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NASA Applications of Structural Health Monitoring Technology

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9th International Workshop on Structural Health Monitoring
Stanford University
September 10, 2013

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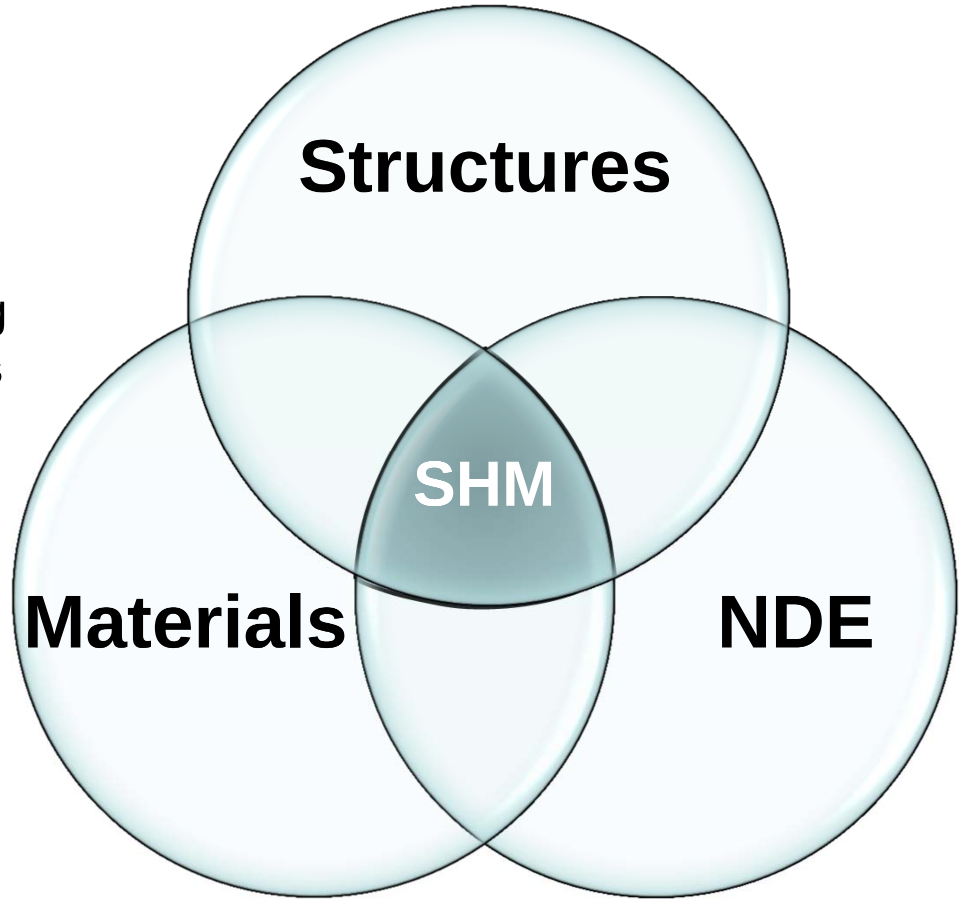
NASA Focused Structural Health Monitoring

Key Drivers

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



Enabling Technologies

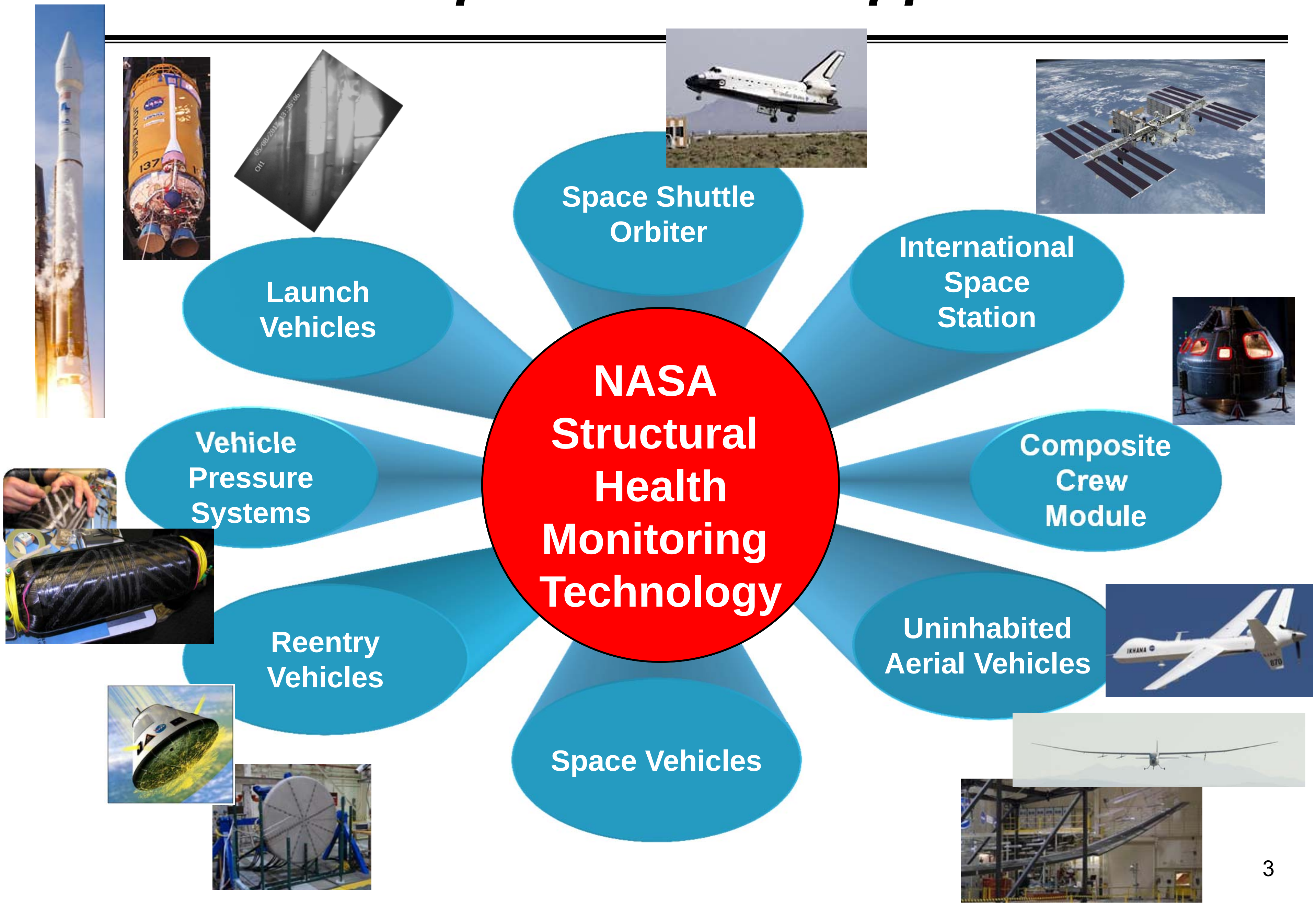
Advanced Sensing
- Multi-parameter
- Sensor arrays

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

Ultra-Efficient Algorithms




SHM Aerospace Vehicle Applications



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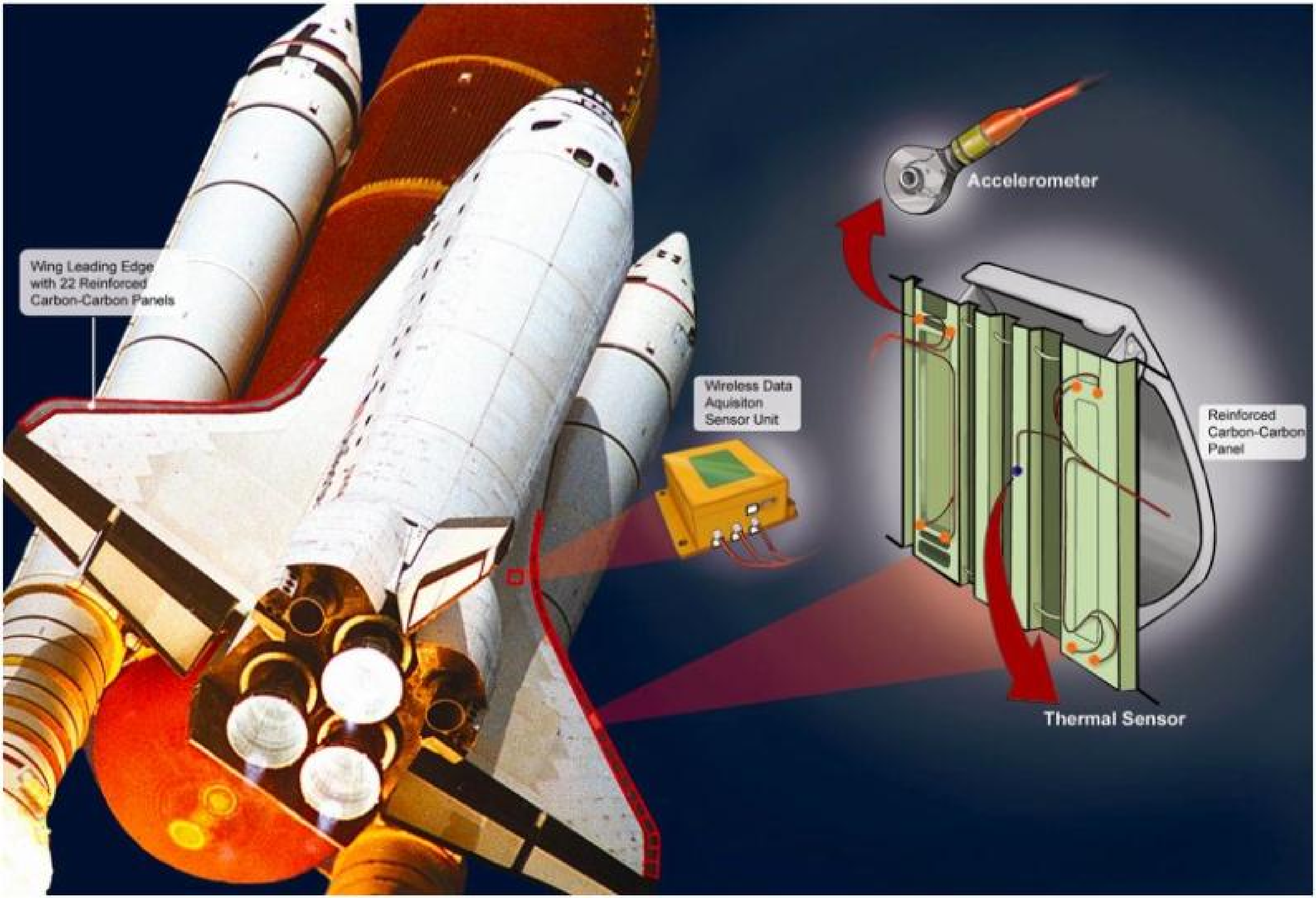
Topics

- **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)



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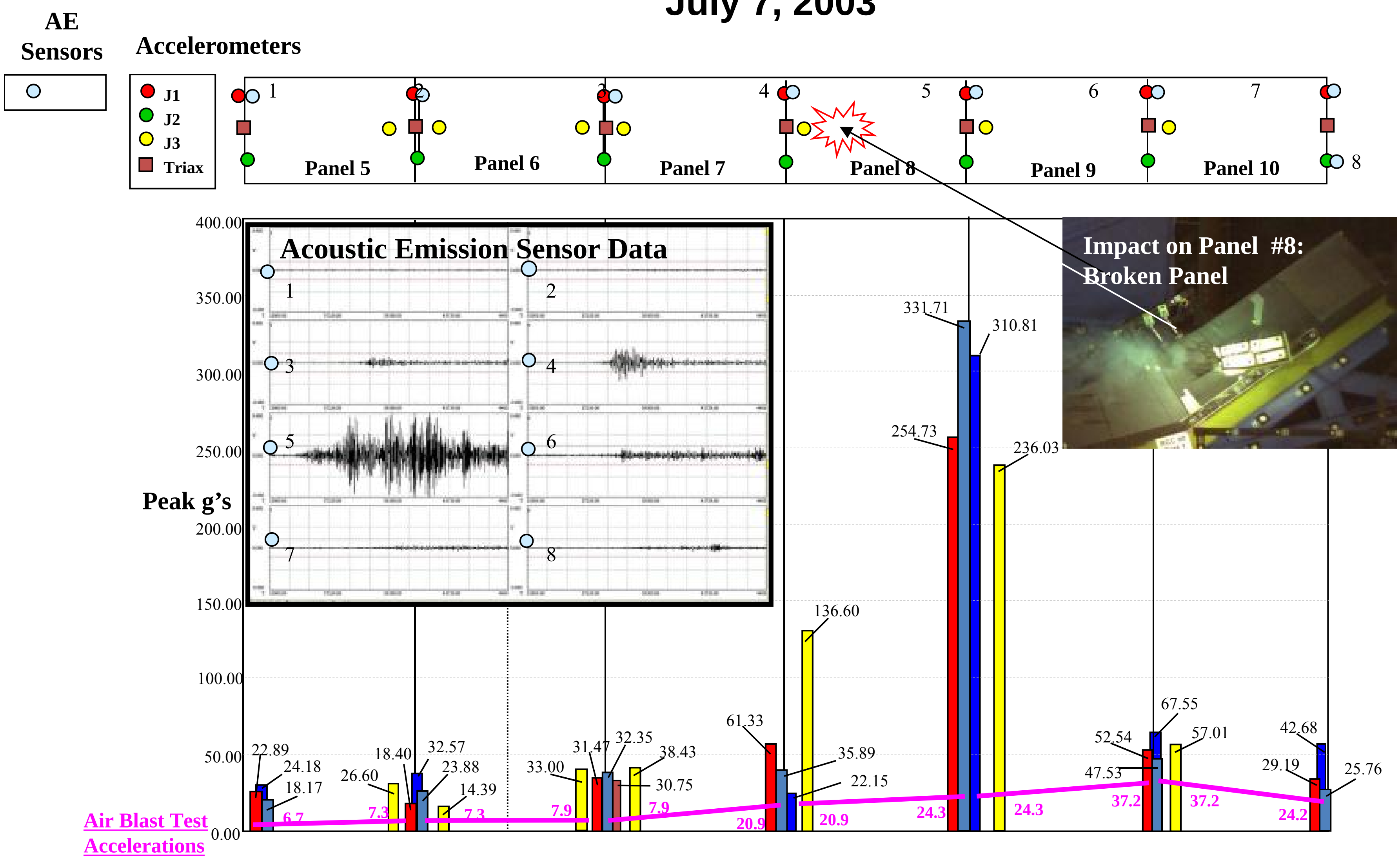
Columbia Accident Investigation
Catastrophic Impact Damage Test on RCC Panel 8

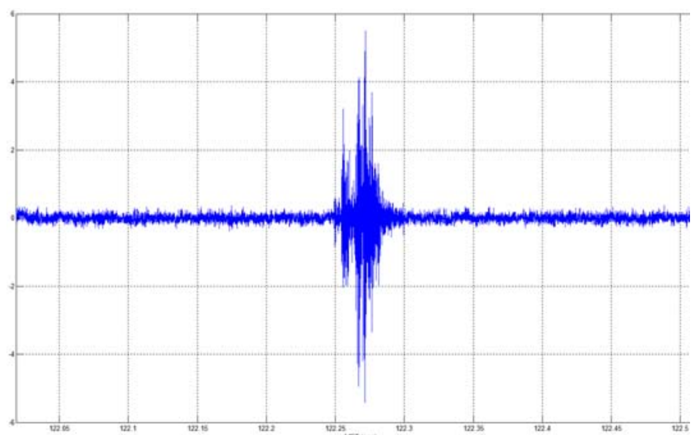
July 7, 2003



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

ISS assembly | Columbia | Shuttle fleet | DIDS

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

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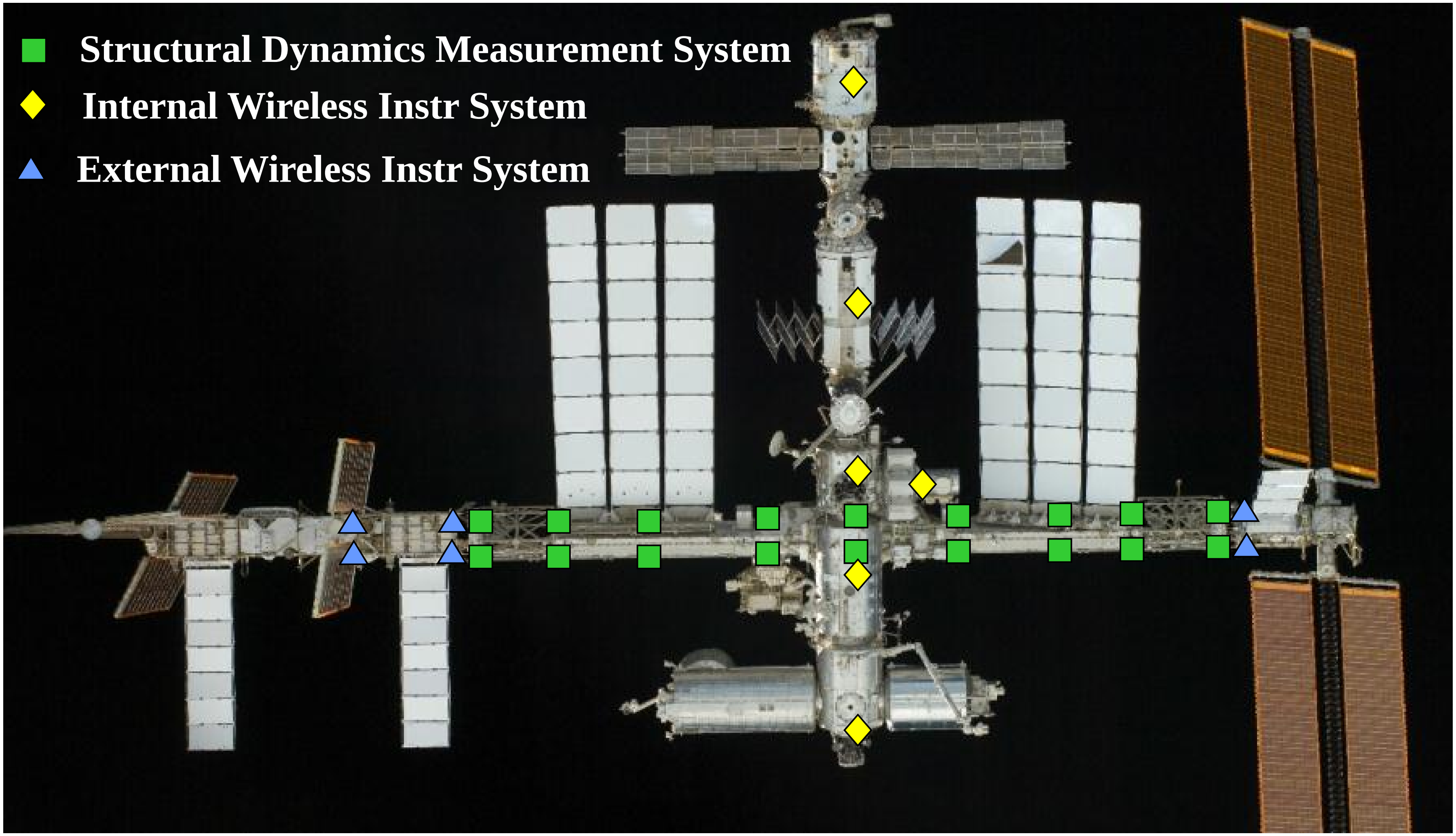
ISS Structural Dynamics Accelerometers



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

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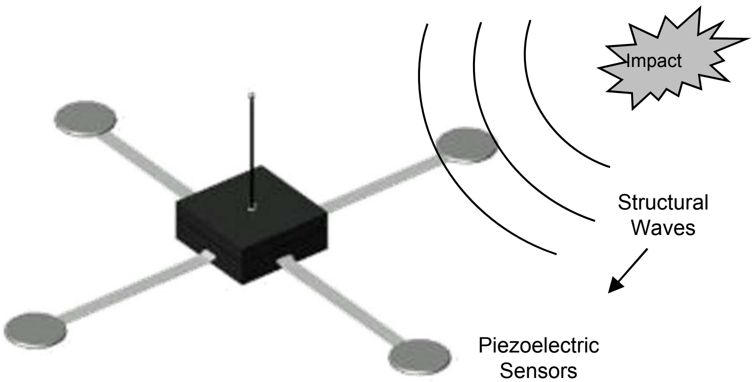
Distributed Impact Detection System Concept

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



DIDS System Concept

MMOD strike example

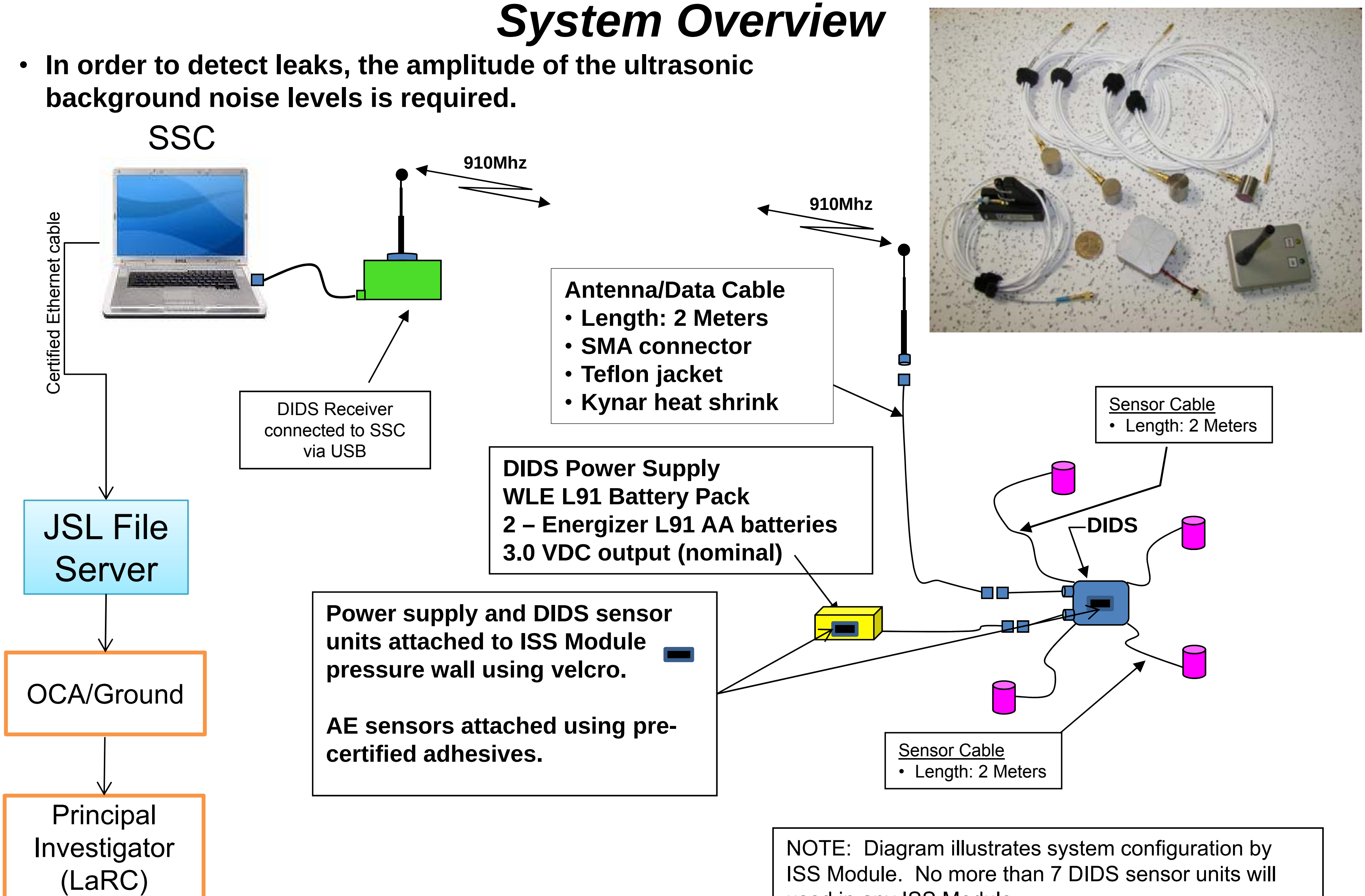
Module is asleep until event signal threshold is crossed.
Sensor module can record four signals at 1MHz rate.
Sensors can record and transmit ~6000 events.
Batteries can last up to 5 years.
Laptop computer can control multiple units.

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

ISS Ultrasonic Background Noise Test (UBNT)

System Overview

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



NOTE: Diagram illustrates system configuration by ISS Module. No more than 7 DIDS sensor units will used in any ISS Module.

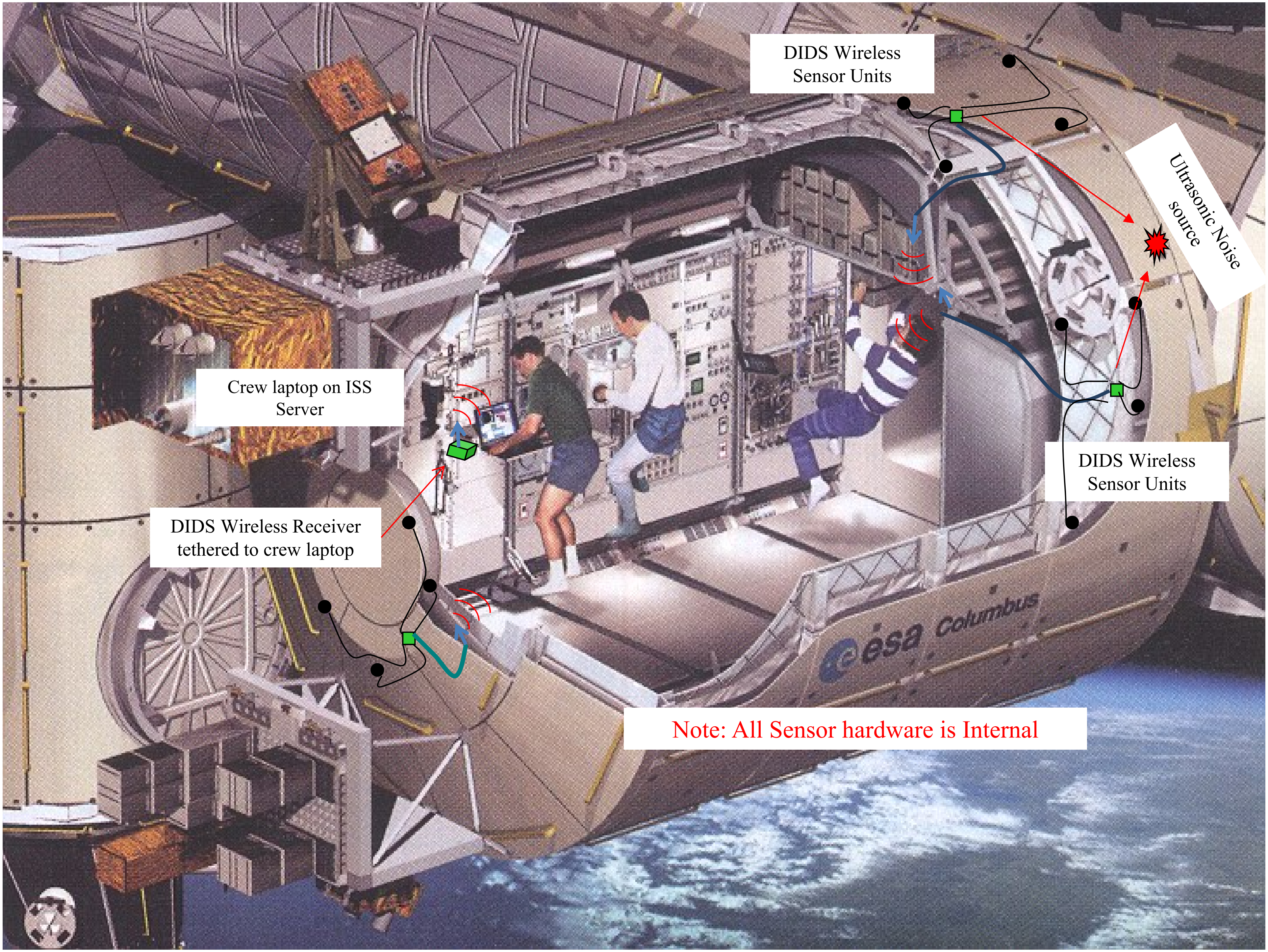

DIDS Wireless
Sensor Units
Ultrasonic Noise
source
Crew laptop on ISS
Server
DIDS Wireless
Sensor Units
DIDS Wireless Receiver
tethered to crew laptop
esa Columbus
Note: All Sensor hardware is Internal

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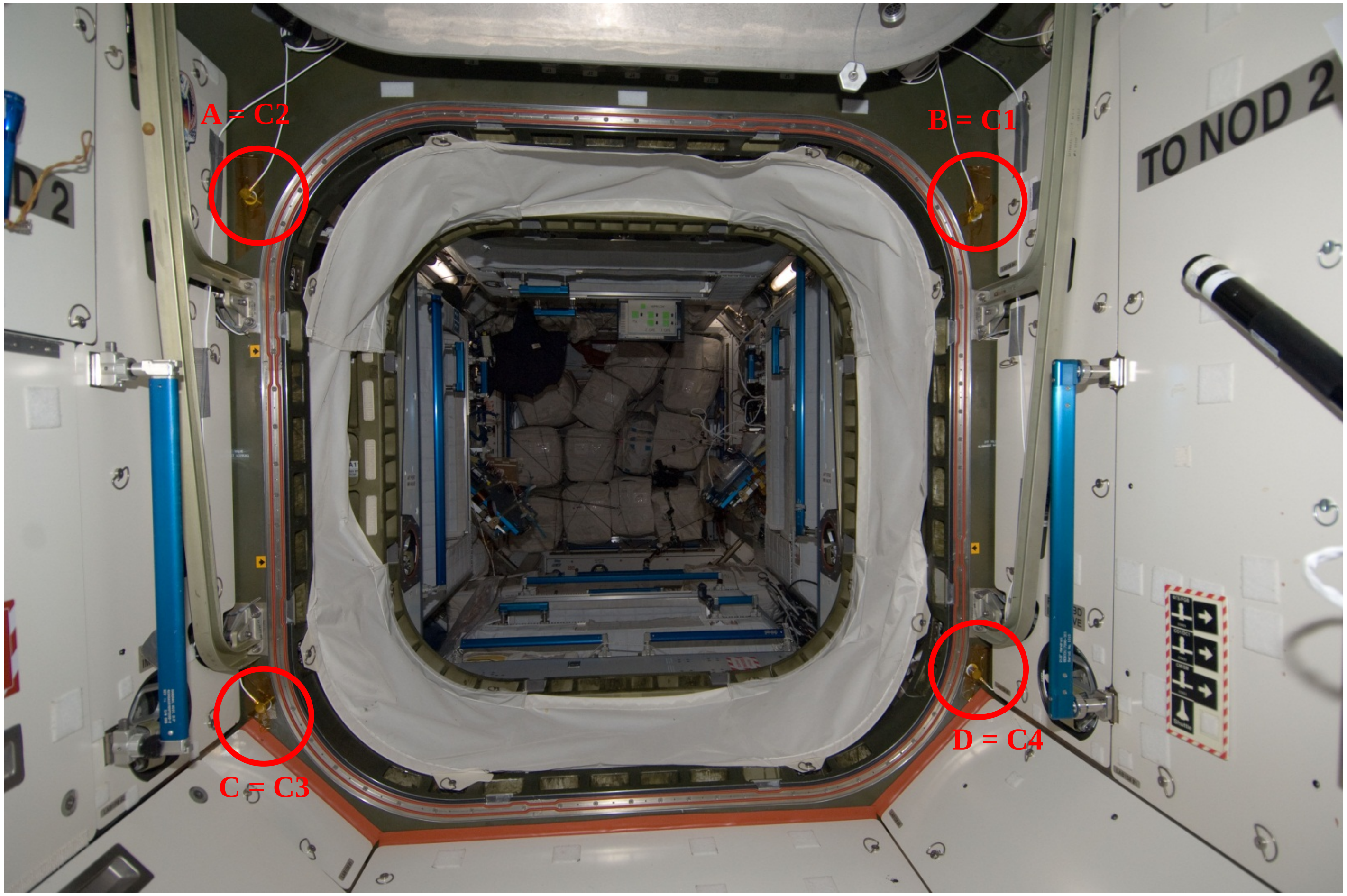
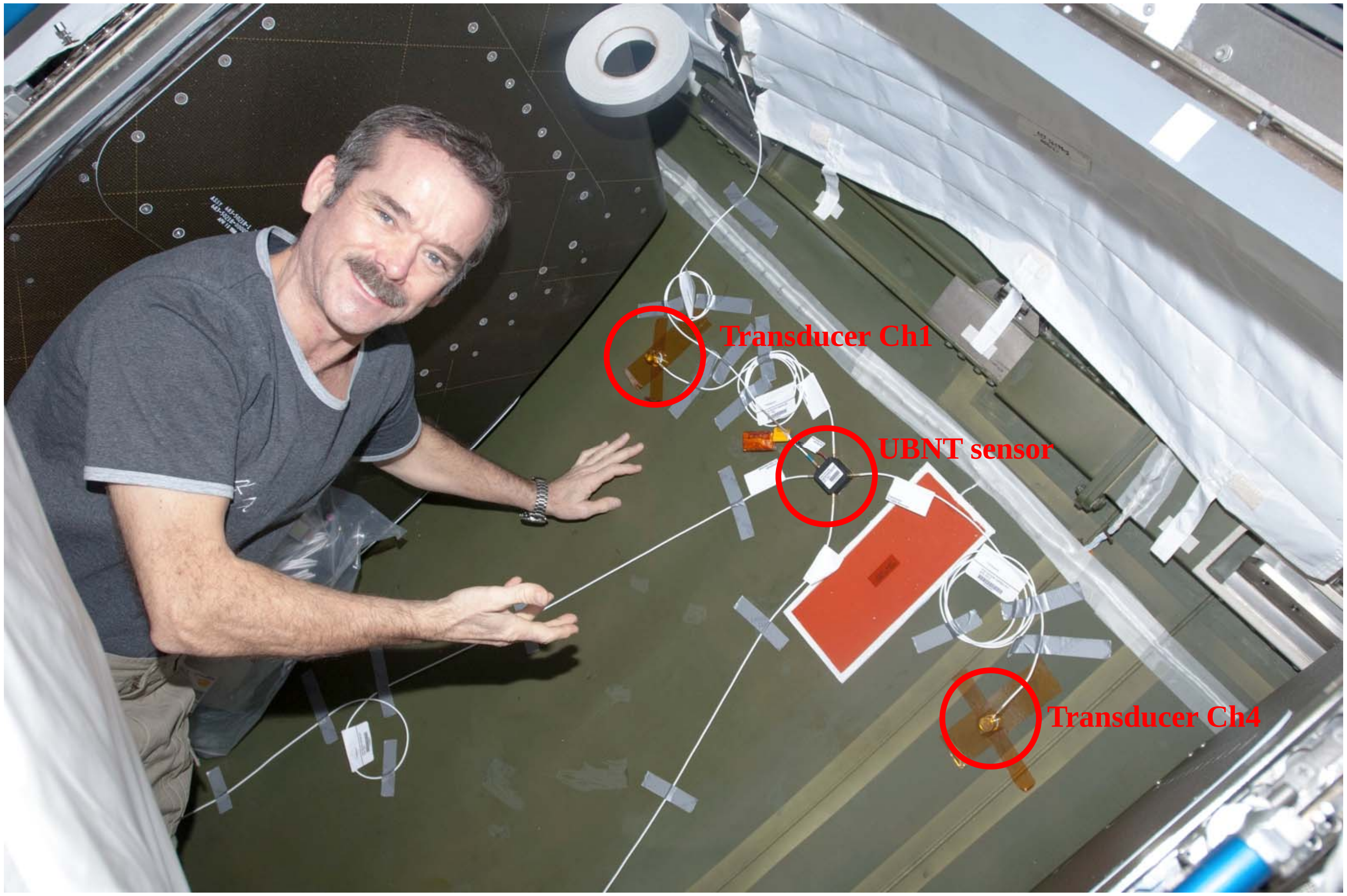
Photo of Forward Hatch with UBNT Sensors Installed



Data recorded on Dec. 12, 2012. Twenty-four hour data take.

Photo of Behind the Rack of USLab1O5 with UBNT Sensors Installed



Installed during Feb, 2013 by Chris Hadfield (shown)

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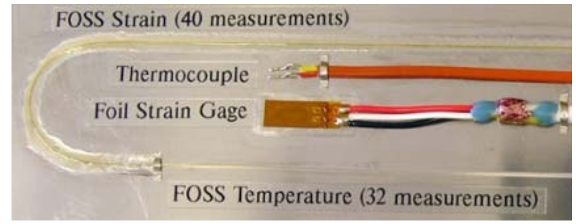
    - **Uninhabited Aerial Vehicles**
    - **Composite Crew Module**
    - **Reentry Vehicles**
    - **Space Vehicles**
    - **Vehicle Pressure Systems**
    - **Expendable Launch Vehicles**

Fiber Bragg Grating (FBG)
Optical Frequency Domain Reflectometry (OFDR)

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

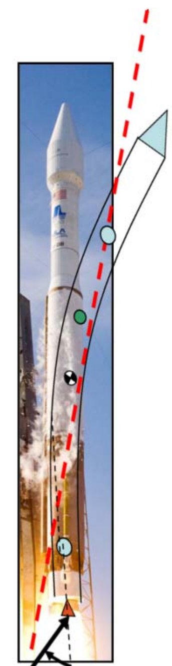


Centaur Coupon

Pressure monitoring

Liquid level sensing

ISS COPV strain & temp monitoring



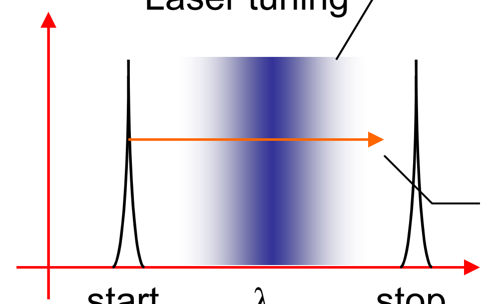
Shape sensing for vehicle control

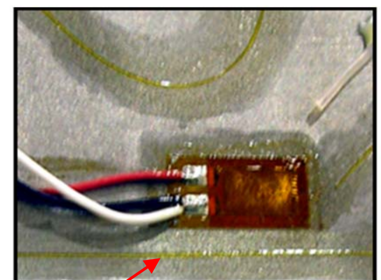
Fiber Optic Sensing System (FOSS)

Operation Overview

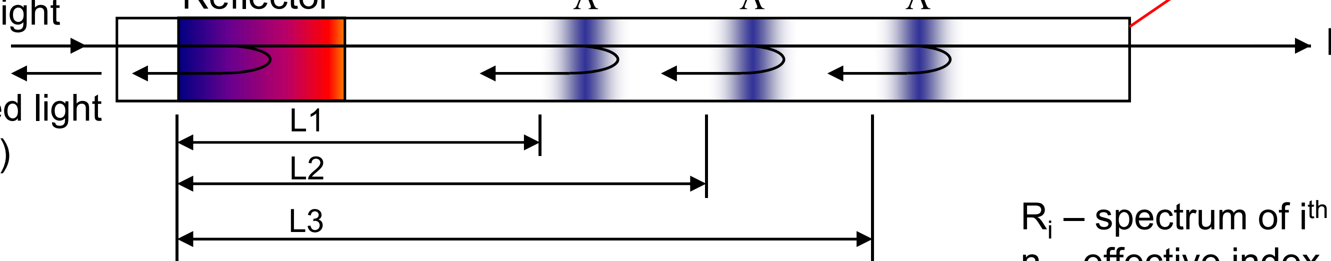
Fiber Optic Sensing with Fiber Bragg Gratings

- **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**





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



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	80 ft
Max sensors / fiber	4000
Total sensors / system	32,000
Max sample rate (flight)	100 sps
Max sample rate (ground)	100 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

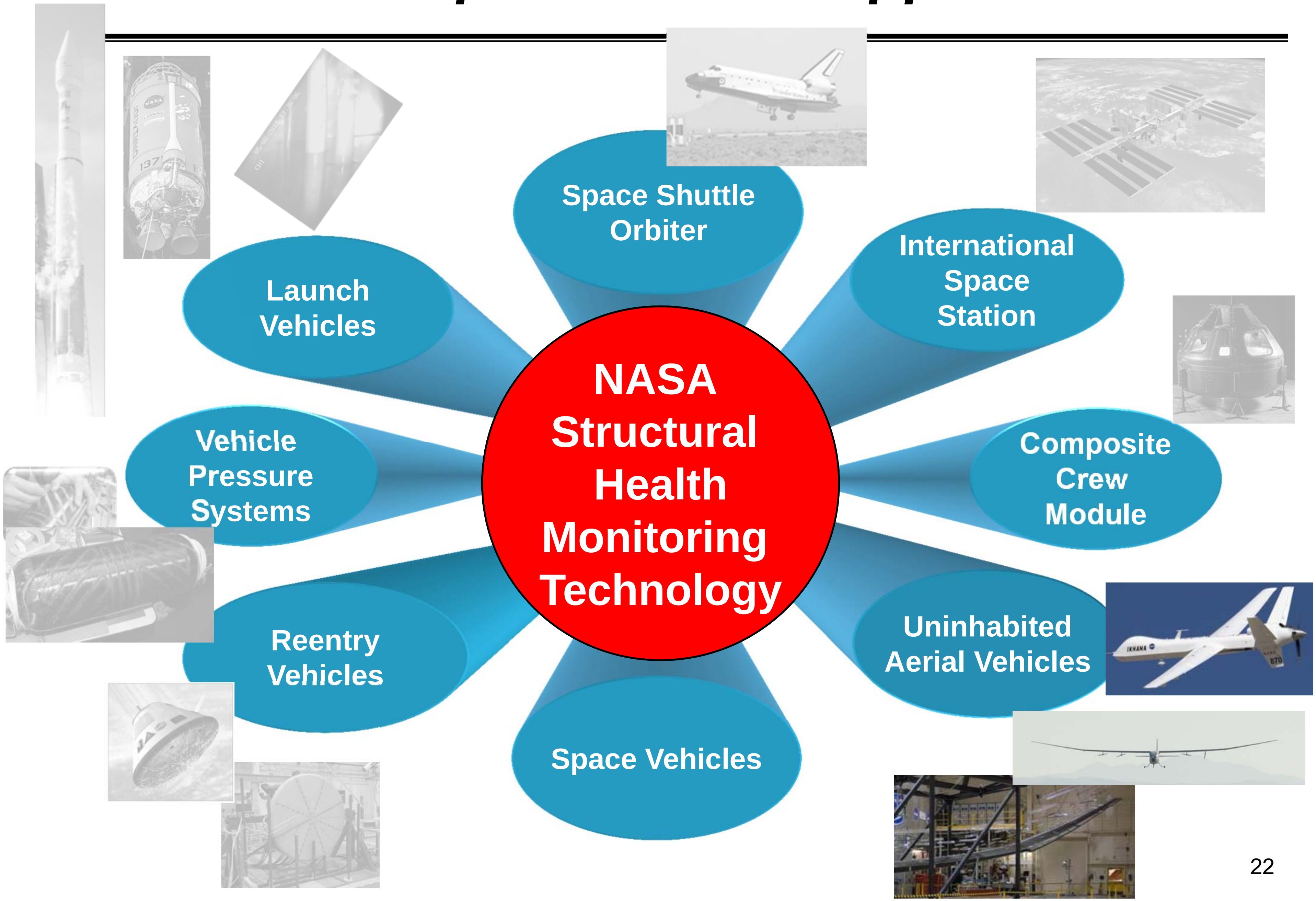
Shock	8g
Vibration	1.1 g-peak sinusoidal curve
Altitude	60kft at -56C for 60 min
Temperature	-56 < T < 40C

Flight System

Ground System

Predator -B in Flight

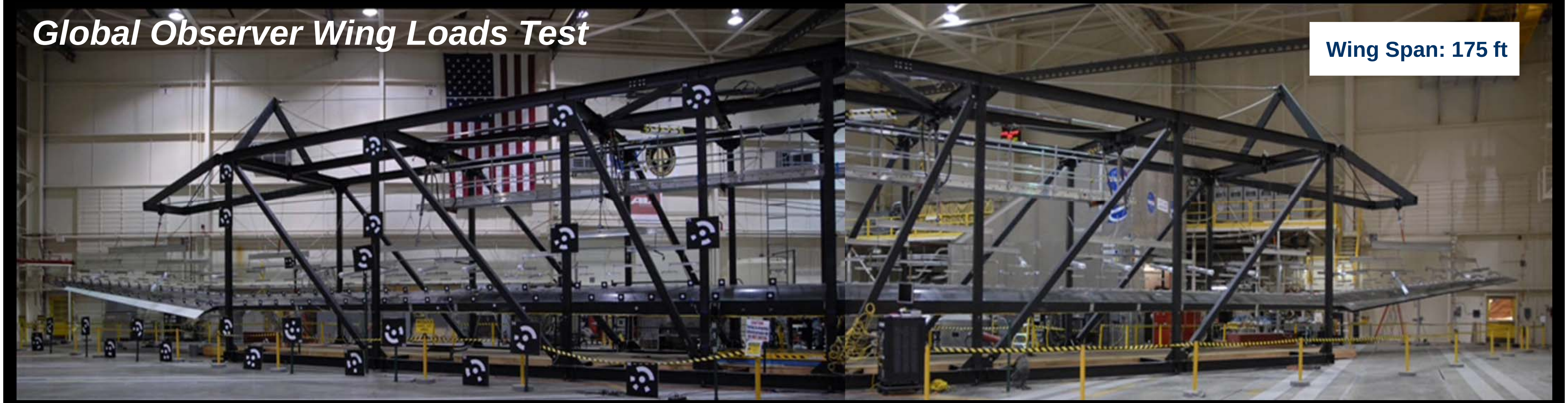
SHM Aerospace Vehicle Applications



Uninhabited Aerial Vehicles

Global Observer UAS - Aerovironment

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



Uninhabited Aerial Vehicles

Global Observer UAS - Aerovironment

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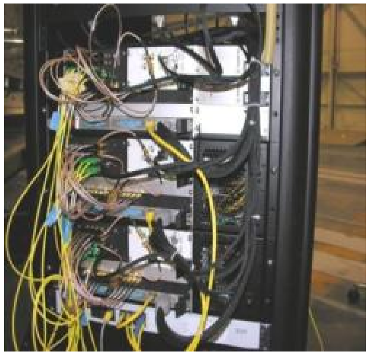
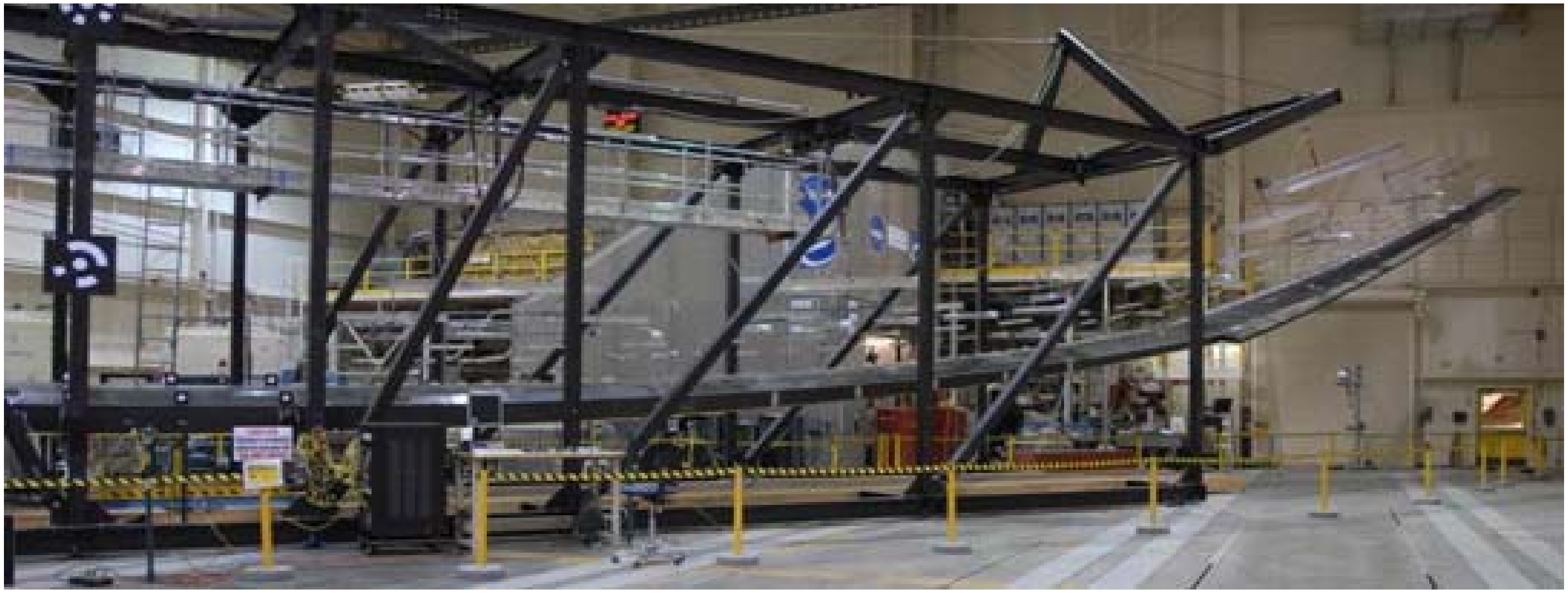
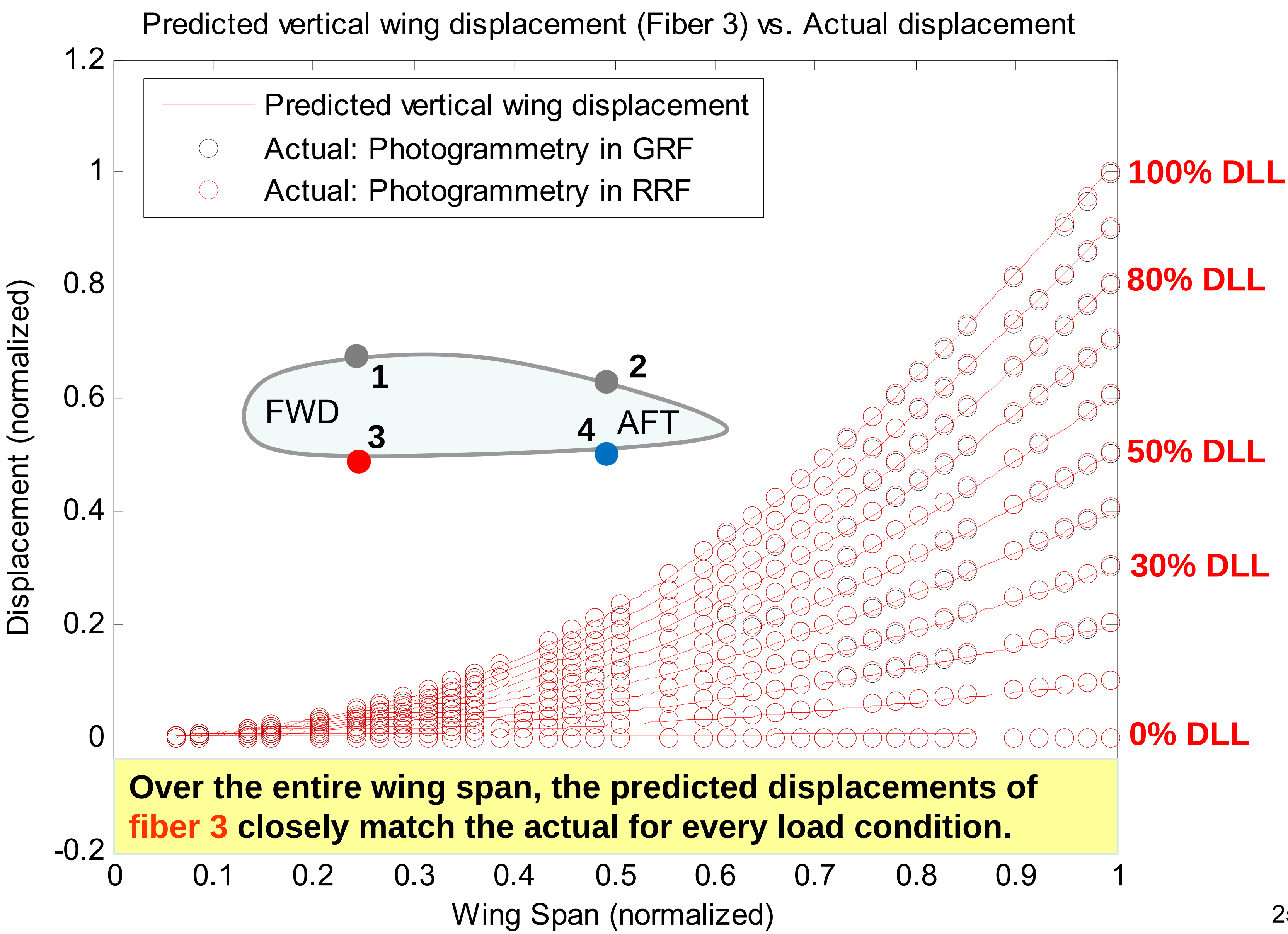
- **Validate strain predictions along the wingspan**
- **Measured strain distribution along the centerline top and bottom as well as along the trailing edge top and bottom.**
- **FO Strain distribution measurements are being used to interpret shape using Dryden's 2D shape algorithm**
- **A 24-fiber system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





Uninhabited Aerial Vehicles

Global Observer (AV) - 2D Shape Sensing Results

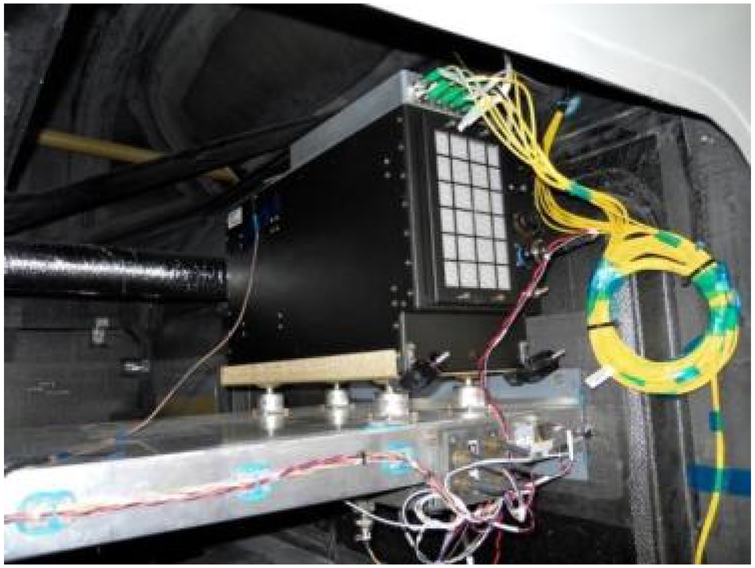


Over the entire wing span, the predicted displacements of fiber 3 closely match the actual for every load condition.

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**



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

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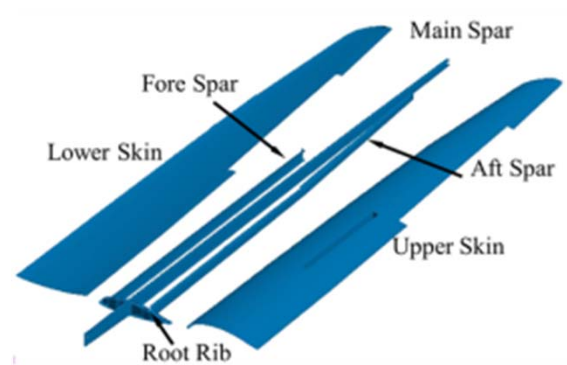
Full-Scale Composite Wings

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	5.54×10^1	1.19×10^2	8.50×10^{-2}
E_{22}, GPa	5.54×10^1	9.31×10^0	--
G_{12}, GPa	4.21×10^0	4.21×10^0	--
ν_{12}	3.00×10^{-2}	3.10×10^{-1}	3.20×10^{-1}
ρ, kg/m^3	1.49×10^3	1.52×10^3	4.95×10^{-1}



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Full-Scale Composite Wings

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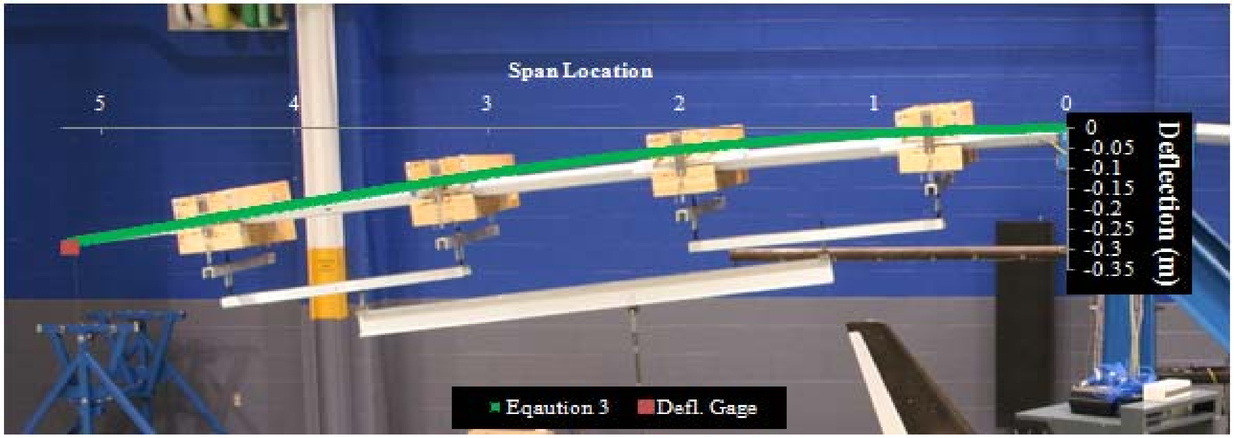


MEASURED AND CALCULATED WING TIP DEFLECTIONS

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**

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			

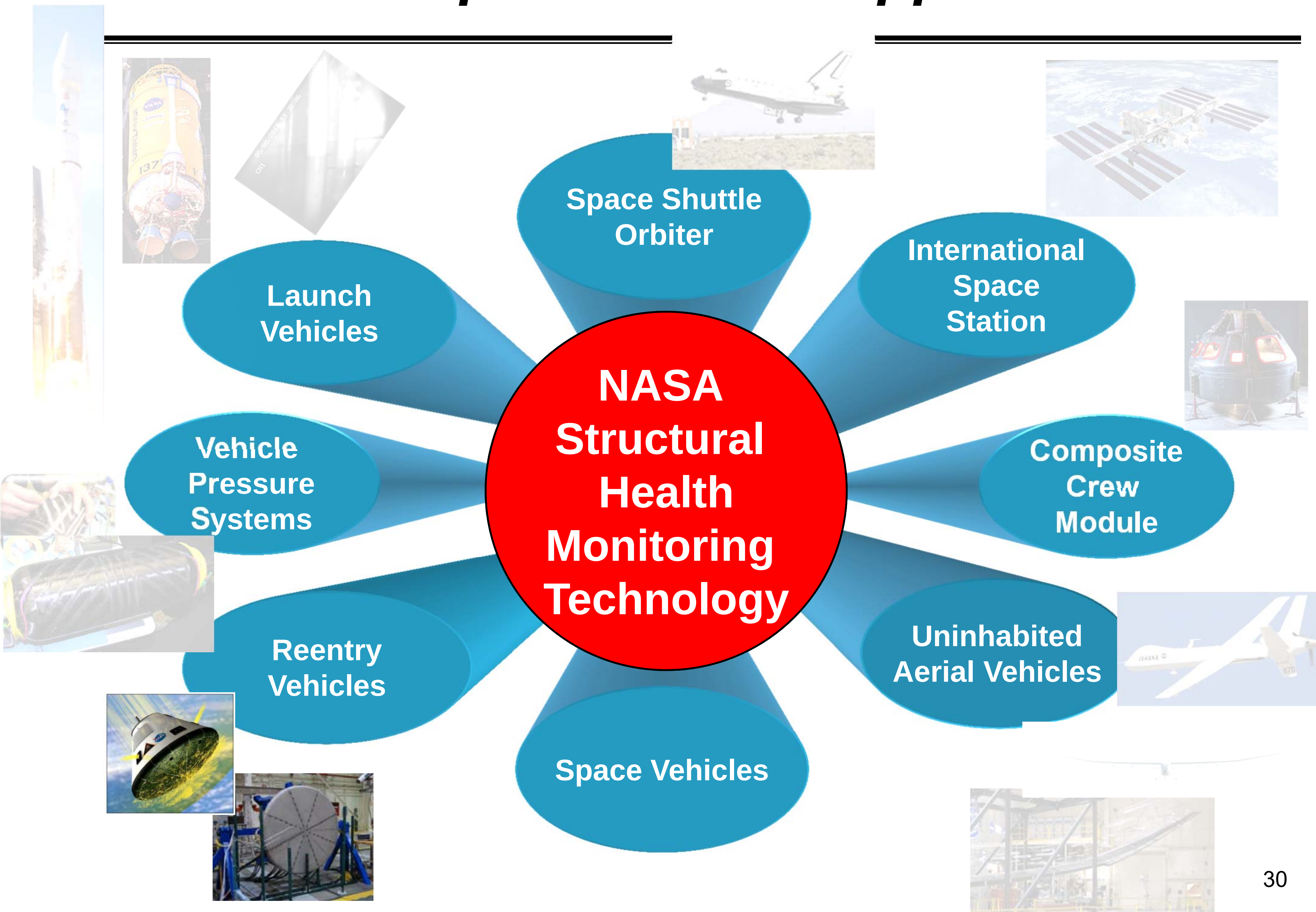
Test Procedure for displacement

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

Test procedure for out-of-plane loads

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

SHM Aerospace Vehicle Applications



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**

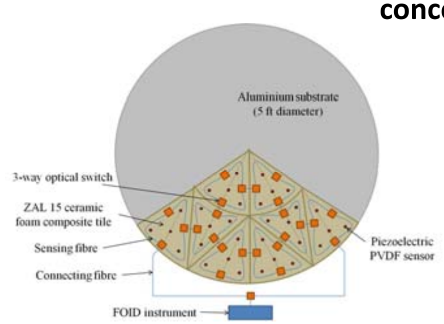
Principles

- **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**

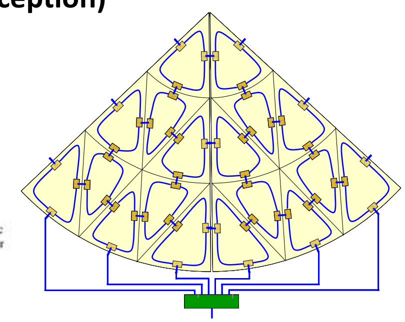
Novel aspects

- **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.**

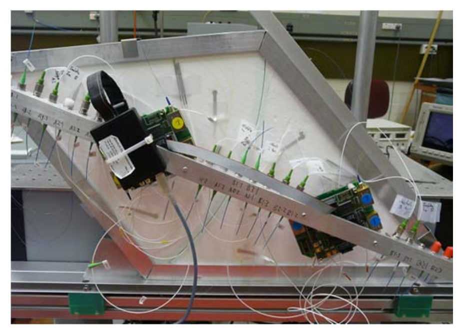
Vehicle Re-entry (artist conception)



Heat shield with TPS



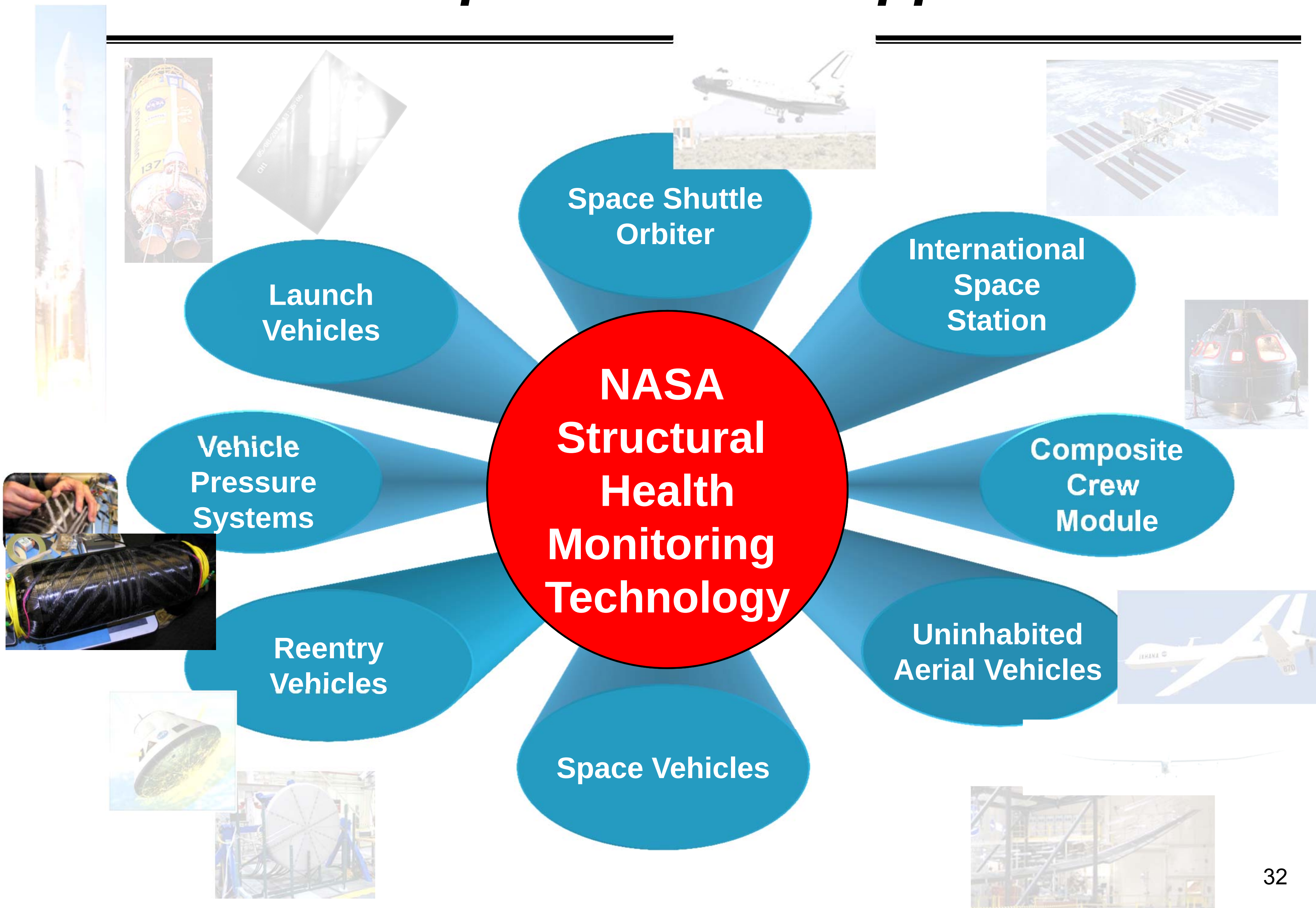
TPS health monitoring system



Two TPS modules

Heat shield Test Setup at Dryden

SHM Aerospace Vehicle Applications



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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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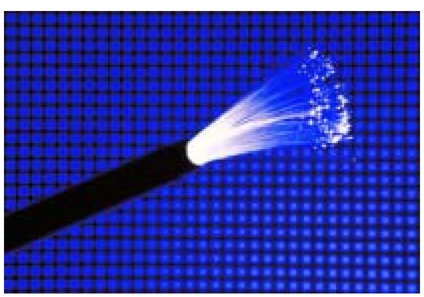

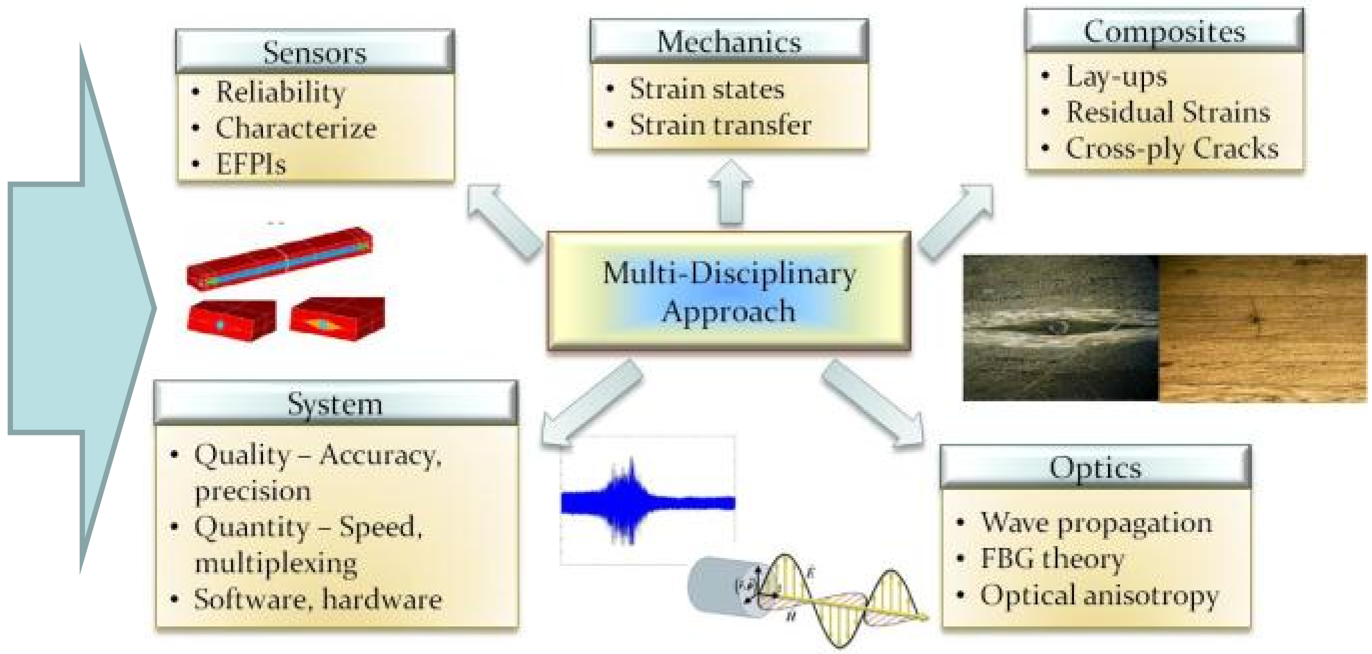

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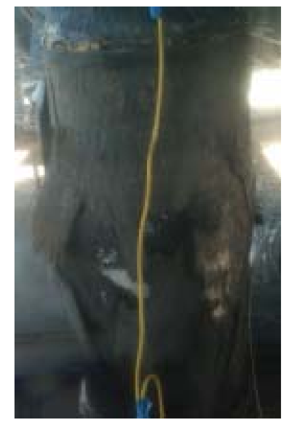
Vehicle Pressure Systems

Composite Overwrapped Pressure Vessels (COPVs)

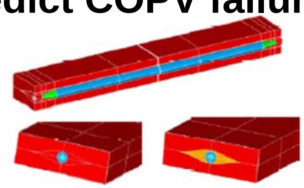
Objectives

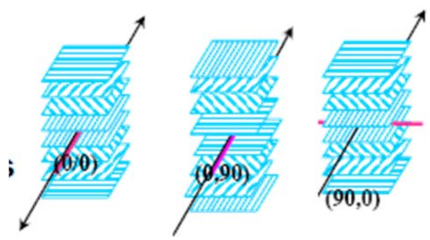
- **Perform real-time in-situ structural monitoring of COPVs with embedded fiber Bragg grating sensor arrays**
- **Develop analytical and experimental methods to reliably interpret embedded strain sensor measurements**
- **Develop a robust "early-warning" indicator of COPV catastrophic failure**
- **Provide 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**





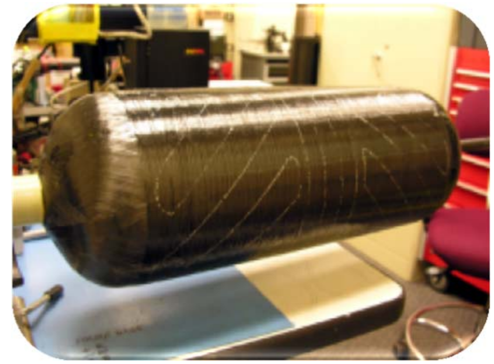
NASA Dryden and WSTF test team

National Aeronautics and Space Administration

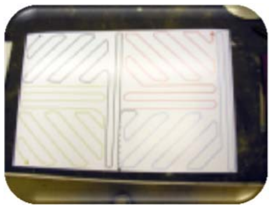
Composite Overwrapped Pressure Vessels

Installation Methods

Installation methods developed



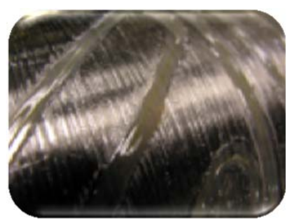
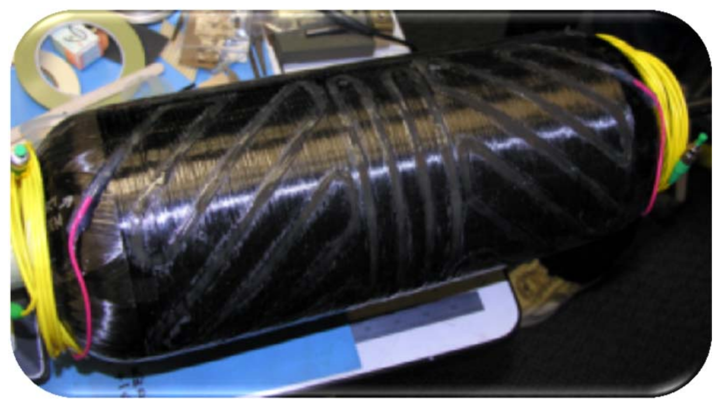
- Transfer pattern to bottle surface



- Mask and fill basecoat paths

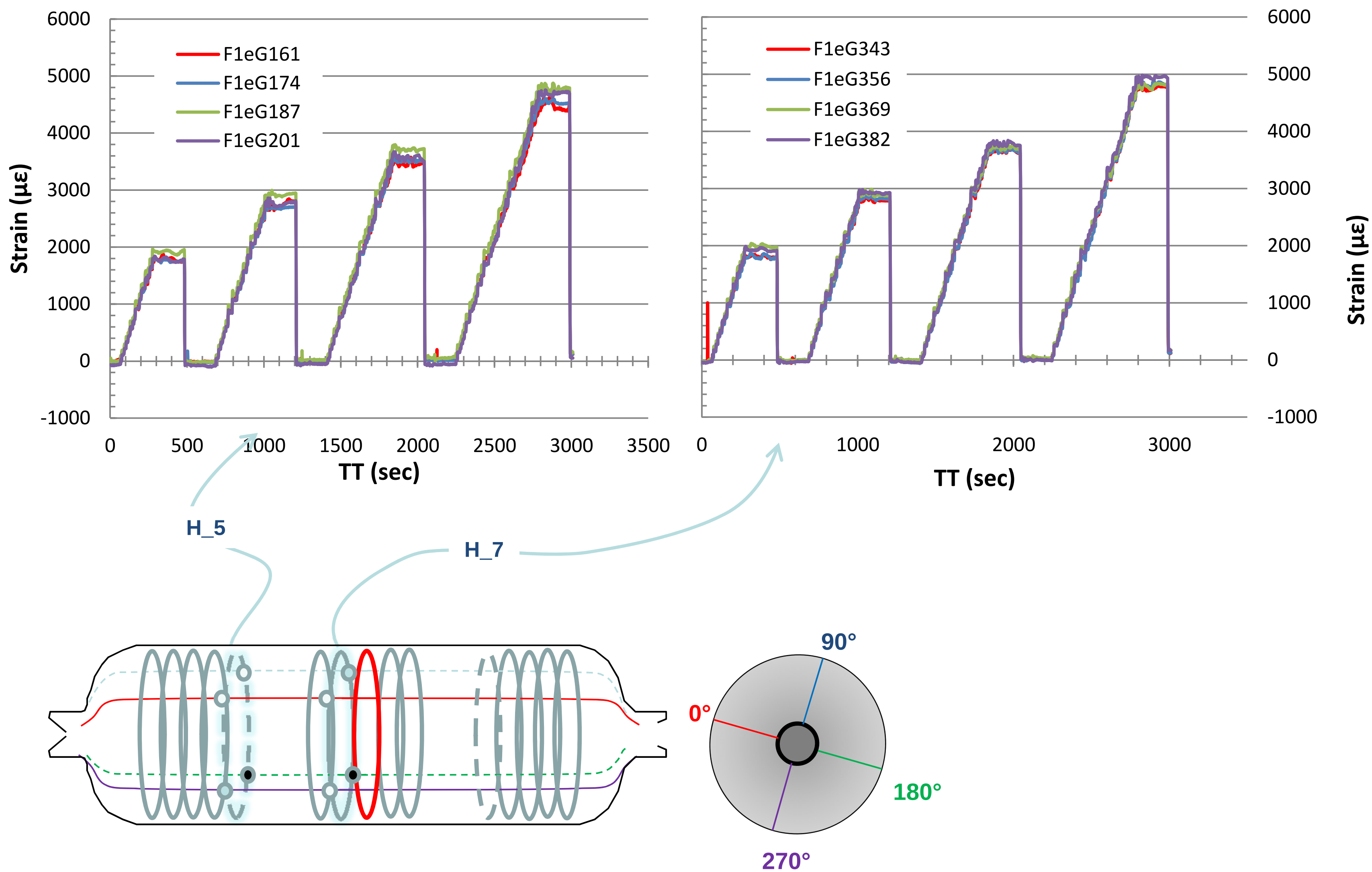



- Sand down close to surface layer

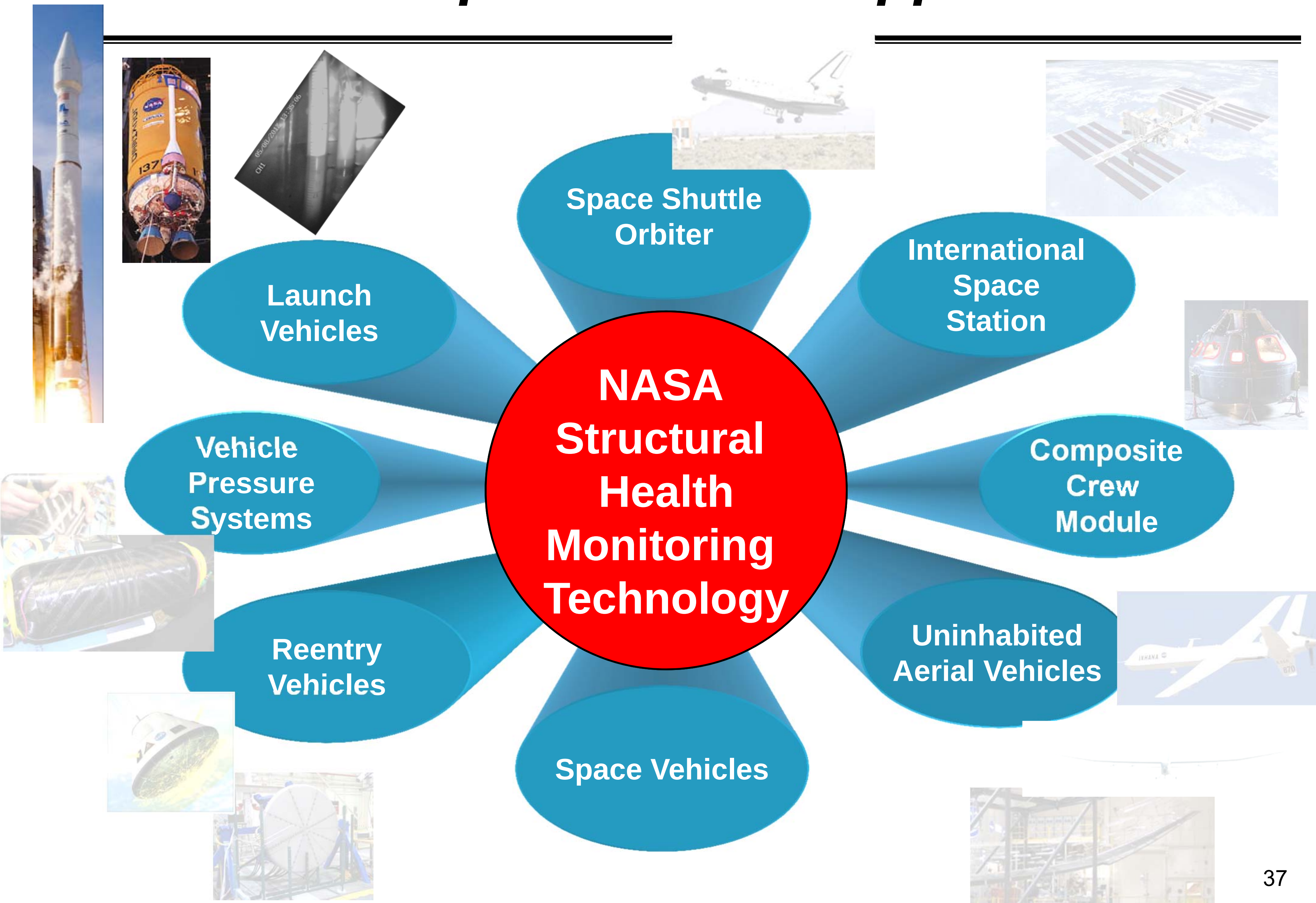




- Route and attach FBGs

Embedded Fiber to 5000 psi
Hoop Direction

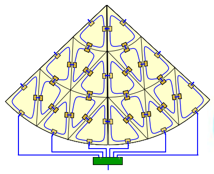


SHM Aerospace Vehicle Applications



FOSS Current and Future Work

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



TPS Health Monitoring

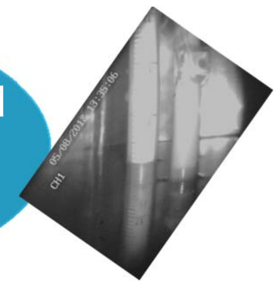
Embedded Strain

Magnetic Field

Applied Loads

Strain

Temperature and *Cryogenic* Liquid Level



2D Shape

3D Shape

Cryogenic Liquid Level-Sensing

National Aeronautics and Space Administration

The Challenge

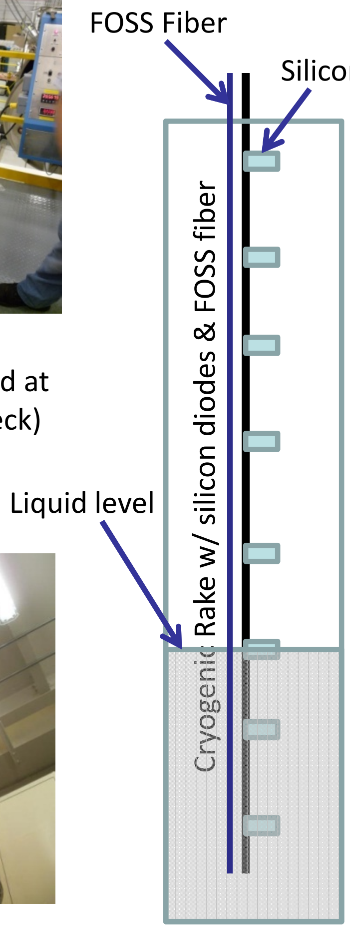
- **The transitional phase between liquid and gas of cryogenics is difficult to discriminate while making liquid level measurements**
- **Using discrete cryogenic temperature diodes spaced along a rake yields course spatial resolution of liquid level along with high wire count**

FOSS Approach

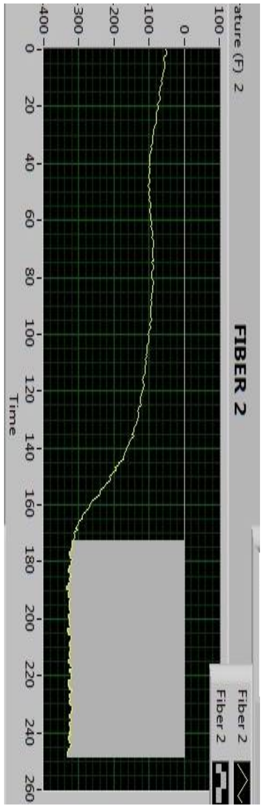
- **While using a uniquely developed fiber optic structure (CryoFOSS), the transitional phase can be mapped more accurately**
- **Using a single continuous grating fiber, a high degree of spatial resolution can be achieved, as low as 1/16”**

Cryogenic Container located at MSFC (above deck)

Cryogenic Container located at MSFC (below deck)



Cryogenic Container



1st Gen CryoFOSS Test Results

LH_2 Testing of CryoFOSS at MSFC

Objective

- **Experimentally validate CryoFOSS using Dryden's FOSS technology**

Test Details

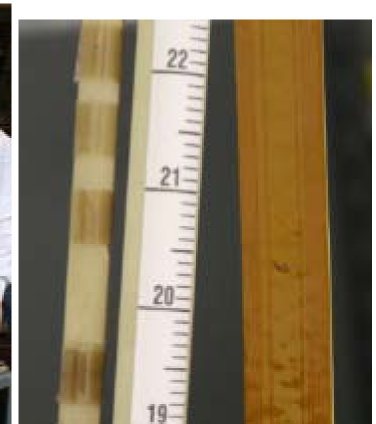
- **Dewar dimensions: 13-in ID x 37.25-in**
- **Fill levels of 20%, 43%, and 60% were performed**
- **Instrumentation systems**
  - **Video boroscope with a ruler (validating standard)**
  - **Cyrotracker (ribbon of 1-in spaced silicon diodes)**
  - **MSFC Silicon diode rake**
  - **Fiber optic LH_2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

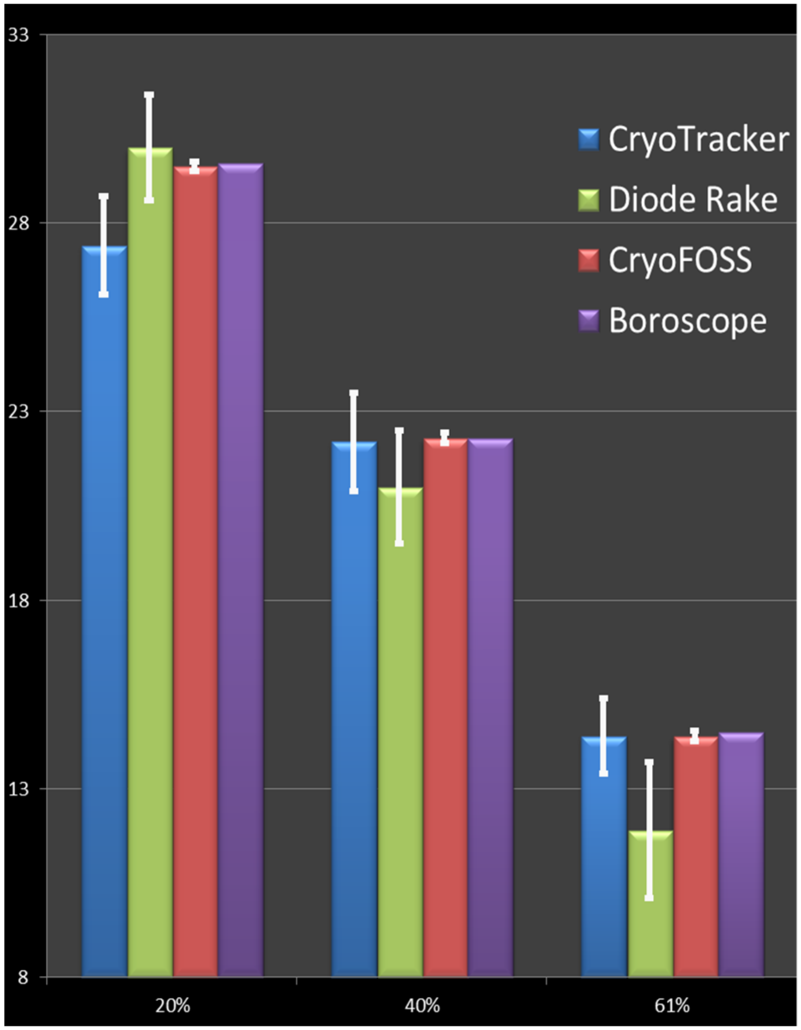
Bottom line

- **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**

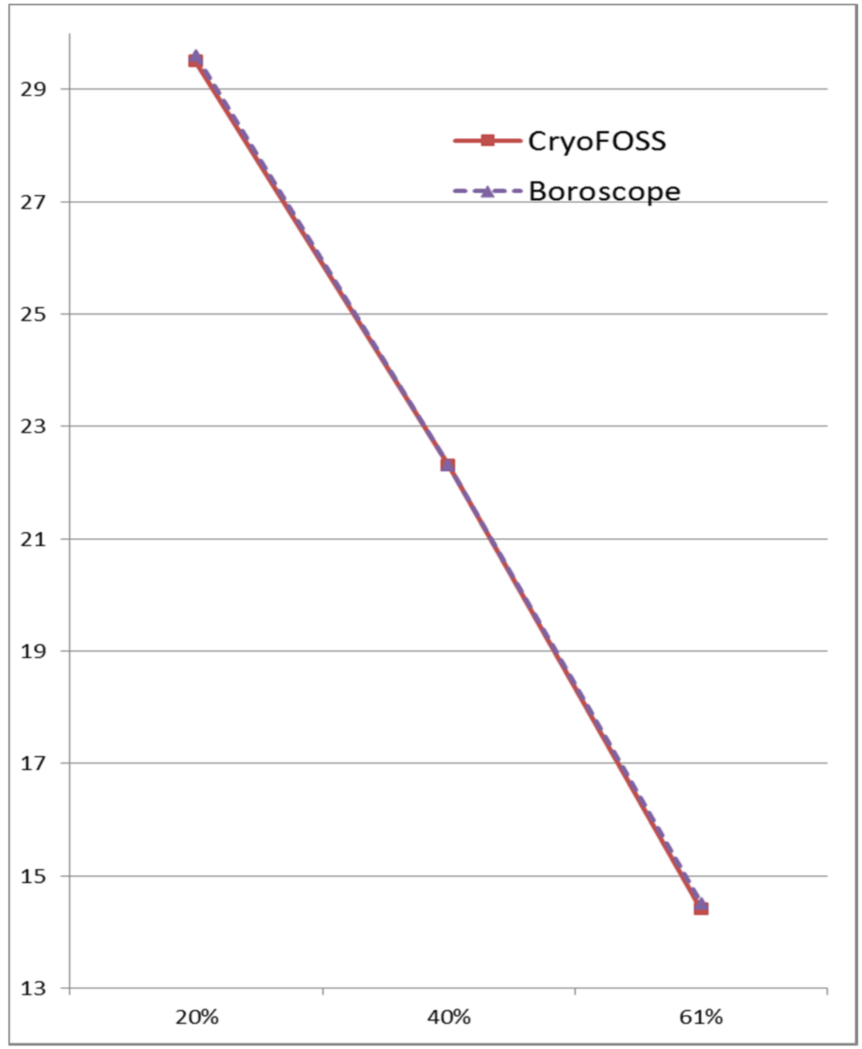


Cryo-FOSS

LH_2 Liquid Level Results



Combined Results



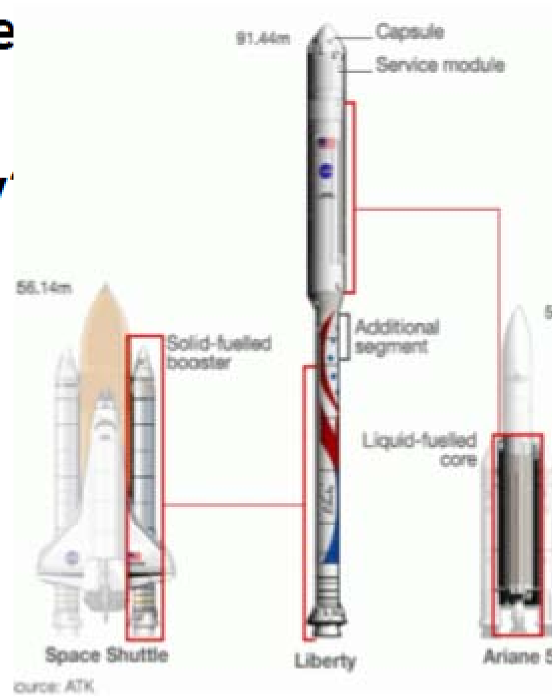
CryoFOSS compared to Boroscope

JOHN F. KENNEDY SPACE CENTER

Solving the Challenge of Flexible Dynamics

LAUNCH SERVICES PROGRAM

- Improved flight performance
- Stretching tanks?
- Improved launch availability?
- The ability to validate structural dynamics?
- Want to drop those expensive body bending sensors?
- **FBG sensor technology:**



- ✓ Large number of sensors
- ✓ Very small weight penalty
- ✓ Insensitive to EM noise
- ✓ High update rate (1 KHz non-multiplexed)

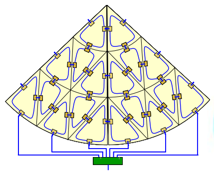
→ Opportunities for real time estimation and control created by novel FBG interrogation technology

Courtesy of KSC LSP and Florida Institute of Technology

National Aeronautics and Space Administration

FOSS Current and Future Work

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



TPS Health Monitoring

Embedded Strain

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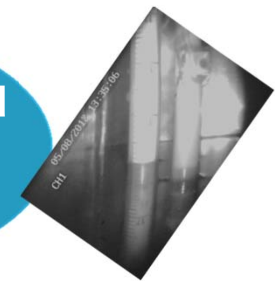


Temperature and *Cryogenic* Liquid Level

2D Shape

3D Shape

Anticipated Impact of Fiber Optic based SHM

- ***Potential to revolutionize aerospace design and performance throughout the vehicle life-cycle***
  - ***Design and development***
  - ***Fabrication***
  - ***Test and Evaluation***
  - ***In-flight operation***
  - ***Off-nominal flight***
  - ***End of life-cycle decisions***

National Aeronautics and Space Administration

National Aeronautics and Space Administration

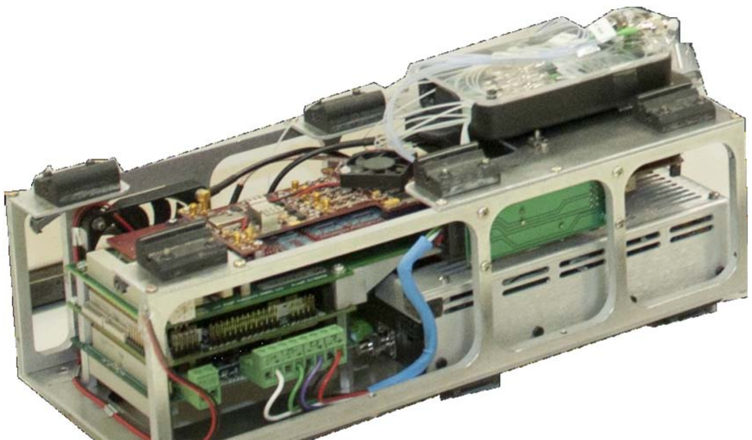
Future work: Small UAS Flight System

Current system specifications

- **Fiber count** — **4**
- **Max sensing length / fiber** — **40 ft**
- **Max sensors / fiber** — **1000**
- **Total sensors / system** — **4000**
- **Max sample rate (flight)** — **100 sps**
- **Power (flight)** — **28VDC @ 2 Amps**
- **User Interface** — **Ethernet**
- **Weight** — **5 lbs**
- **Size** — **3 x 5 x 11in**

sUAS Research Vehicle

2000 FBG Strain Sensors



sUAS Flight System

sUAS in Flight

Questions?