1Mbyte	256Mbytes	256Mbytes	1Gbyte
Battery Life	9 months	10+ years	2-3 missions	1 mission	1 mission	3 years
Sensor Types	Temperature (Flight Cert) and Resistive sensors: Strain, Accelerometer, Pressure	Temperature (Flight Cert) and Resistive sensors: Strain, Accelerometer, Pressure	Acceleration & Strain (Flight Cert) or Resistive sensors. Includes Pressure as Trigger Channel.	Accelerometer & Temperature (Flight Cert) or Piezoelectric and Resistive Sensors	Accelerometer & Temperature (Flight Cert) or Piezoelectric and Resistive Sensors	Ultrasonic Microphone and Acoustic Emission

Wireless Instrumentation Systems
Unique Solutions To Real Shuttle Problems

- **Temperature Monitoring**
  - Validation of thermal models for design modifications and operations
  - Micro-WIS (first flown in non-RF configuration)
- **Structural Loads and Dynamics**
  - SSME support strain data needed for certification life predictions
  - Cargo to orbiter trunion dynamics and loads
  - Micro Strain Gauge Unit (Micro-SGU) and Micro Tri-Axial Accelerometer Units (Micro-TAU)
- **SSME Feed-Line Crack Investigation**
  - Main propulsion system flow-liner dynamics
  - Wide-Band Micro-TAU
- **Wing Leading Edge Impact Detection**
  - Sense impact of ascent debris and MMOD on-orbit
  - Enhanced Wide-Band Micro-TAU (EWBMTAU)
- **SRMS On-Orbit Loads**
  - Increases needed to support contingency crew EVA repairs at end of boom
  - Wireless Strain Gauge Instrumentation System (WSGIS) and EWBMTAU
  - Also used for monitoring Shuttle Forward Nose dynamics during roll-out

ISS Structural Dynamics Accelerometers



Current accelerometer count on ISS is 81 (SDMS: 33 EWIS: 30 IWIS: 18).

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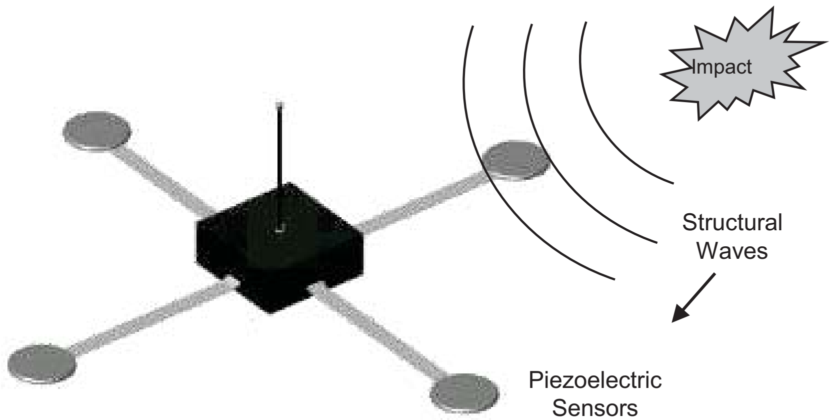
Distributed Impact Detection System Concept

- **Original DIDS concept is to detect and locate impacts via a wireless sensors system.**

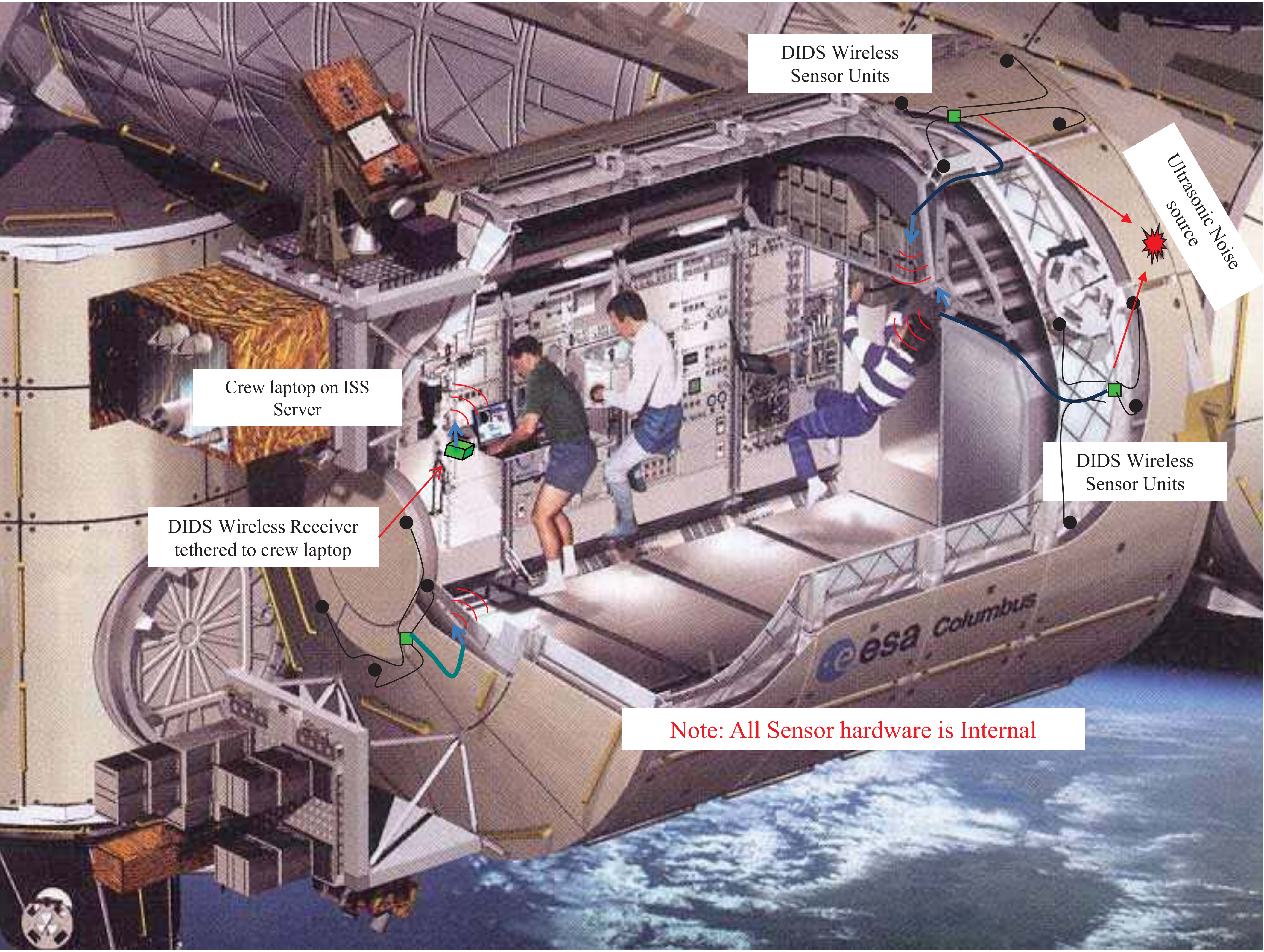


DIDS System Concept

Module is asleep until event signal threshold is crossed.
Sensor module can record four signals at 1MHz rate.
Sensors can record and transmit ~6000 events.
Batteries can last up to 5 years.
Laptop computer can control multiple units.

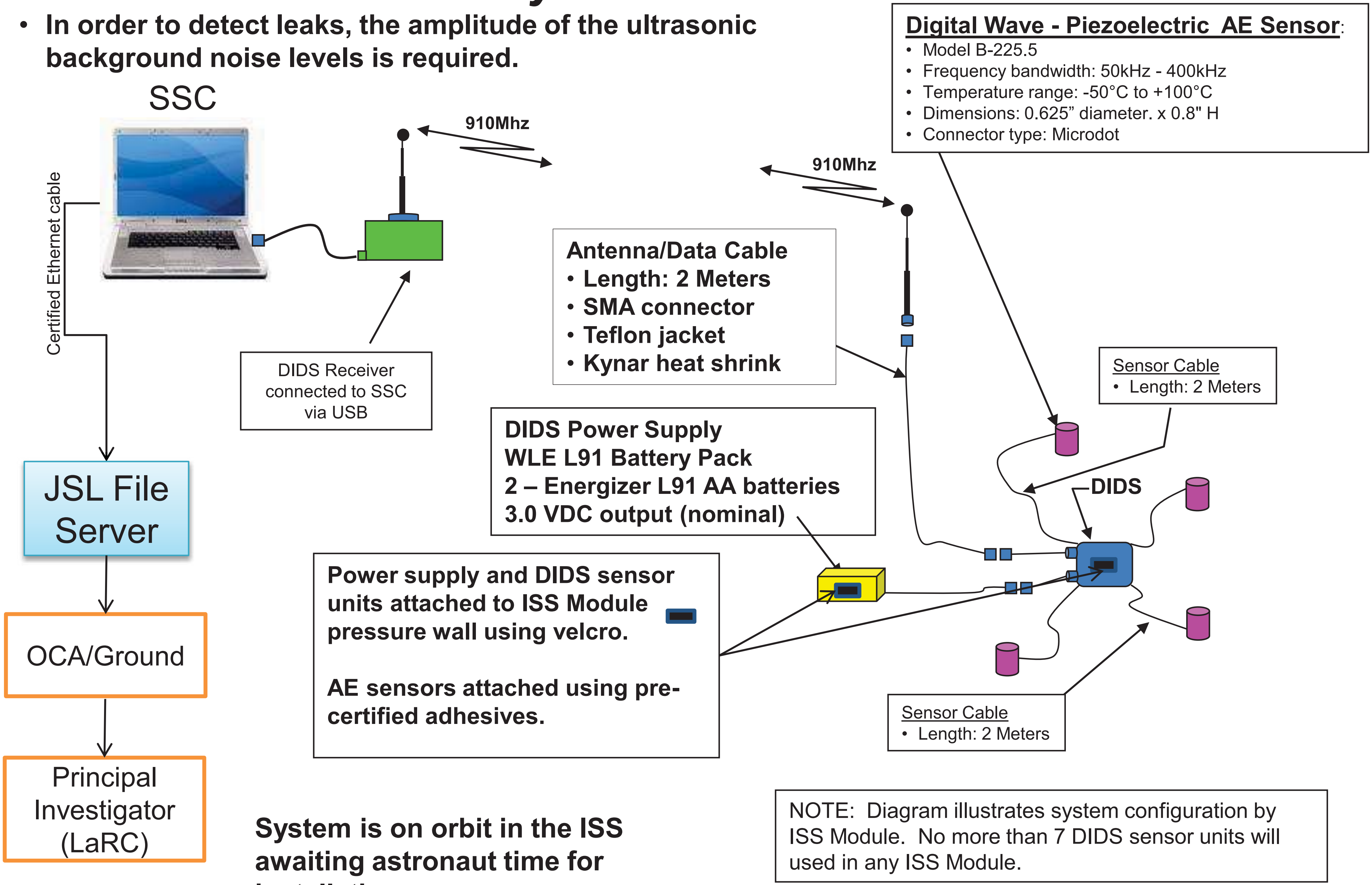
MMOD strike example

- **Current DIDS system concept is to detect leak locations on space vehicles.**


DIDS Wireless
Sensor Units
Ultrasonic Noise
source
Crew laptop on ISS
Server
DIDS Wireless
Sensor Units
DIDS Wireless Receiver
tethered to crew laptop
esa Columbus
Note: All Sensor hardware is Internal

ISS Ultrasonic Background Noise Test (UBNT)
System Overview

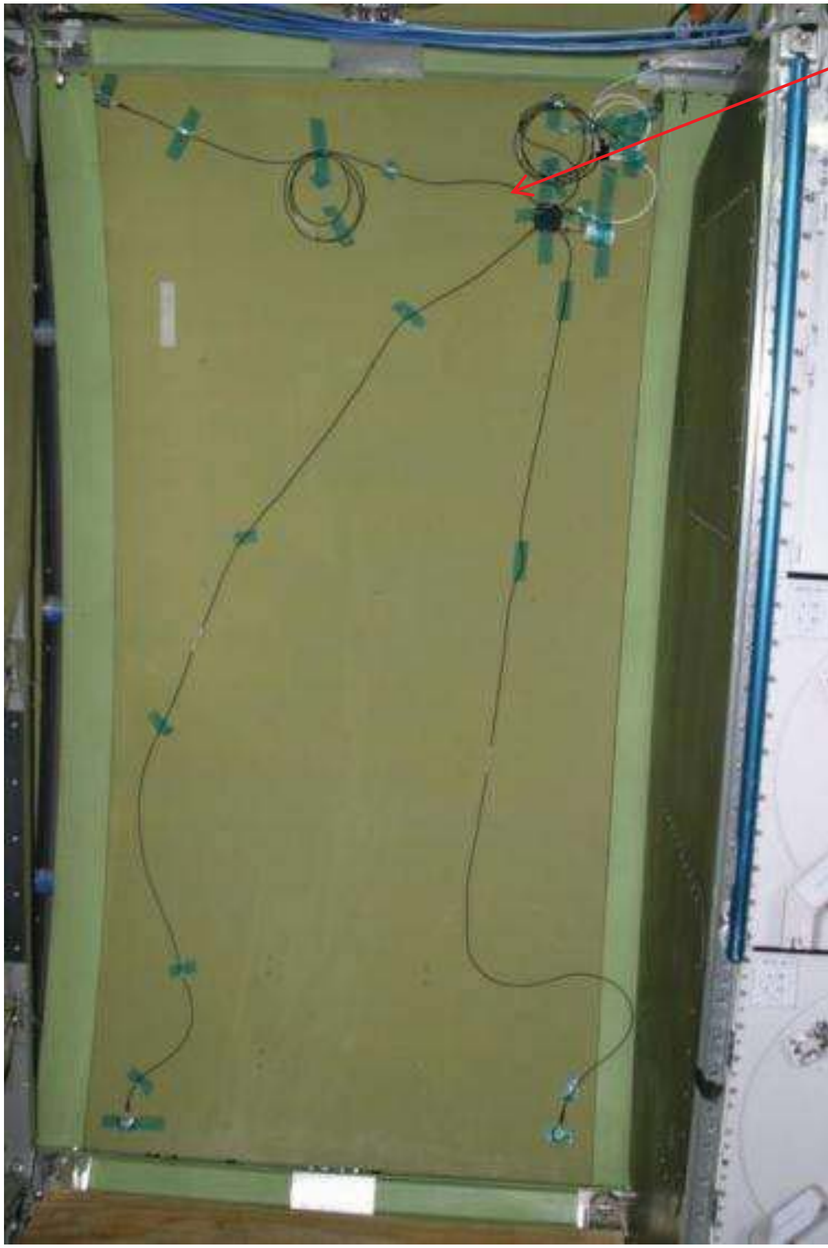
- **In order to detect leaks, the amplitude of the ultrasonic background noise levels is required.**



System is on orbit in the ISS awaiting astronaut time for installation

Example of installation behind ISS equipment ramp

(Fit Check in B9 US Lab Mockup)



DIDS unit installed in open rack in mockup

UBNT Extended Antenna in ISS hallway

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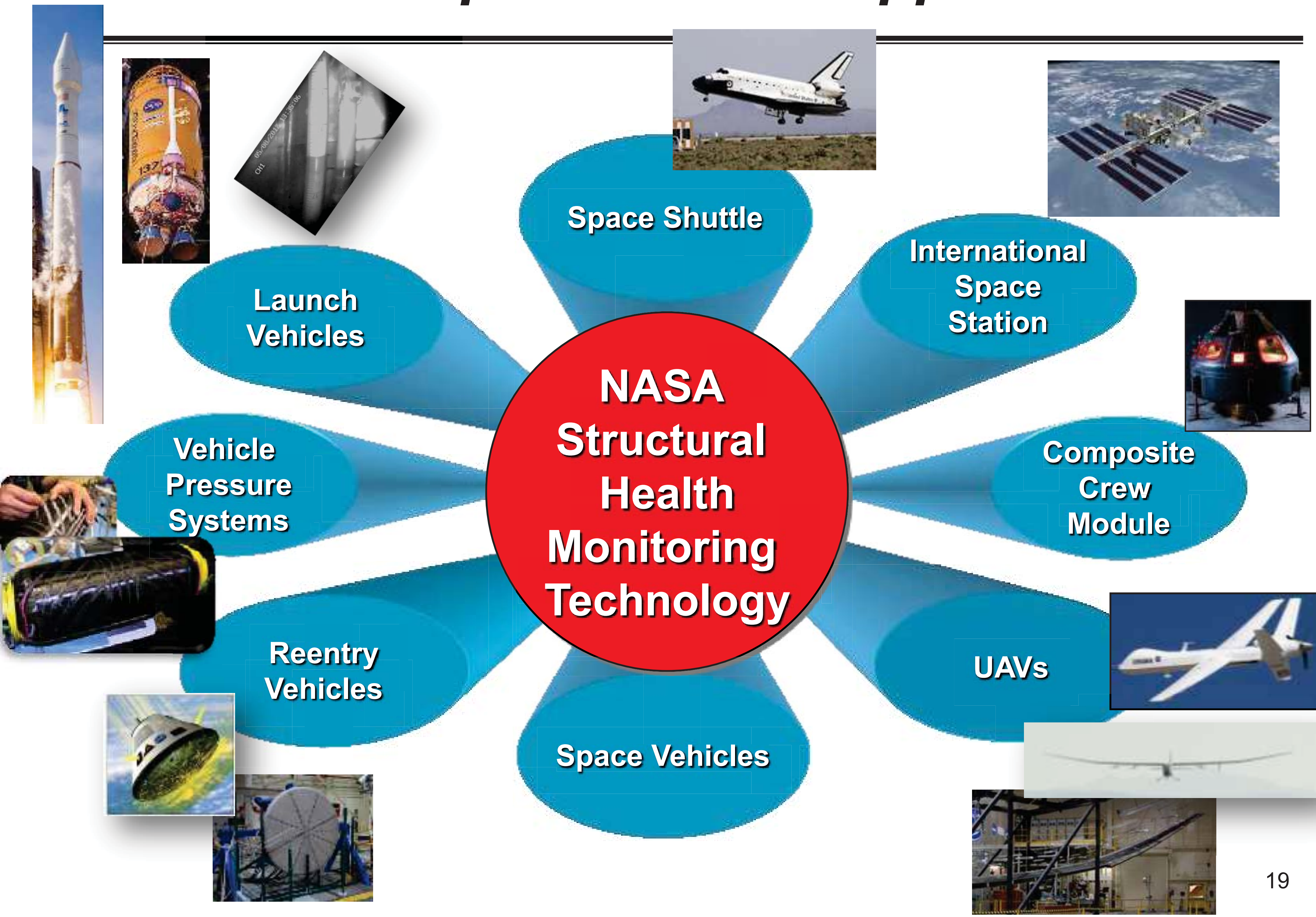
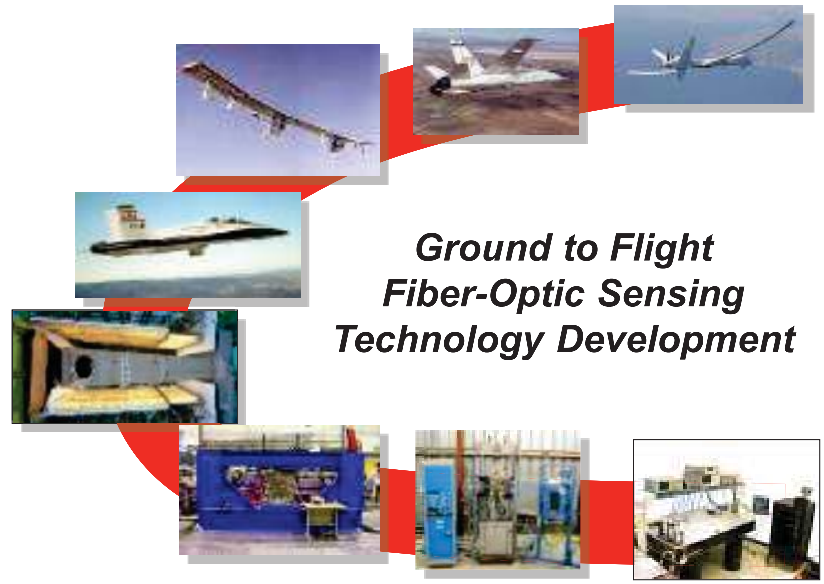
    - **Uninhabited Aerial Vehicles**
    - **Composite Crew Module**
    - **Reentry Vehicles**
    - **Space Vehicles**
    - **Vehicle Pressure Systems**
    - **Expendable Launch Vehicles**

SHM Aerospace Vehicle Applications

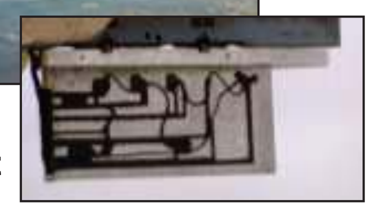


Fiber Optic Sensing System (FOSS)
Background

- **Dryden initiated fiber-optic instrumentation development effort in the mid-90's**
  - **Dryden effort focused on atmospheric flight applications of Langley patented OFDR demodulation technique**
- **Dryden focused on developing system suitable for flight applications**
  - **Previous system was limited due to laser technology**
  - **System limited to 1 sample every 90 seconds**
- **Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight**
- **Partnering with Kennedy Space Center, Launch Services Program, Dryden has developed a comprehensive portfolio of intellectual property that is now ready to be commercialized by the private sector.**



Ground to Flight Fiber-Optic Sensing Technology Development



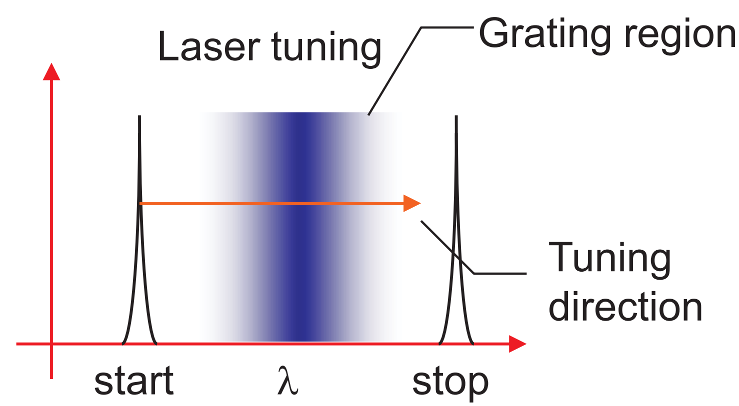
X-33 IVHM Risk Reduction Experiment

Fiber Optic Sensing System (FOSS)

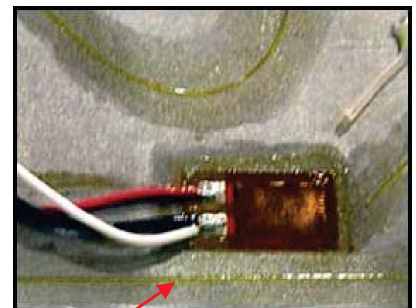
Operation Overview

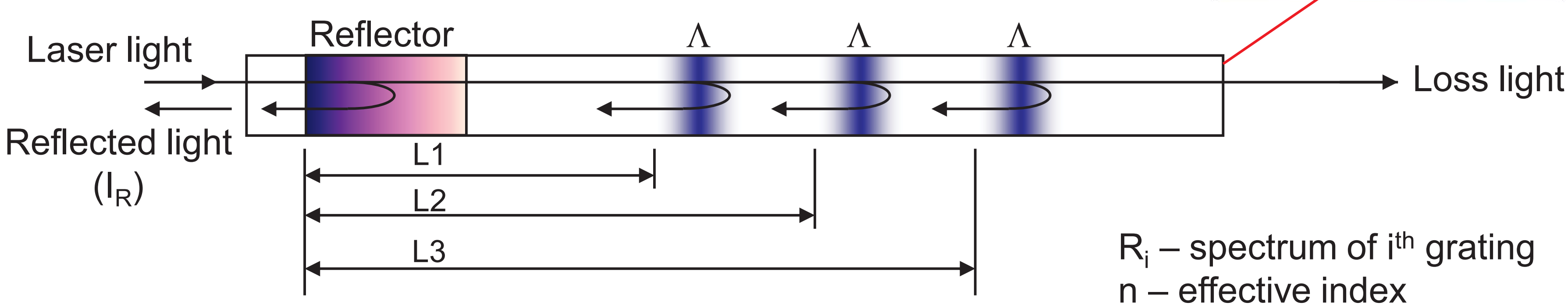
Fiber Optic Sensing with Fiber Bragg Gratings

- **Multiplex 1000s of sensors onto one "hair-like" optical fiber**
- **All gratings are written at the same wavelength**
- **Uses a narrowband wavelength swept laser source to interrogate sensors**
- **In addition to measuring strain and temperature, these sensors can be used to determine a variety of other engineering parameters**



$$I_R = \sum_i R_i Cos(k2nL_i) \qquad k = \frac{2\pi}{\lambda} \qquad \frac{\Delta\lambda}{\lambda} \rightarrow \mu\varepsilon$$





R_i – spectrum of i^{th} grating
n – effective index
L – path difference
k – wavenumber

Dryden's FOSS
Current Capabilities

Current system specifications

Fiber count	8
Max sensing length / fiber	40 ft
Max sensors / fiber	2000
Total sensors / system	16000
Max sample rate (flight)	100 sps
Max sample rate (ground)	60 sps
Power (flight)	28VDC @ 4.5 Amps
Power (ground)	110 VAC
User Interface	Ethernet
Weight (flight, non-optimized)	27 lbs
Weight (ground, non-optimized)	20 lbs
Size (flight, non-optimized)	7.5 x 13 x 13 in
Size (ground, non-optimized)	7 x 12 x 11 in

Environmental qualification specifications for flight system

Shock	8g
Vibration	1.1 g-peak sinusoidal curve
Altitude	60kft at -56C for 60 min
Temperature	-56 < T < 40C

Flight System

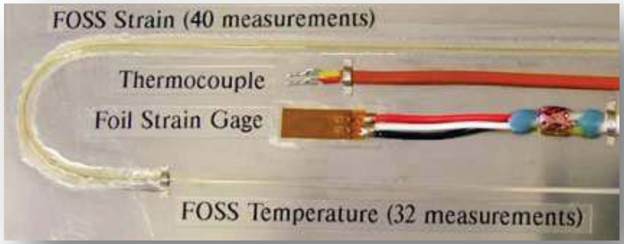
Ground System

Predator -B in Flight

Fiber Bragg Grating – Optical Frequency Domain Reflectometry

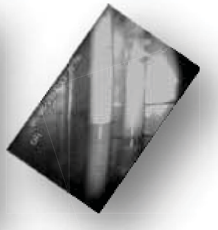
FBG-OFDR can dramatically improve structural and system efficiency for space vehicle applications by improving both affordability and capability by …

- Providing >100x the number measurements at 1/100 the total sensor weight
- Providing validated structural design data that enables future launch systems to be lighter and more structurally efficient
- Reducing data system integration time and cost by utilizing a single small system for space / launch vehicles
- Increasing capability of measuring multiple parameters in real time (strain, temperature, liquid level, shape, applied loads, stress, mode shapes, natural frequencies, buckling modes, etc.
- Providing an unprecedented understanding about system/structural performance throughout space craft and mission life cycle



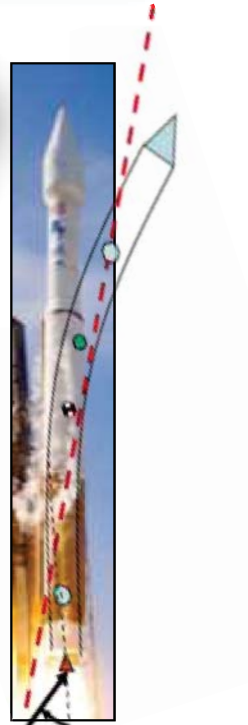
Centaur Coupon shown at PPBE review

Pressure monitoring



Liquid level sensing

ISS COPV strain & temp monitoring

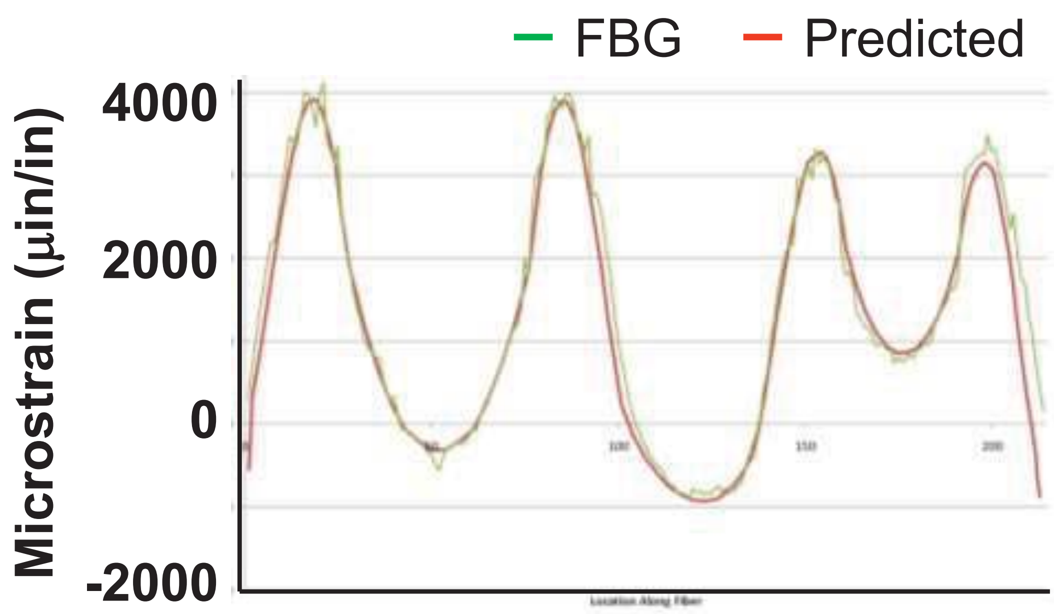


Shape sensing for vehicle control

Composite Crew Module
NASA NESC - Strain Sensing

National Aeronautics and Space Administration

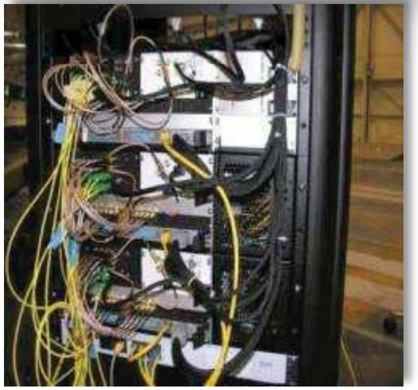
- Four fibers were installed around the module's three windows and one hatch
- 3300 real-time strain measurements were collected at 30Hz as the module underwent 200%DLL pressurization testing
- Measured strains were compared and matched well to predicted model results
- Project concluded:
  - "Fiber optics real-time monitoring of test results against analytical predictions was essential in the success of the full-scale test program."
  - "In areas of high strain gradients these techniques were invaluable."



Inner Hatch FBG Strains, Max Pressure

Uninhabited Aerial Vehicles
Global Observer UAS - Aerovironment

- Validate strain predictions along the wingspan
- Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.
- FO Strain distribution measurements are being used to interpret shape using Dryden's 2D shape algorithm
- A 24-fiber system was designed of which 18, 40ft fibers (~17,200 gratings) were used to instrument both left and right wings



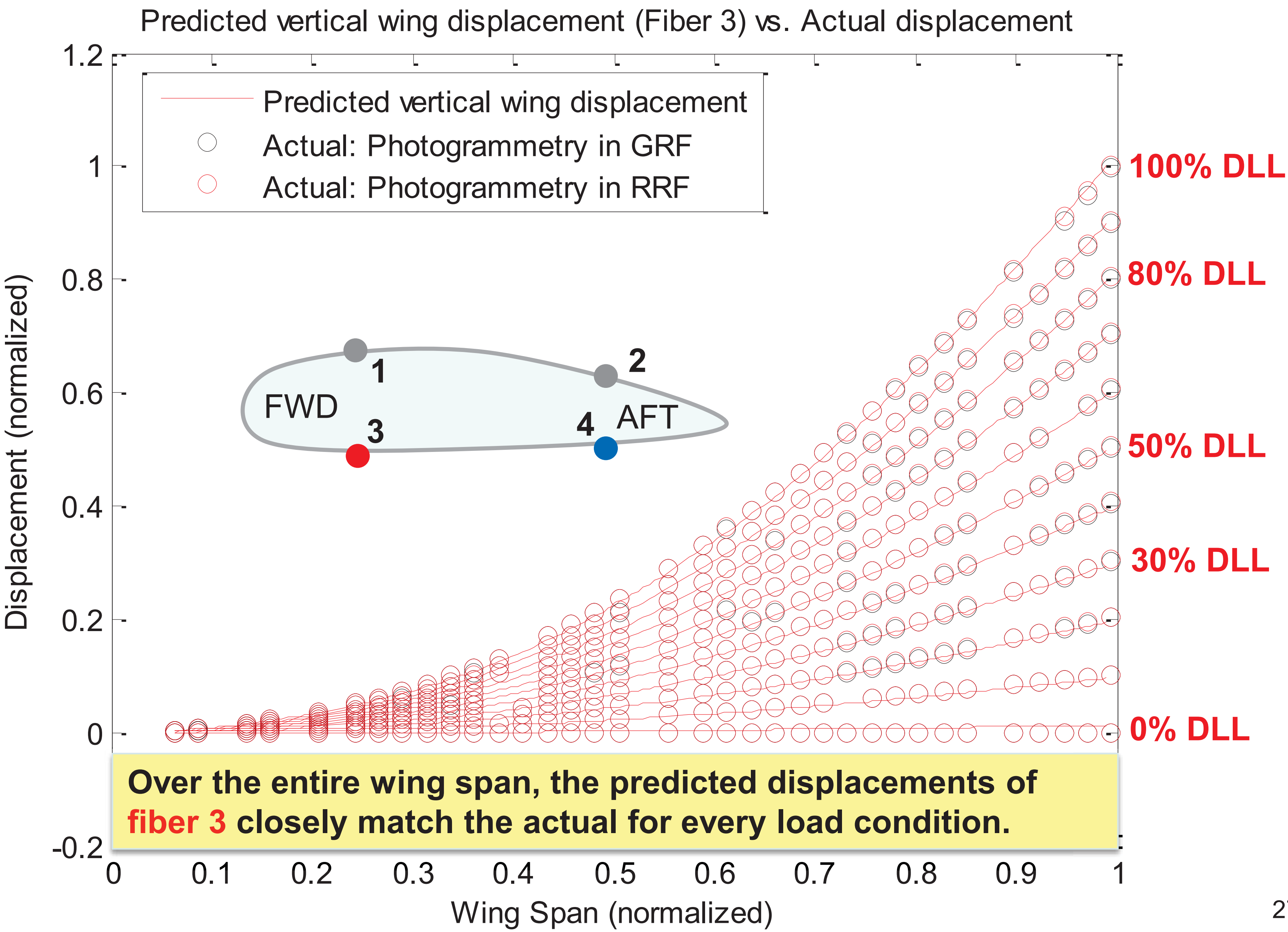
Uninhabited Aerial Vehicles

Global Observer UAS - Aerovironment

- Proof-load testing of components and large-scale structures

Uninhabited Aerial Vehicles

Global Observer (AV) - 2D Shape Sensing Results

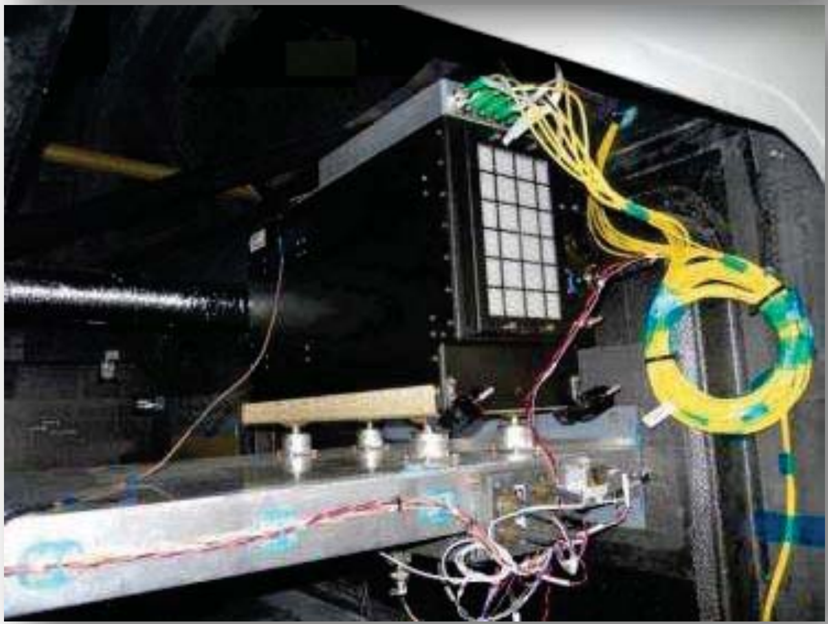


Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.

UAVs - Global Observer UAS (AV)

Flight Testing of Strain and 2D Shape Sensing

- Validate strain predictions along the left wing in flight using 8, 40ft fibers (~8000 strain sensors)
- An aft fuselage surface fiber was installed to monitor fuselage and tail movement
- Strain distribution were measured along the left wing centerline top and bottom as well as along the trailing edge top and bottom.
- 8 of the 9 total fibers are attached to the system at any give time
- The system performed well and rendered good results



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Predator-B UAS - Flight Testing
Strain and 2D Shape Sensing

- 18 flights tests conducted; 36 flight-hours logged
- Conducted first flight validation testing April 28, 2008
- Believed to be the first flight validation test of FBG strain and wing shape sensing
- Multiple flight maneuvers performed
- Total of 6 fibers (~3000 strain sensors) installed on left and right wings
- Fiber optic and conventional strain gages show excellent agreement
- FBG system performed well throughout entire flight program

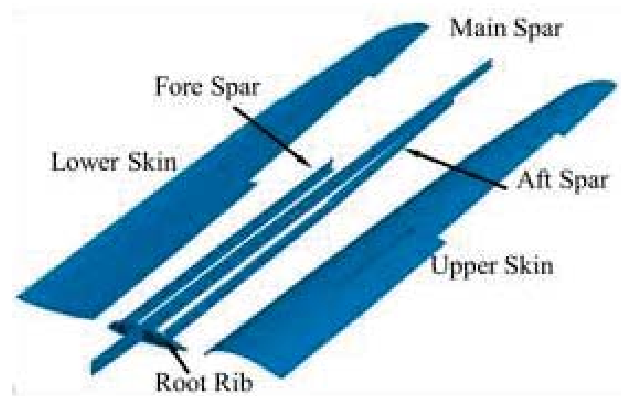
Video clip of flight data superimposed on Ikhana photograph

Full-Scale Composite Wings

Strain, Applied Loads, and 2D Shape - Mississippi State

ENGINEERING PROPERTIES OF COMPOSITE MATERIALS.

Material Properties	Woven fabric Toray-T700G	Unidirectional fabric Toray-T700S	Foam core DIAB Divinycell HT 50
E_{11}, GPa	5.54 x 10^{1}	1.19 x 10^{2}	8.50 x 10^{-2}
E_{22}, GPa	5.54 x 10^{1}	9.31 x 10^{0}	--
$G_{12,}$ GPa	4.21 x 10^{0}	4.21 x 10^{0}	--
ν_{12}	3.00 x 10^{-2}	3.10 x 10^{-1}	3.20 x 10^{-1}
ρ, kg/m^3	1.49 x 10^{3}	1.52 x 10^{3}	4.95 x 10^{-1}



Full-Scale Composite Wings

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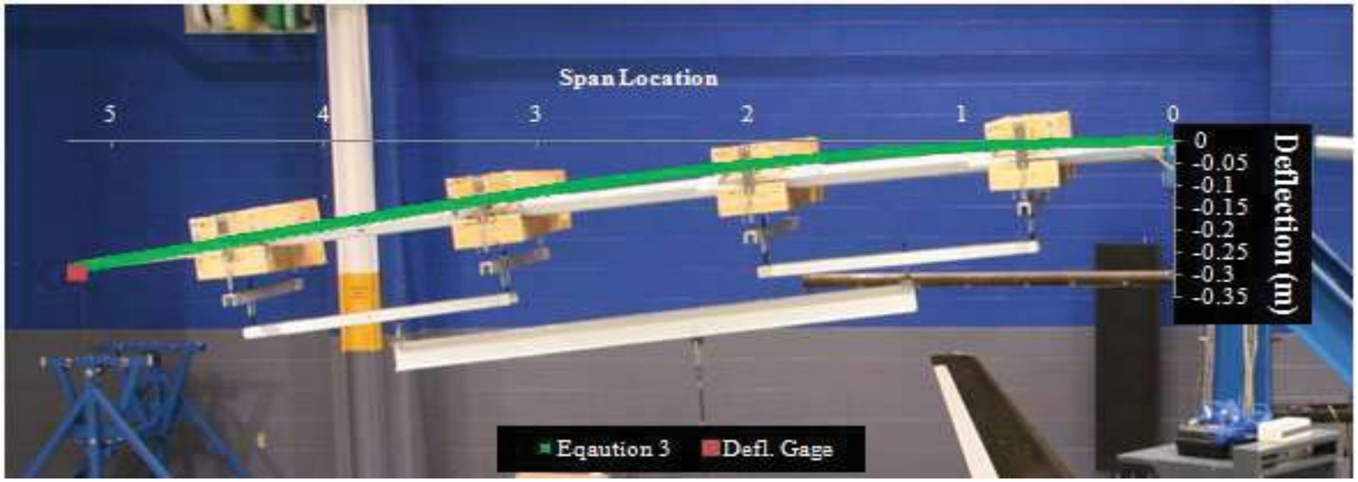


MEASURED AND CALCULATED WING TIP DEFLECTIONS

F, N	Measured δ_L, m	Calculated δ_L, m	Error, %
1373	-0.184	-0.178	3.02
1592	-0.209	-0.205	2.29
1837	-0.241	-0.231	4.08
2036	-0.265	-0.257	3.23
2269	-0.295	-0.284	3.75

Test Procedure for displacement

- Collect FBG strain data
- Use displacement Eq. and Strain data to calculate deflection

OUT-OF-PLANE APPLIED LOAD

Applied Load, N	Calculated Load, N	Error, %	Difference, N
-185.5	-178.8	3.60	6.7
-194.4	-210.0	7.98	15.5
-241.5	-252.0	4.35	10.5
-288.5	-291.5	1.05	3.0
-333.3	-332.9	0.12	0.4
-378.1	-381.1	0.80	3.0
-422.9	-435.9	3.07	13.0
-472.2	-486.4	3.01	14.2
Average EI=98728.2-N*m^2			

Test procedure for out-of-plane loads

- Determine EI for the wing
- Determine moment acting on wing
- Determine Load applied

Next Generation Structural Health Monitoring on Reentry Vehicles

Personal Observations

- The Shuttle never returned in the same condition as when it launched
- Flight operations always reveals the unexpected and make known the unknowns
- NASAs SHM fiber optic sensors are much lighter than conventional strain gage sensors
- FOSS-OFDR provides massive amounts of quantitative structural performance information in real time and for post test analysis
- This quantitative information can overcome some of the unknown unknowns that may allow you to fly another day

STS Landing at Edwards AFB

Post-flight Inspection

Dream Chaser Re-entry (artist conception)

Monitoring of MMOD Impact Damage to TPS
NASA Dryden / CSIRO Australia collaboration

Objective

- Detect & evaluate Micrometeoroid and Orbital Debris (MMOD) impact damage to Thermal Protection Systems (TPS) using embedded acoustic and thermal sensor networks

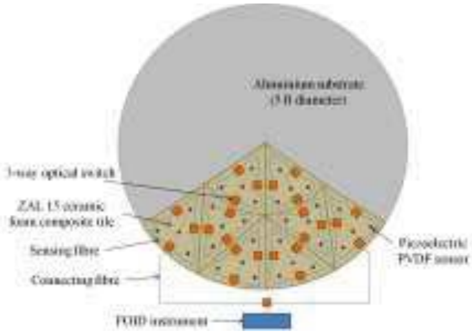
Principles

- Detect and locate impacts using acoustic emission sensor networks
- Evaluate severity of damage with optical fiber thermal sensor network
- Utilize centralised or self-organising operation with local network architecture on modular tiled structure

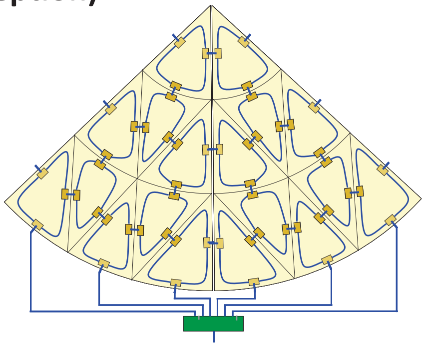
Novel aspects

- Development of switched optical fiber sensor network to enhance robustness
- Capable of central control or autonomous self-organising operation.
- Functional damage evaluation – monitor effect on thermal properties.

Vehicle Re-entry (artist conception)



Heat shield with TPS



TPS health monitoring system

Two TPS modules

Heat shield Test Setup at Dryden

Vehicle Pressure Systems

Embedded Strain - The Multidisciplinary Challenge

- **Fiber Optic Sensors embedded within Composite Overwrapped Pressure Vessels**
- **Goal is to understand embedded FBG sensor response**
  - **Requires comprehensive, multi-disciplinary approach**

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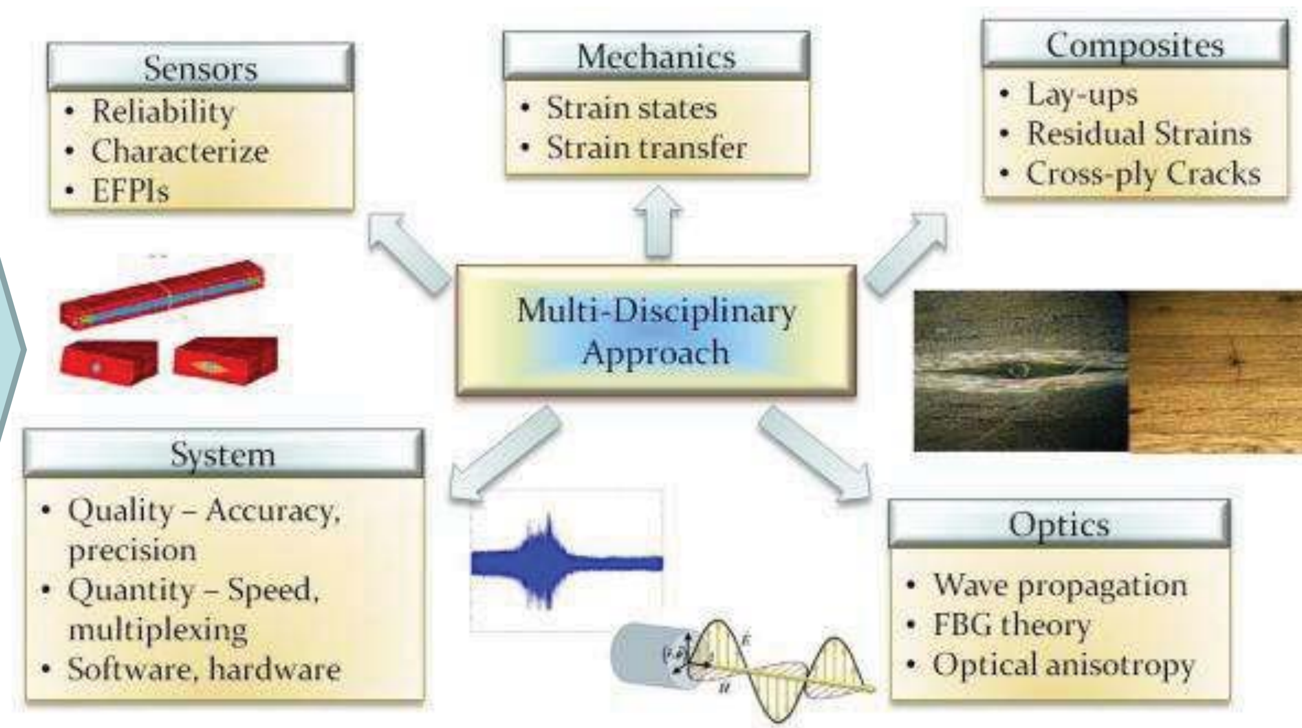


Vehicle Pressure Systems

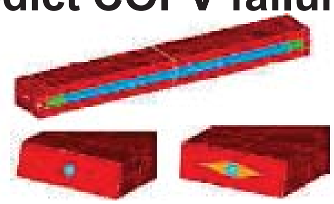
Composite Overwrapped Pressure Vessels (COPVs)

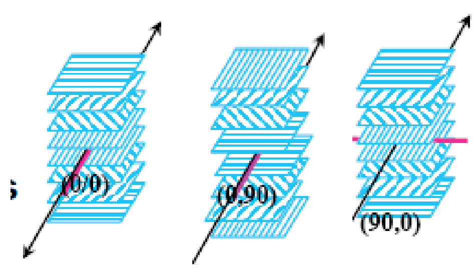
Objectives

- Perform real-time in-situ structural monitoring of COPVs with embedded fiber Bragg grating sensor arrays
- Develop analytical and experimental methods to reliably interpret embedded strain sensor measurements
- Develop a robust “early-warning” indicator of COPV catastrophic failure
- Provide finite-element-like experimental strains in real time for:
  - Health Monitoring on International Space Station
  - Model validation to improve future designs

Approach

- Develop and evaluate surface-attachment techniques
- Install surface fiber optic sensors
- Conduct test to 80% of burst pressure
- Overwrap surface FBGs with composite layers
- Install new surface FBGs over “embedded” FBGs
- Conduct burst test
- Develop data analysis and visualization techniques to reliably predict COPV failure





NASA Dryden and WSTF test team

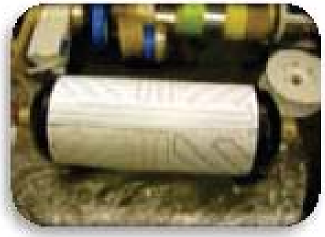
Composite Overwrapped Pressure Vessels

Installation Methods

Installation methods developed

- Transfer pattern to bottle surface

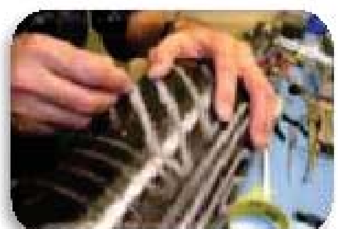





- Mask and fill basecoat paths

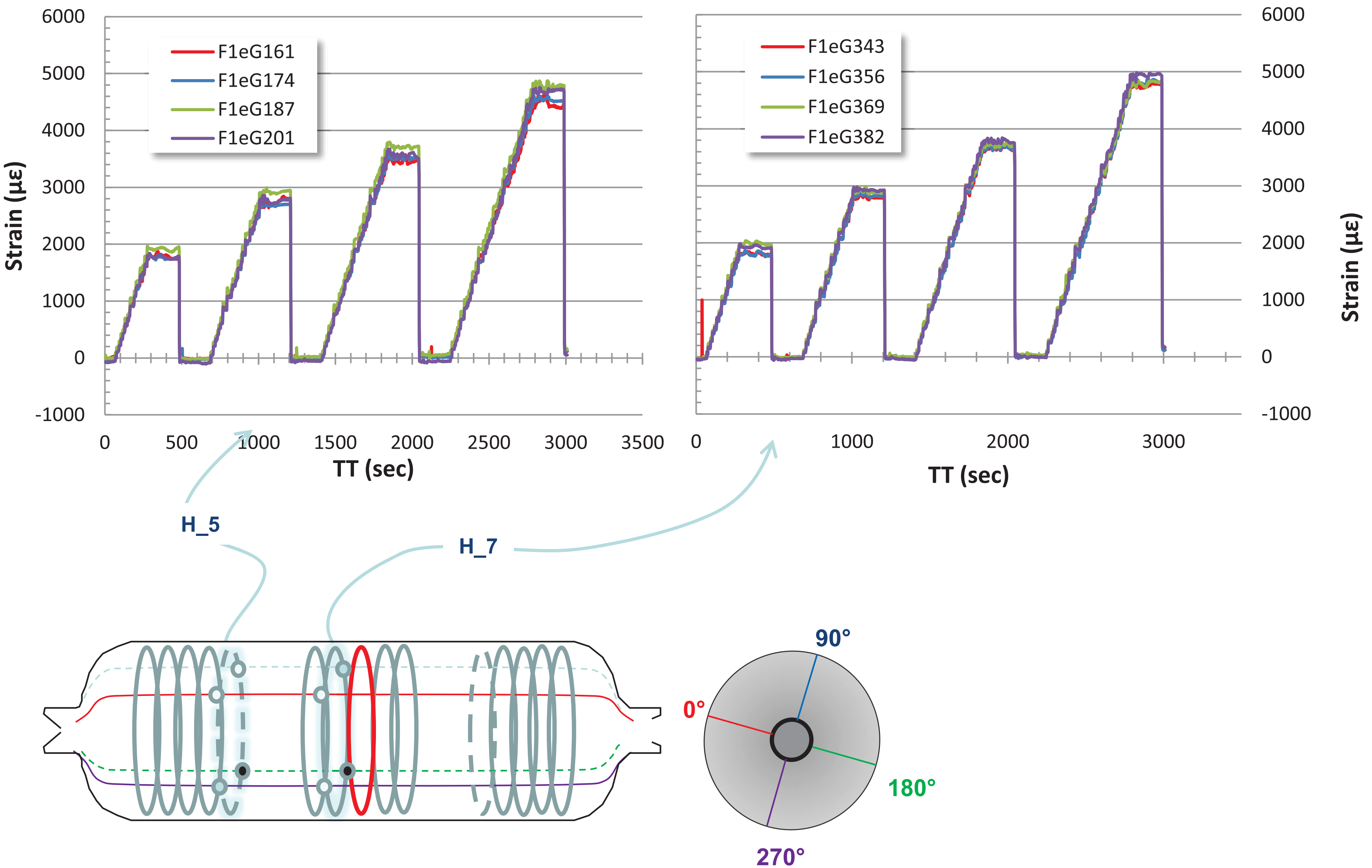



- Sand down close to surface layer



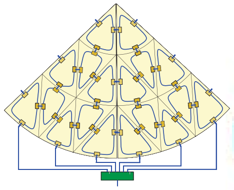
- Route and attach FBGs

Embedded Fiber to 5000 psi
Hoop Direction



FOSS Current and Future Work

Flight Demonstration on a Launch Vehicle (KSC-Launch Services)



TPS Health Monitoring

Embedded Strain

Magnetic Field

Applied Loads

Strain

Temperature and *Cryogenic* Liquid Level

2D Shape

3D Shape

National Aeronautics and Space Administration

Cryogenic Liquid Level-Sensing

The Challenge

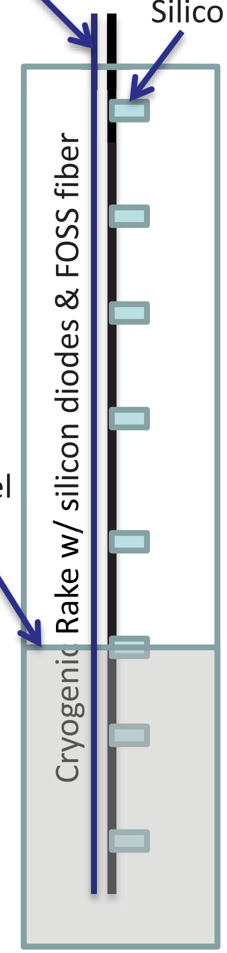
- The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements
- Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level along with high wire count

FOSS Approach

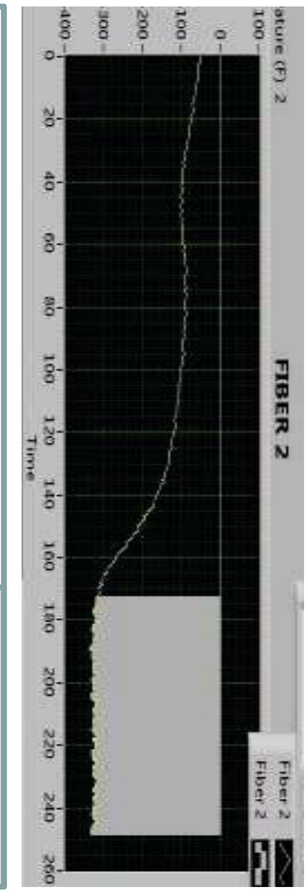
- While using a uniquely developed fiber optic structure (CryoFOSS), the transitional phase can be mapped more accurately
- Using a single continuous grating fiber, a high degree of spatial resolution can be achieved, as low as 1/16"

Cryogenic Container located at MSFC (above deck)

Cryogenic Container located at MSFC (below deck)



Cryogenic Container



1st Gen CryoFOSS Test Results

National Aeronautics and Space Administration

LH_2 Testing of CryoFOSS at MSFC

Objective

- Experimentally validate CryoFOSS using Dryden's FOSS technology

Test Details

- Dewar dimensions: 13-in ID x 37.25-in
- Fill levels of 20%, 43%, and 60% were performed
- Instrumentation systems
  - Video boroscope with a ruler (validating standard)
  - Cyrotracker (ribbon of 1-in spaced silicon diodes)
  - MSFC Silicon diode rake
  - Fiber optic LH_2 liquid level sensor(CryoFOSS)

Results

- CryoFOSS sensor discerned LH_2 level to ¼" in every case
- Excellent agreement achieved between CryoFOSS, boroscope, and silicon diode Cryotracker

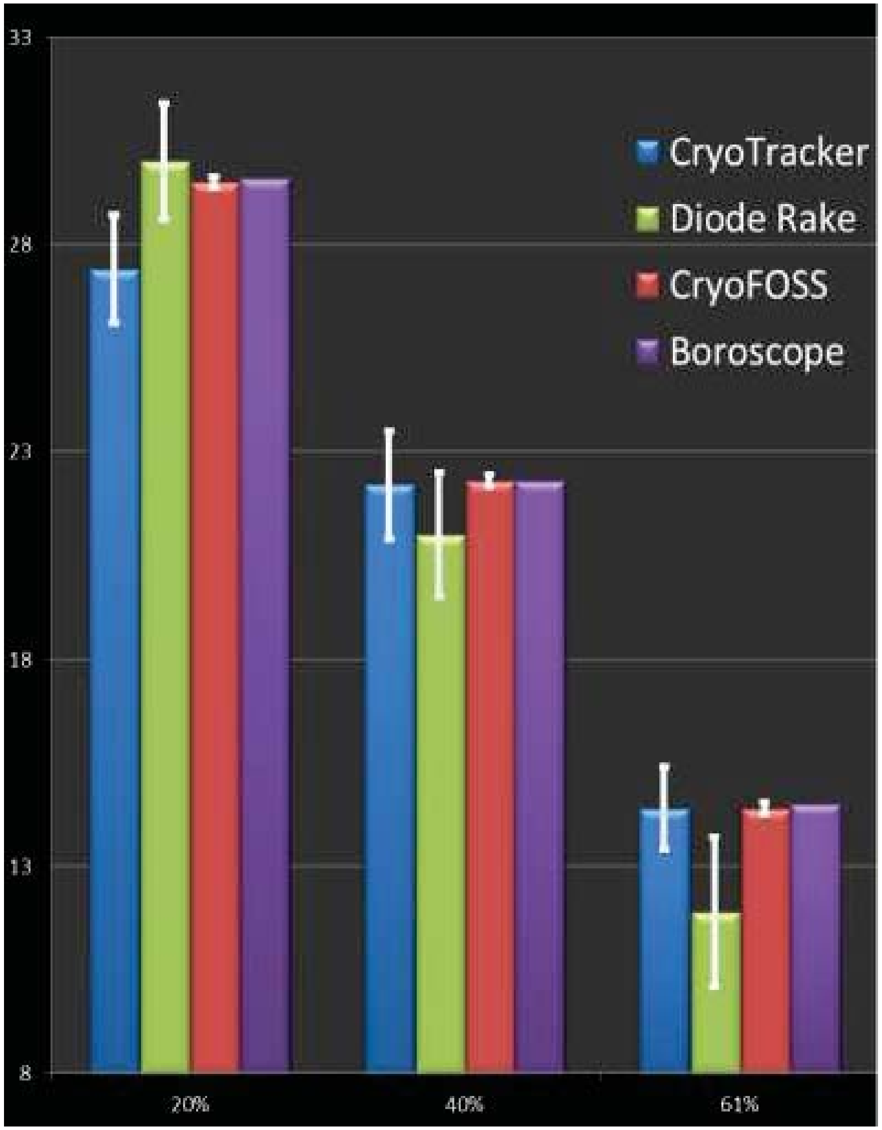
Bottom line

- Validated concept for a lightweight, accurate, spatially precise, and practical solution to a very challenging problem for ground and in-flight cryogenic fluid management systems

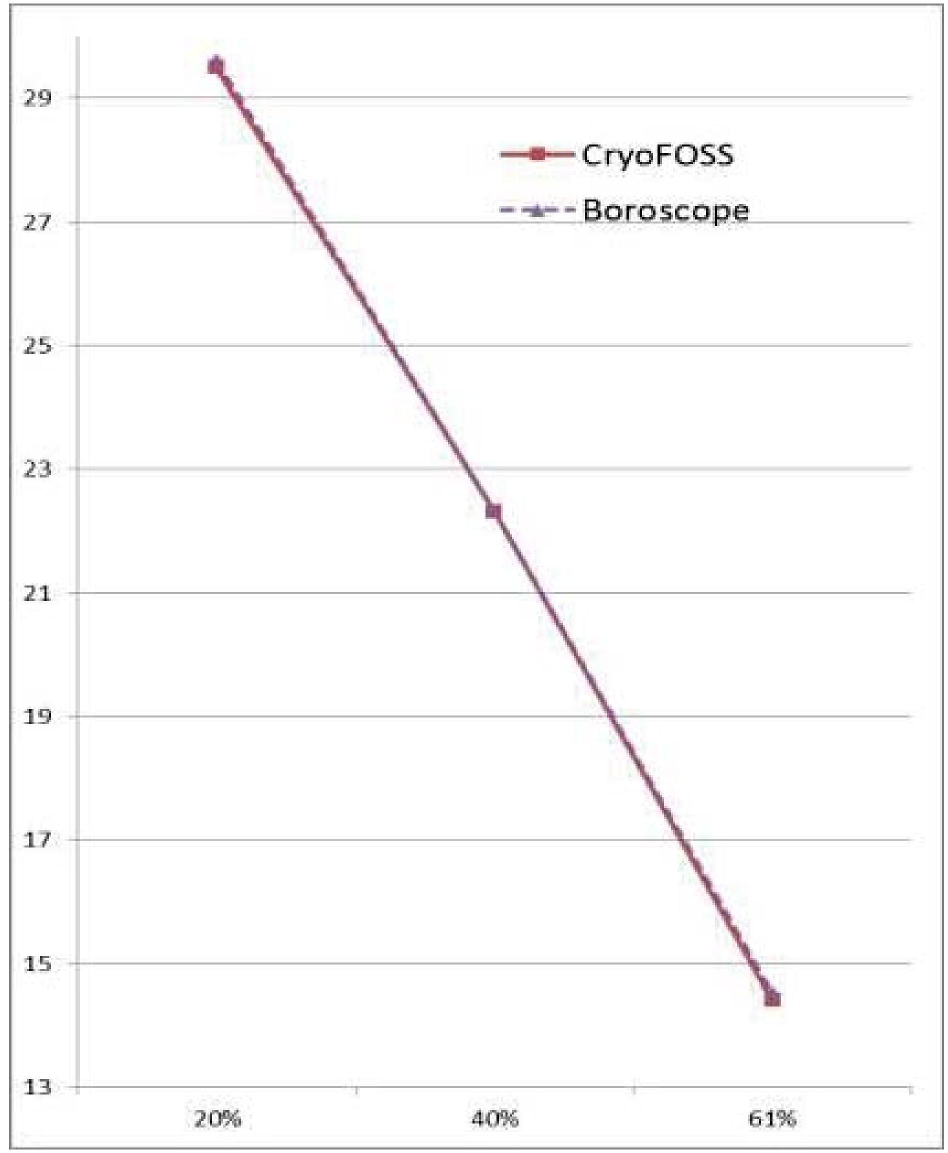
Cryo-FOSS

National Aeronautics and Space Administration

LH_2 Liquid Level Results



Combined Results



CryoFOSS compared to Boroscope

Magnetic Field Sensing

NASA Dryden / UCLA collaboration

Objective

- To utilize the same magnetically sensitive particles that birds use, for example, to sense Earth's magnetic field for migratory purposes

Application

- Installing distributed magnetic sensors on a structure could help with navigation
- Identifying disturbances in Earth's magnetic field could indicate the presence of another vehicle or a missile

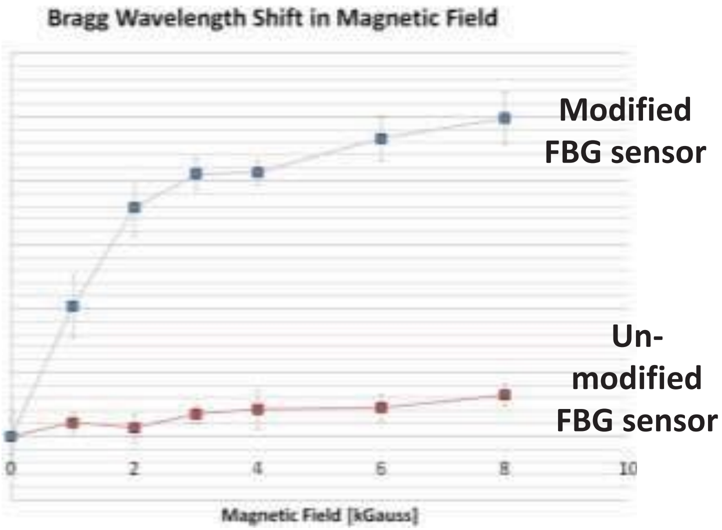
Approach

- Fabricate new fiber optic sensor with greater sensitivity to magnetic field (H)
- Apply magnetic field to sensors
- Measure wavelength shifts ($\Delta\lambda_B$)
- Behavior of λ_B should follow magnetization behavior of modified sensor

Results

- Experimental results corroborate the theory
- Currently developing new methods for increasing sensitivity of detecting magnetic fields

Lohmann, Nature, V.464 (2010)



Fiber optic Magnetic Field Sensor