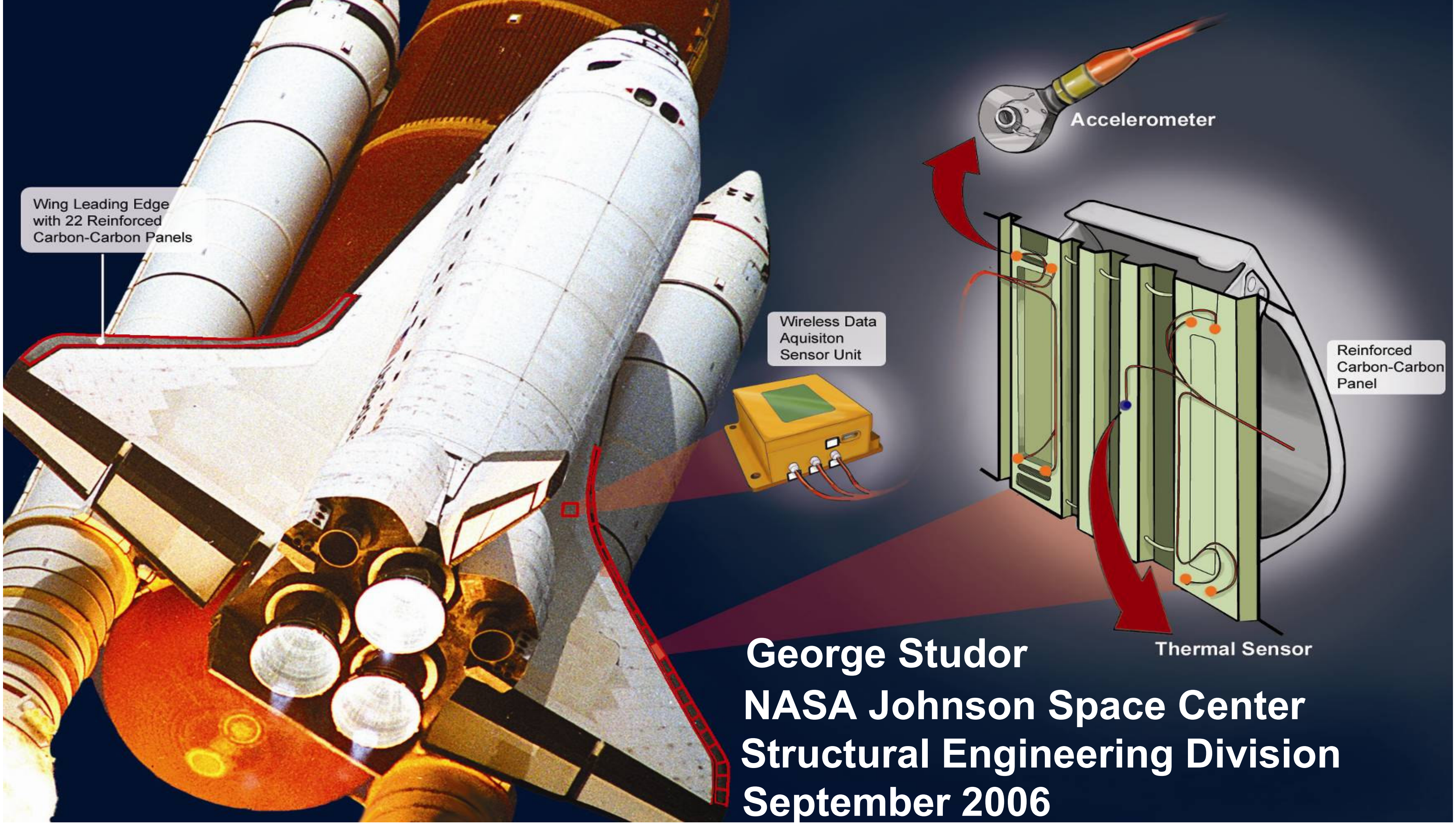
Lessons Learned
JSC Micro-Wireless Instrumentation Systems on Space Shuttle and International Space Station
CANEUS 2006



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JSC Micro-Wireless Instrumentation Lessons Learned

Outline: **Page**

Micro-Wireless Instrumentation Background

- **Shuttle Development Flight Instrumentation was limited** to one Orbiter and needed a pallet of avionics in the cargo bay to accomplish the task.

- **Structural Engineering issues on Shuttle and ISS required more data** for real-time use and for predicting loads, dynamics, and temperatures, but the changes were unaffordable.
  - Wired instrumentation requires integration of hardware, software, power, data handling, operations downlink, cabling and EMI/EMC compatibility into existing systems.

- **Small, bolt-on systems were developed** to capture low-rate accelerometer data and download it after the mission, but was not accessible during flight.

- A Small Business Innovative Research **(SBIR)** project developed a network-capable **Wireless Instrumentation System (WIS)** – **still needed to be bolted on, and some wires were still needed** to be run from the sensor to the box.

- Micro-Nano sensors were in development, but nothing was being developed for spaceflight use that was a **Micro-sized version of the WIS** to interface with them**.**

- An **SBIR** project developed Micro-Wireless Instrumentation System **(Micro-WIS)** to meet the need.

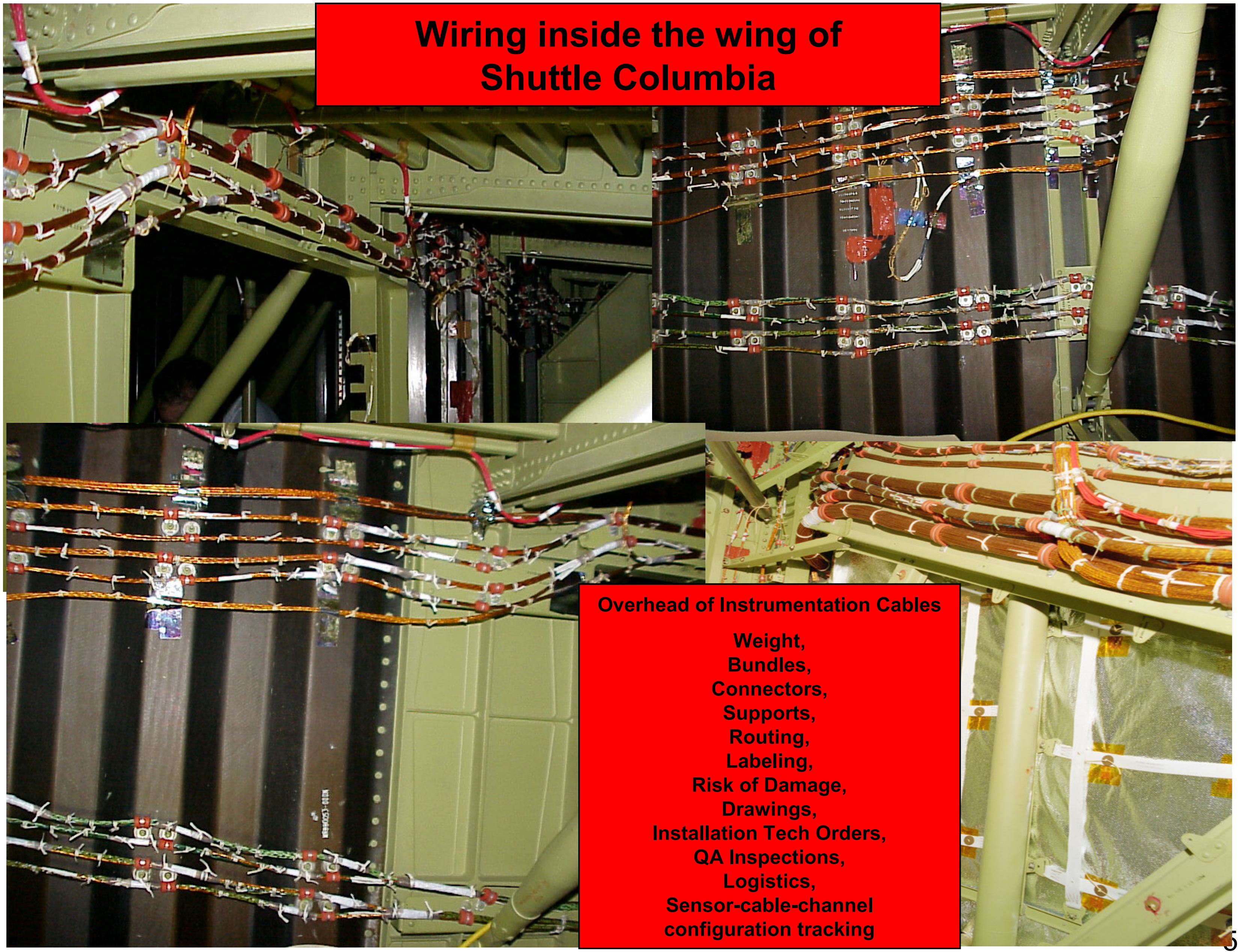
Micro-Wireless Instrumentation Rationale

Micro-Wireless Instrumentation:

- **Can provide monitoring/troubleshooting data to reduce risks** to safety, maintainability & performance.
- **Can make the measurement where standard wired systems can't** (no penetrations, deployable or dynamic structures, articulating joints and mechanisms, EVA ops)
- **Can be added to existing vehicle/upgraded with less integration than wired instrumentation.**
- **Can be easily re-configured** for redundancy at various levels.
- **Can evolve with the maturity and knowledge** of the system, vehicle, environments, operations, age and problems needing investigation.
- **Can evolve with technology improvements**, because it is modular by nature.
- **Can reduce resources needed** in weight, cost, schedule, integration.
- **Has proven record on Space Shuttle and ISS** with flight tests and operational use.

A new generation of aerospace vehicles can and should be built with wireless instrumentation accommodations and eventually wireless controls.

Wiring inside the wing of Shuttle Columbia

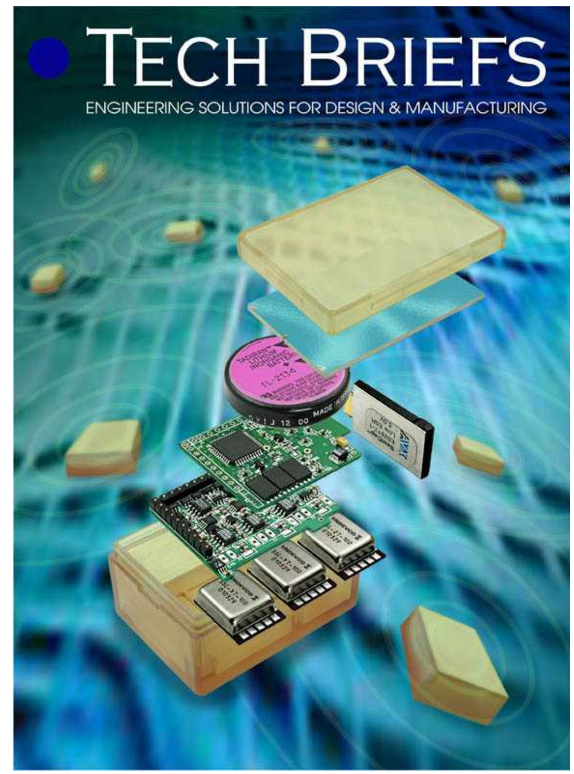


Overhead of Instrumentation Cables

Weight,
Bundles,
Connectors,
Supports,
Routing,
Labeling,
Risk of Damage,
Drawings,
Installation Tech Orders,
QA Inspections,
Logistics,
Sensor-cable-channel configuration tracking

Wireless Instrumentation System Sensors Benefits to Spacecraft

- **Self Contained**
  - Minimal Vehicle Resources Required
  - Battery or scavenge powered
- **Reduced Weight**
- **Low Integration Costs**
  - Low installation costs
  - Reduced number of drawing changes
  - Minimal cable routing/maintenance
- **Flexibility**
  - Vehicle design allocates measurements by weight.
  - Suite of sensor types provide maximum response to problems/requests for data.
  - Install as needed, remove easily.
  - Sensors can be integrated late in vehicle flow



JSC Micro-Wireless Instrumentation Vision

- **Stand-alone Micro-Wireless Instrumentation Units & Sensors**.
  - Minimum wires to do the job - doesn't have to have an RF link to be "wire-less".
  - Very low power operations, no power wake-up radios.
  - Long-lasting or scavenging power sources with robust performance at low temperatures.
  - Robust communications - adaptable radio/antennas as required and/or temporary wired port connections for upload/download.
  - Programmable micro-processor with very large data storage.
  - Validated algorithms that compute "answers" individually and collectively near the source.
  - Easily added to vehicle - not required to be bolted-on – easier methods require very low weight.
  - Control points to consolidate and prioritize downlink of answers from multiple zones as needed.
  - High reliability system versions for real-time critical applications.
  - No power sensor-tags

- **No Power, Stick-on RF Sensor-Tags with Central Interrogators:** data returned in signature of the reflected pulse.

- **Vehicle Accommodations Optimize the Use and Upgrade of Wireless Instrumentation**
  - Wireless Nodes in each vehicle zone, linked to the vehicle avionics backbone
  - Systems rely on wireless data for validation and some operations.
  - Accessible vehicle zones to allow upgrade and maintenance.
  - Avoid pre-mature specification of sensors/locations – use weight and resource allocation.
  - Radio frequency allocations, standards and plug-and-play provisions.
  - Cargo/payloads and crew/passengers get more services and are more easily integrated/de-integrated.

- **Vehicle Accommodations to Reduce Wires in General**
  - Use of embedded materials with non-contact, next generation remote sensor detection and inspection.
  - "Zero-base" wires – make each sub-system justify the wiring proposed.
  - RF transmission penetrations: composite plugs, access holes, antenna pass- through…
  - Wave-guides, EMI shielding and absorbing coatings as applicable.

Micro-Wireless Instrumentation System Approach

Structural Health Monitoring

1. **Get to know monitoring is needed and why:** the Structure, Environments, Operations, Failure Modes, Hazards, Materials, Vehicle System, the life cycle and the cost of change.
2. **Demonstrate ability to measure the phenomenon with current technology** and use models in operational scenarios to understand the impact of measurement limitations.
3. **Develop technologies and system implementation options** to conquer the limitations of current technology and change limitations to get what you need, incrementally.

Micro-Wireless Instrumentation System Applied to Structural Health Monitoring

1. **Demonstrate ability to measure the phenomenon with prototype system** and ability to use it in a timely way. The Micro-WIS SBIR was successful because potential customer base (NASA) was included and hardware was designed to be flight certifiable.
2. **Match the capability with a specific customer** who has a specific need.
3. **Develop the "System Concept" with the customer**, including: Goals, Objectives, Effectivity, and Vehicle Configuration, Environments, Phenomenon to be measured, sensor configuration and instrumentation in an end-to-end configuration.
4. **Obtain project funding for the flight implementation** by comparing costs, schedule and other advantages over alternative solutions to a specific problem.
5. **Develop system requirements through prototyping/test:** Materials, Components, Vehicle Interfaces, Manufacturing/Critical Skills, Monitoring System Reliability.
6. **Generate integrated models of the system and validate predictions** of it's capability.
7. **Incrementally add functionality** to the proven Micro-WIS technology application as there becomes an identified need from new customers.

Wireless Instrumentation Systems Solving Unique Real-World Problems for Shuttle & Space Station

- **ISS Assembly** – Thermal limits too close for some avionics boxes during assembly and prior to hook-up… No power/data path available. External temperatures were needed for boxes in near real time. **Result: Wireless Data Acquisition System DTO** leading to **Shuttle-based WIS(SWIS) for P6 & Z1.**
- **ISS Structural Loads/Dynamics i**s different at every assembly step, so relocatable stand-alone accelerometer data acquisition units were needed to be RF time-synchronized, Micro-G sensitive. **Result: Internal WIS(IWIS) was first flown on STS-97 and is still in use today.**
- **Shuttle Temp Monitoring** – Validation of thermal models became important for design of modifications and operations, but the cost of conventional wire/data acquisition was prohibitive. **Result: Micro-WIS was developed by SBIR, first flown in a non-RF configuration.**
- **Shuttle Structural Loads and Dynamics Concerns** – SSME support strut strain data needed to refine certification life predictions for related parts. **Result: Micro Strain Gauge Unit (Micro-SGU**). **and Micro-Tri Axial Accelerometer Units (Micro-TAU**) for Cargo to Orbiter Trunion Dynamics/Loads**.**
- **Shuttle SSME Feed-line Crack Investigation:** High data rates, RF synchronization and more storage needed to see how Main Propulsion System flow-liner dynamics affect SSME Feed-line Cracks. **Result: Wide-band Micro-TAU.**
- **Shuttle Impact Sensors** were needed to determine if and where the Orbiter Wing Leading Edge has been impacted by debris. **Result: Enhanced Wideband Micro-TAU (EWB Micro-TAU**).
- **SRMS On-Orbit Loads were increased** because of contingency crew EVA repairs at the end of the boom - extension of the SRMS arm. **Result: Wireless Strain Gauge Instrumentation System (WSGIS) and Instrumented Worksite Interface Fixture (IWIF)** – EWBMTAU/Triax MEMS Accels (DC to 200hz)
    - **Also used for measuring Shuttle Forward Nose area dynamics during roll-out (10 hours)**
- **ISS MMOD Impact/Leak Monitoring** is needed for high risk modules to reduce time necessary to locate a leak to vacuum so that it can be repaired. **Result: Ultrasonic WIS (UltraWIS) & DIDS SBIRs**

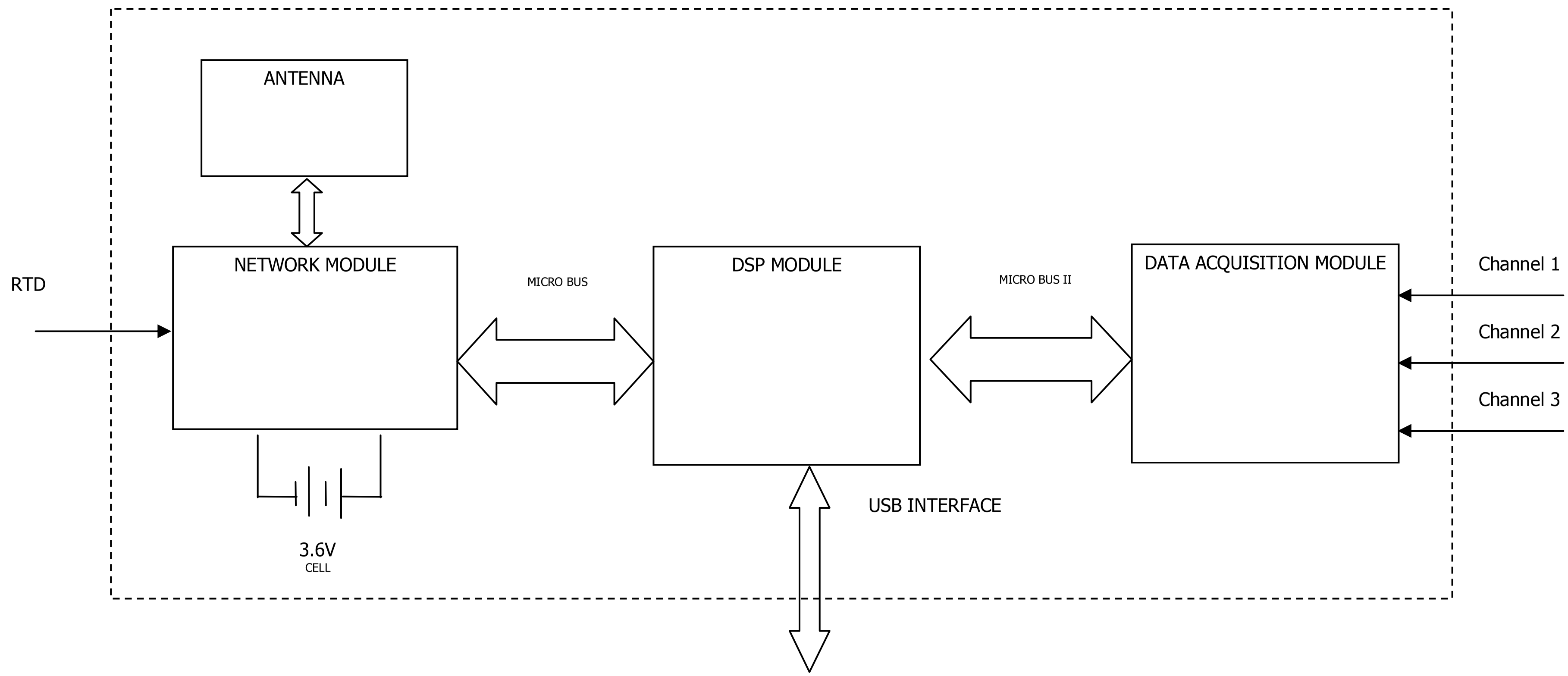
Evolution of Micro-WIS Systems

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 (projected)
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 Sync	No	No	Yes	Yes	Yes	Yes
Data Storage	None	2Mbytes	1Mbyte	256Mbytes	256Mbytes	1Mbyte
Data Transmit / Relay	Real-time Transmit to PC	Real-time Transmit to PC / Relay	On-demand Transmit	On-demand Transmission	On-demand Transmission	On-demand Transmission

Evolution of Micro-WIS Systems

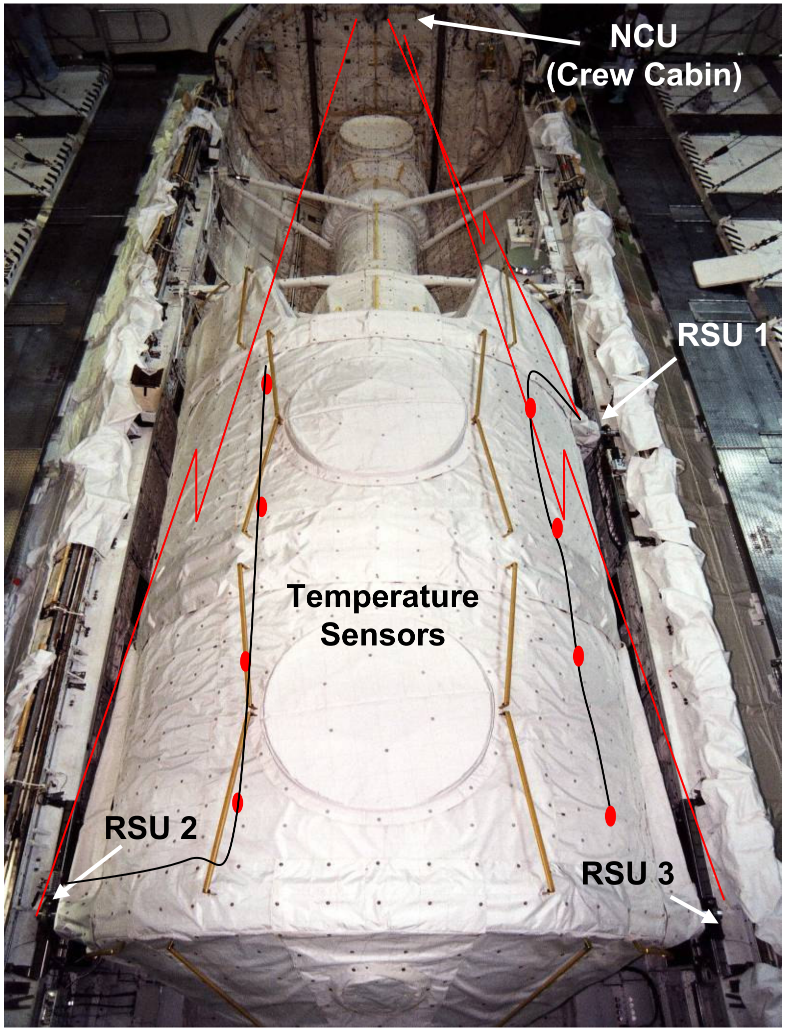
System	MicroWIS (SBIR)	Extended Life MicroWIS	MicroSGU / MicroTAU	Wideband MicroTAU	Enhanced WB MicroTAU	Ultra-sonic WIS (new Ph2 SBIR)
Local Data Processing	No	No	8bit micro-controller	High-speed DSP Not used on data	High speed DSP Numerous Routines	High speed DSP Numerous Routines
Triggering	No	No	Data/Time Trigger	Data/Time Trigger	RF/Data/Time	Impact
Battery type	Tadiran 400mAhr	BCX Lithium C-cell	Tadiran 1000mAhr	BCX Lithium C-cell	Energizer L91 2-AA pack	BCX Lithium C-cell
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

Typical Micro-WIS Block Diagram



- Each unit is a multi-processor system
  - Network Communication board
  - Digital Signal Processor board
  - Front-end Data Acquisition board
  - Patch or WIP/Di-pole antenna

Wireless Data Acquisition System (WDAS)



Shuttle Payload Bay

STS-83 (4/97) and STS-94 (7/97)

- Dynamically re-configurable RF network
- 100mW DSSS Proxim WLAN
- Data Rate - 115kbps
- Battery powered
- **Lessons Learned:**
  - Perfect Line-of-sight not-required
  - Cost of Bolted Interface
  - Cost of wires to temp sensors
  - Data rate higher than needed

Shuttle Wireless Instrumentation System (SWIS)

- ISS Flights 3A (10/2000) and 4A (11/2000)
- Temp monitoring of critical ISS electronics during un-powered assembly operations for Z1 & P6 truss sections.
- 200mW Spread Spectrum WLAN
- 915 MHz
- Data Rate - 2Mbit/sec
- Excellent RF coverage even when no line-of-sight available, automatic relay paths seldom used

Lessons Learned:

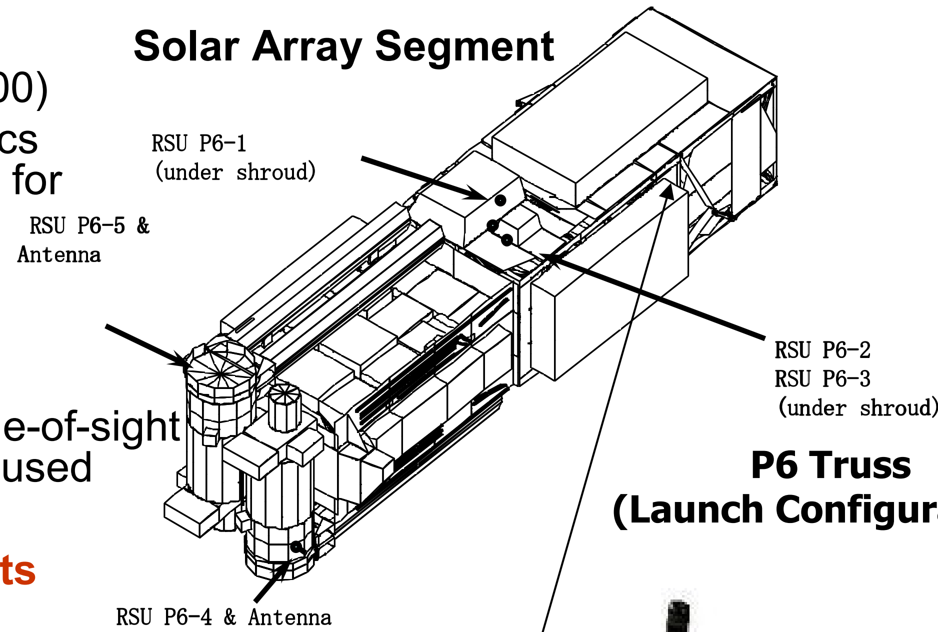
High Installation and Integration Costs

- Bolted interface

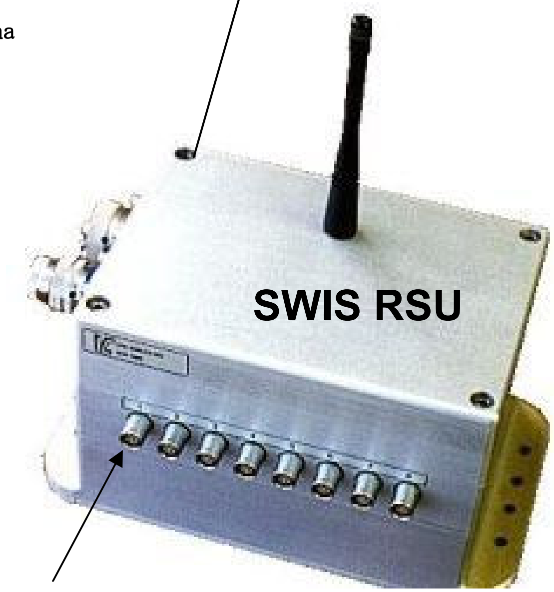
- RTD wiring / drawings

Data rate overkill, but used sister project IWIS

Solar Array Segment



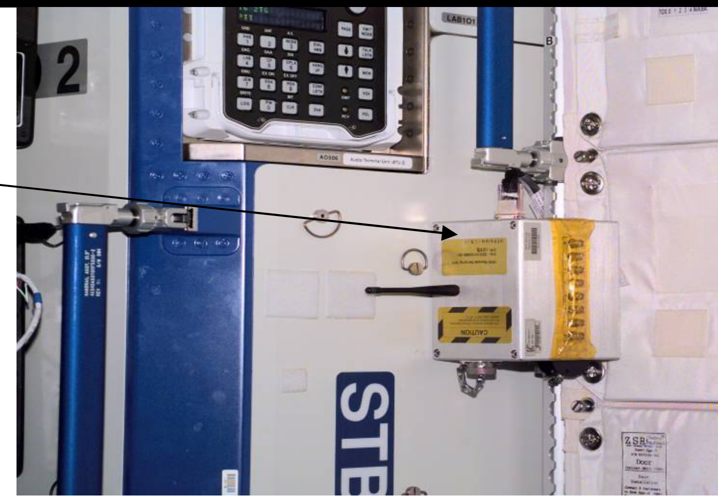
P6 Truss
(Launch Configuration)



8 Temperature Channels

ISS Wireless Micro-gravity Accelerometer Systems

- **IWIS**
  Internal Wireless Instrumentation System

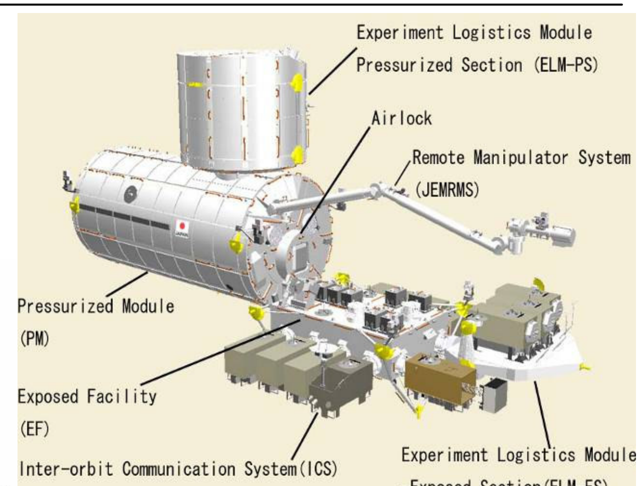


- ISS Structural Dynamic Model Validation Tests – IVA
- Launched on ISS assembly flight 4A(11/2000)
- Micro-G sensitive triax accelerometers are large

Lessons Learned:

- Unplanned additional uses drive power
- Li-BCX Batteries are a hazard
- Rechargeable battery not prepared
- Vehicle power interface cable in work

- MMA
  Micro-gravity Measurement Apparatus



- "Kibo" Japanese Experiment Module
- IVA Micro-gravity Monitoring
- *Micro-g resolution (18bits)*
- *900MHz DSSS WLAN Module*

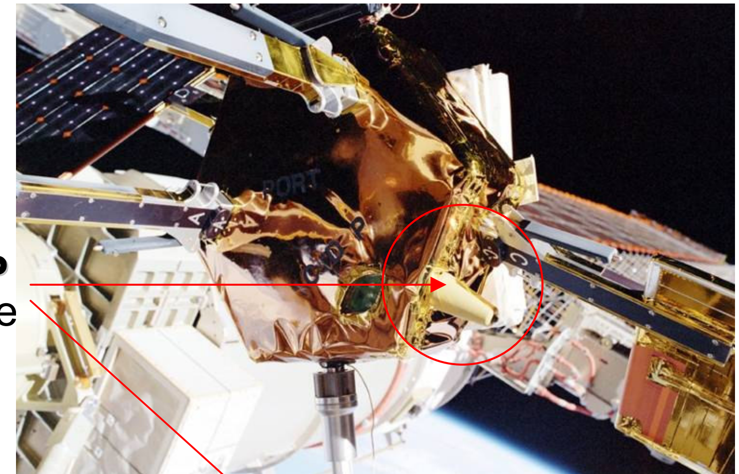
Lessons Learned:

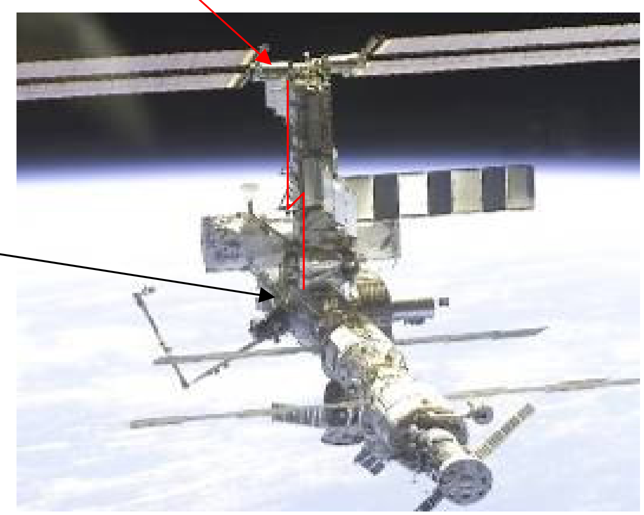
- Good precision
- Power hungry

Wireless Floating Potential Probe (FPP)

- FPP monitored the plasma potential on ISS near P6 Solar Arrays. Developed by NASA Glenn Research Center.
- Installed on STS-97, extremely short time to delivery.
- WIS network module enabled the FPP to communicate data from the top of the P6 truss to the inside of the Unity Node 1.
  - Non line-of-sight link (~30m)
  - EVA installed, receiving antenna on Unity Node Hatch

Wireless FPP





Lessons Learned:

- Short time to deployment + contracting delays

- Multi-center involvement needed more integration

- On-orbit failure of integrated system due to lack of integrated ground testing.

Photos courtesy of NASA

MicroWIS Temperature Transmitters

- **The Original MicroWIS flight system**
  - – Low-power narrowband radio module
  - – External RTD and internal temp channels
  - – Asynchronous data transmission with random back-off retransmissions
  - – 6mo life - button cell battery (20 year life - C-cell)

1.7″ dia x 0.7″

- **Multiple flights flown**, including Joint Airlock on ISS 7A
  - – Decision to use came at L-2 months
  - – Good RF coverage in Payload Bay, partial blockage due to Orbiter Docking System (ODS)
  - – Record-only units used to build thermal models

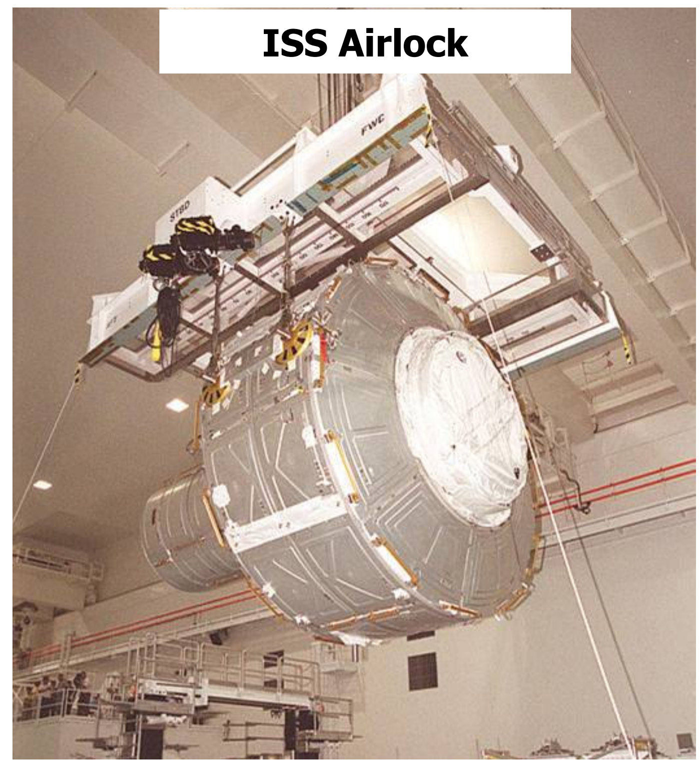


Photo courtesy of NASA

Lessons learned:

- Low data rate useful for many applications

- Radio upgrade useful for large number of units

- Lead to Micro-WIS XG for space/commercial uses:

- **– Reduced size**
- **– Water resistant**
- **– TDMA network (more than 60 units at 1 sample/sec)**

Micro-Strain Gauge Unit (Micro-SGU) and Micro-Tri-axial Accelerometer Unit (Micro-TAU)

Micro-SGU for Life Extension of Composite Struts supporting SSME pitch actuators

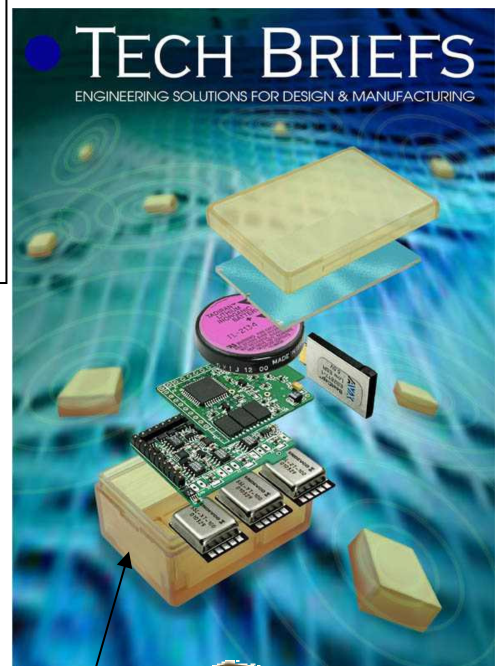
Micro-TAU for Loads Model Validation of Orbiter to Payload Interfaces

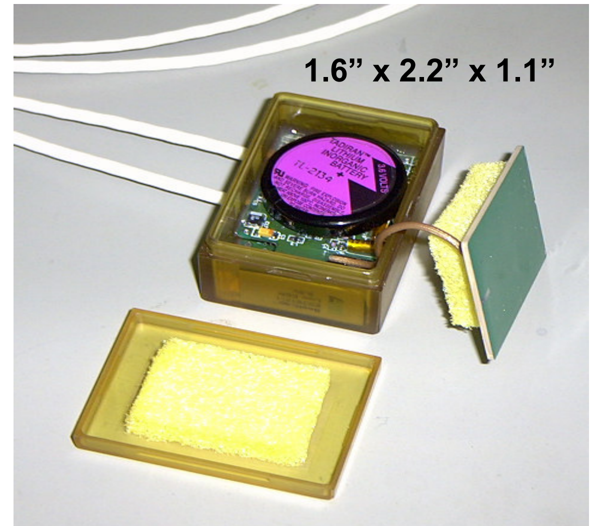
- RF transceiver: ¼mW 916MHz
- Omni-directional Patch Antenna
- 3 Channel Accel or Strain
- 250 samples/sec
- 1 Mbyte data memory
- Self-contained/Lithium Battery
- Synchronization via RF
- Multiple Ops Modes
- Trigger Options:
  – Real-time clock
  – Primary data channel
  – Auxiliary trigger sensor (pressure)

Lessons Learned:

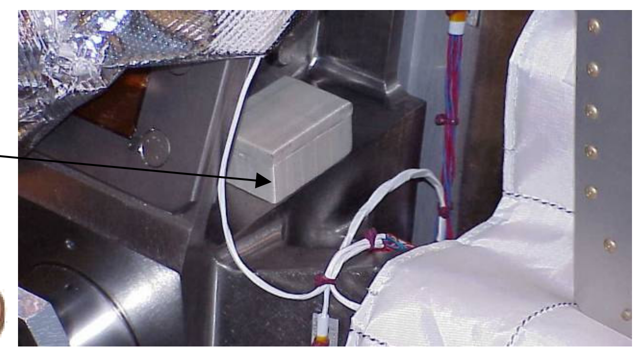
- Explosive Environment difficult

- Micro-TAU (sensors inside) easier to integrate than Micro-SGU.





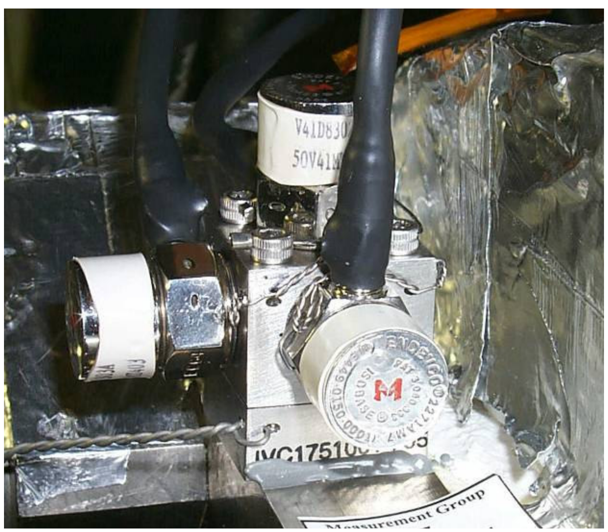
Micro-Strain Gauge Unit
7 Shuttle missions on SSME Struts since 12/01



Micro-Triaxial Accelerometer Unit installed on MPLM
– 2 Shuttle Missions since 12/01

Wideband Micro-TAU (WBMicro-TAU)

WB Micro-TAU bonded near aft struts



Tri-axial Accelerometer
bonded to very cold feed-line

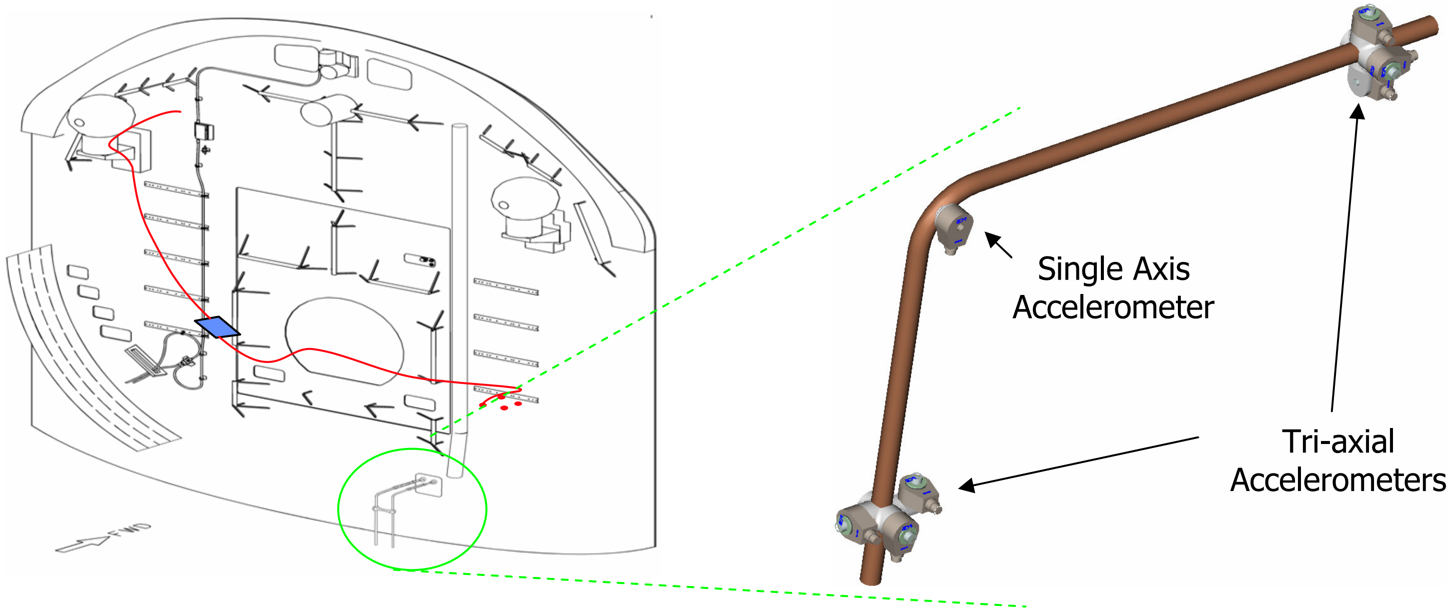
- **Monitor SSME Feed-lines** to investigate high-cycle fatigue cracks in SSME flow-liner. Installed on Columbia.
- **System Enhancements**:
  - **20K samples/second(3 channels)**
  - 128Mbyte Flash memory, enough to monitor entire ascent with margin
  - External **cryogenic** temperature piezoelectric **accelerometers**
  - **USB interface:** faster downloads
- **Columbia Accident Investigation** Impact Tests - Used to demonstrate ability to monitor for impacts – then included with Return to Flight Impact Testing.
- Used for Enhanced WBMicro-TAU - Wing Leading Edge Impact Detection System

Lessons Learned:

- Safe for Explosive Atmosphere requirements

- Safety concerns for bond verifications

Enhanced Wide-Band Micro-TAU for Shuttle Flex-hose Dynamics Assessment



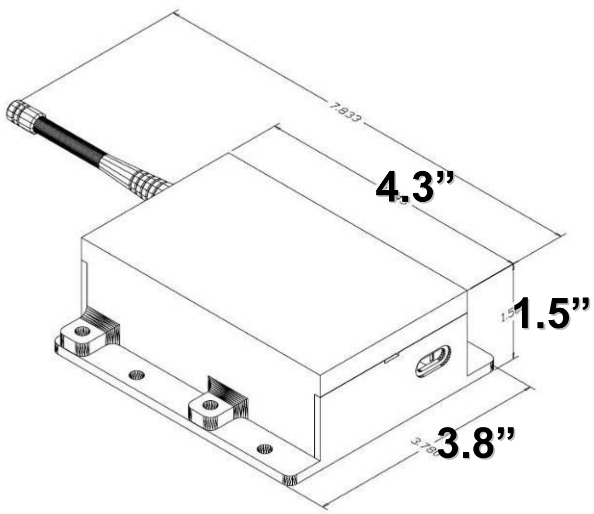
- **Leaks in the Shuttle Orbiter flex-hoses** carrying oxygen and nitrogen for the Environmental Control Life Support System (ECLSS)
- Reverse bending fatigue identified as a possible failure mechanism.
- Concerns caused a **launch delay for STS-113** and extensive troubleshooting.
- **Enhanced WBMTAU was prepared for monitoring the flex-line dynamics**:
  - Extensive Ground Operations (OPF to Launch Pad)
  - Mission Operations: Launch, Ascent, Reentry and Landing
- **Cargo Bay Wireless Node provisions included with WLE monitoring**

Lessons Learned:

- Some systems are prepared that don't get flown as intended (losses)

- Capability remains ready when needed

Micro-WIS Shuttle Rollout Monitoring System



Mobile Launch Platform Produces Vehicle Stack Motion during roll to the launch pad, first noticed by structural engineers in video of Vertical Tail motion.

Motion may be a loads concern – never before measured.

Drag-on instrumentation not practical for Orbiter Nose.

Modified Enhanced Wideband Micro-TAU design prepared for STS-115 roll-out to launch pad:

- Up to 10 hrs of recording time at 512 samples/sec
  - Uses 3 AA size L91 cell pack
- Internal Tri-axial MEMS Accelerometers (Colibrys)
  - No External wires
  - High accuracy
  - 100Hz bandwidth
- Synchronized wireless sensors to within ±4μs.
- Flexible base station design with relaying synchronization and IRIG timing

Lessons Learned:

- Valuable practice instrumented roll-out completed.

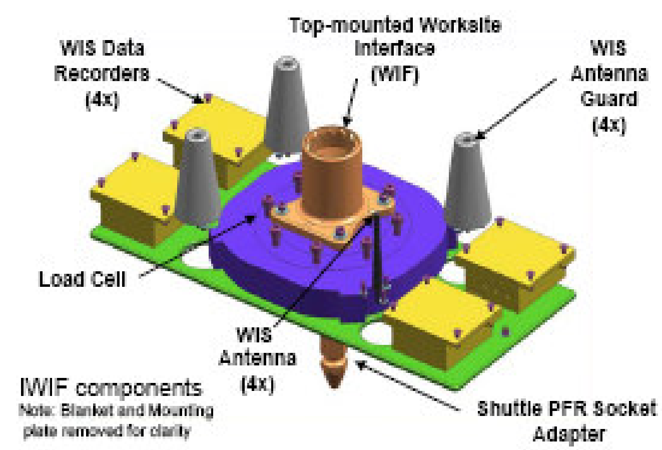
Wireless Strain Gauge Instrumentation System (WSGIS)

DTO 852 - SRMS Loads – STS-121 – MD Robotics/Dynacs

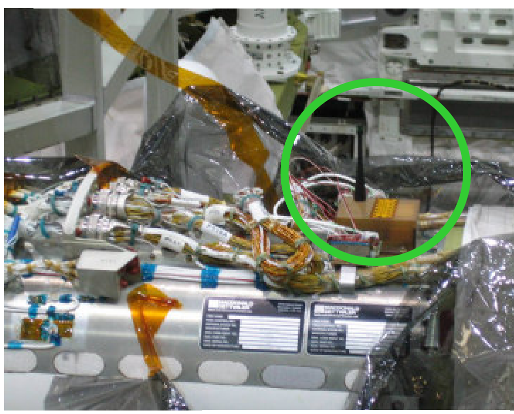
Instrumented Worksite Interface Fixture (IWIF)

DTO 849 - Worksite Stabilization – STS-121 Boeing/Oceaneering

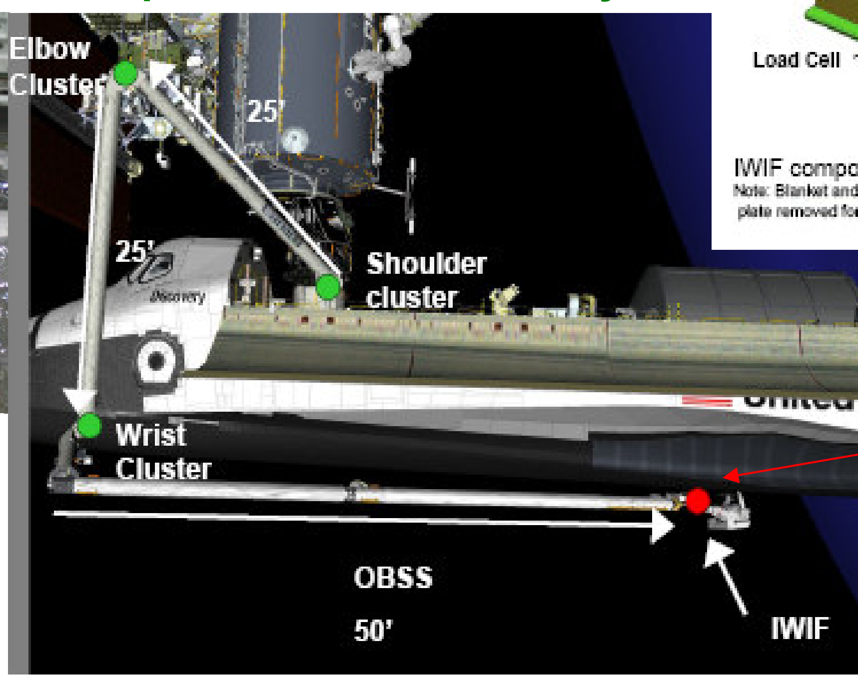
- EVA Loads on SRMS and Astronaut Worksite increased for repair missions with crewmember operations at the end of the long boom extension.
- EWBMTAU modified to handle long data takes(10hrs) and MEMS accels (DC to 200hz)
- IWIF: 6 Strain gauges, 6 Accels(100 Hz sample rate), temperature sensors.
- WSGIS: SRMS Loads - 3 Strain Gauge channels x 3 locations
- Crew activated by RF from laptop
- SRMS removed and WSGIS data is compared to calibrated sensors at the manufacturer (MD Robotics)

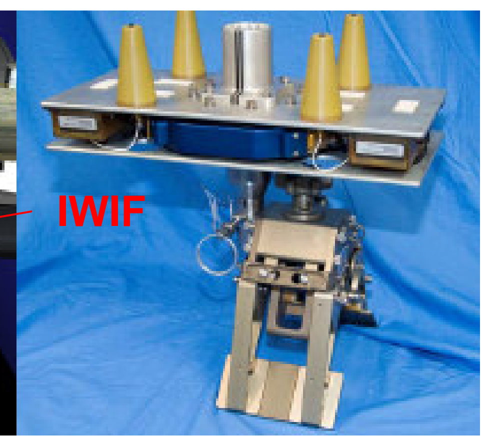


Lessons Learned: STS-121 ops successful – no LL yet.



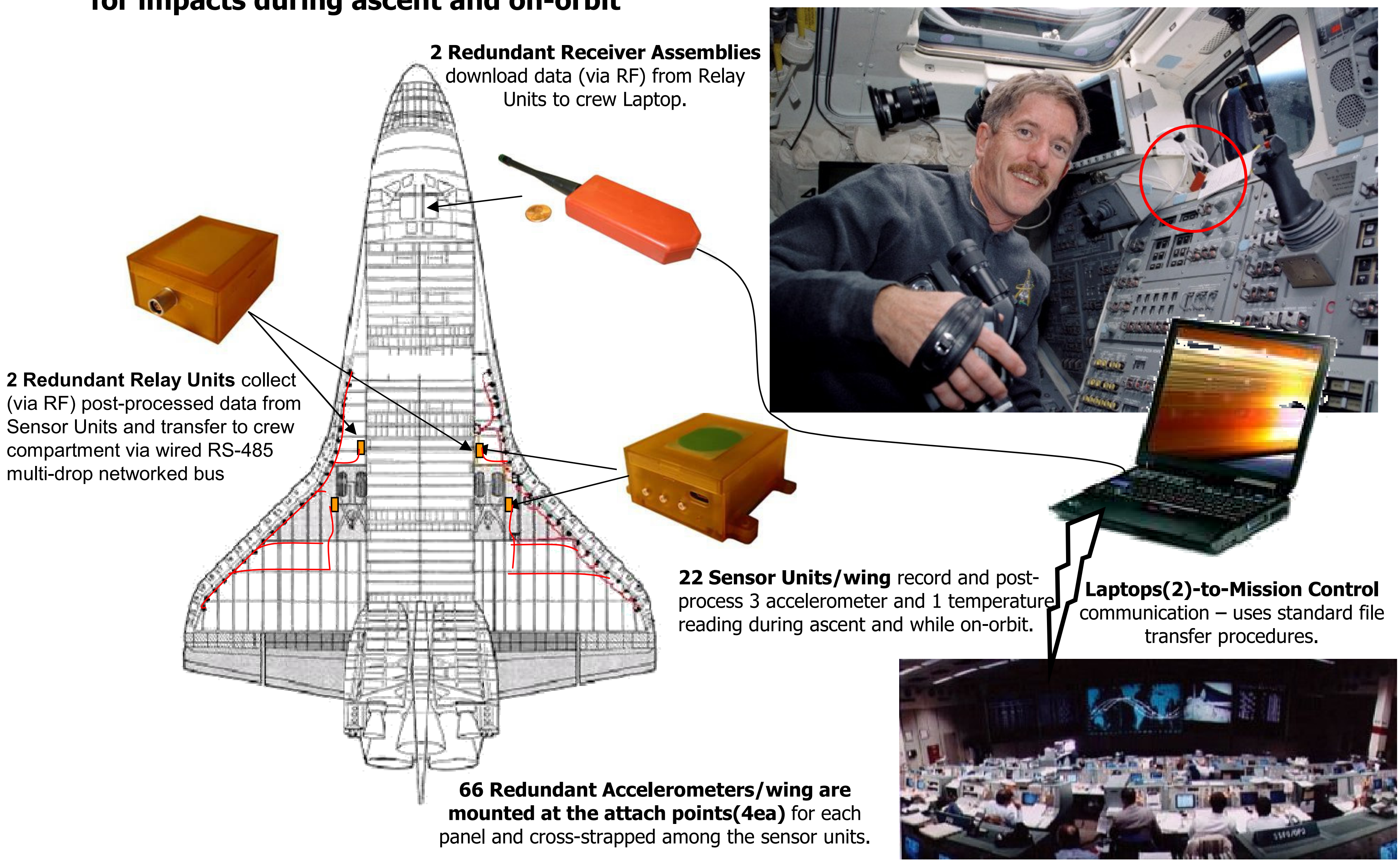
WSGIS Locations(3)





Wing Leading Edge Impact Detection System
using Enhanced Wide-band Micro-TAU (STS-114 & Subs)

Monitors Shuttle Orbiter Wing Leading Edge
for impacts during ascent and on-orbit



Micro-WIS Program Lessons Learned:

Programmatics:

- Programs need to be prepared to quickly obtain flight data to address issues: Vehicle infrastructure and State-of-the-art strap-on instrumentation systems. Fortunately Micro-wireless instrumentation Systems had been proven before the Columbia disaster.

- SBIR funding has proven to be a good source for the DTO development, and the relationship of contractor to NASA potential customer helped.

- Strong Project Management is needed to achieve the visions and keep costs and schedule under control, because integration is still a significant effort, even with a small, standalone system like Micro-WIS.

- Models, Predictions and Analysis tools are needed for understanding, predicting and planning the phenomenon, environment and use of the system.

- Data User Involvement and Ownership are very important to project success.

- Team member expertise and cooperation over an extended period is essential. Vendor support for training, integration, and operations activities until operations are mature.

Micro-WIS Program Lessons Learned:

System Architecture:

- Reliable Micro-Wireless Instrumentation Systems can be built from low power COTS radios if the system architecture provides redundancy and the use of the system allows for multiple transmissions and non-real-time data needs.

- Computing answers and summary data files close to the sensor (at the data acquisition unit reduces the data RF transmit rates. So understanding what data analysis methods work best are important for programming these computations.

- Bonding Micro-WIS sensor units to the vehicle greatly decreases the integration cost and schedule, increases the flexibility of the antenna orientation to ensure RF coverage, and reduces the vibration load into the box and electronics.

- Functionality per unit size and weight is greater value than modularity of the internal electronics design, since applications change and electronics parts improve or become obsolete quickly and each change in component means recertification for flight.

- Multiple power source types are necessary since battery technologies change and safety evaluations can eliminate the use of one source over another. Safe, low temperature, long-life power sources are desirable.

Micro-WIS Program Lessons Learned:

Operations:

- Up-front consideration of Micro-WIS as an indicator for a critical hazard or condition (like WLE impacts) needs up-front consideration and planning, or some risk remains that it can ever be used without modifications for critical hazards.

- Realistic Integrated System Tests for operations, procedures, communications and thermal/battery performance are very important to understanding capability of the system.

- Space to Ground Communication Limitations need to be accounted for.

- Data File Handling needs to be planned for.

- Vendor post-delivery support is needed for complex tests, check-out, flight operations and data interpretation.

- Laptops have not been a reliable base, it can be mitigated somewhat by full back-up laptop redundancy.

Other Current Projects:

WLEIDS Improvements

- Software and Battery voltage regulator **(JSC/EB)**
- Models and Assessment tools **(JSC/ES)**

External Wireless Instrumentation System (ISS/Boeing/Invocon)

- ISS truss dynamics – Micro-g measurements on truss

Ultra-WIS for ISS module DTO (JSC/LaRC)

– airborne ultrasonic impact/leak location

Distributed Impact Detection System (LaRC SBIR Phase 2)

– structure-borne acoustic emission impact/leak location – potential for ISS impact

No-power Sensor-Tags (Sandia/JSC) – prototypes working, interrogator in work.

Structural Health Monitoring System for inflatable habitats (JPL, Invocon, Sandia)

– architecture, sensor development and integrated tests

"Bio-net" Integrated Data Assimilation Architecture

– modular architecture for incorporating heterogeneous sensing and control devices.

Micro-WIS Power Scavenging (JSC/EB)

– Thermal and Solar

STTR for Human Space Flight Impact Technologies (**JSC/ES:** Structural Engineering)

Wireless and RFID Working Group (JSC EA + other NASA and contractors)

Wireless Local Area network for ISS laptops – operational.

Wireless Instrumentation Systems Improvements

- **RF Transceivers/Networks:** High data rates, interference and multi-path resistance and compensation, real-time adaptable/programmable characteristics, low power – high bandwidth, simpler mechanically, smaller packaging, robust environment, ready for mass production.

- **No Power Sensor-Tags**: No power, high response rate, compatible with a wide variety of sensors, reliable readings and small packaging.

- **Antenna Systems**: Smaller form factor, adaptable, selectable, more sensitive.

- **Power Systems**: Longer life, smaller, safer batteries, capacitors, fuel cells, etc. Rechargeable batteries and scavenge/remote power systems. Micro-power sources on circuit to maximize efficiency.

- **Components:** Smaller, yet high reliability, low power/high efficiency, reliable fabrication techniques/quality control.

- **System Capability**: Robustly tested as standalone parts and integrated system to design environments and contingency operations. Production prototyping and testing have demonstrated mature design/approach and validated design requirements. Prove through incremental improvements addressing unique vehicle system needs.

Vehicle Accommodations for Wireless Instrumentation Systems

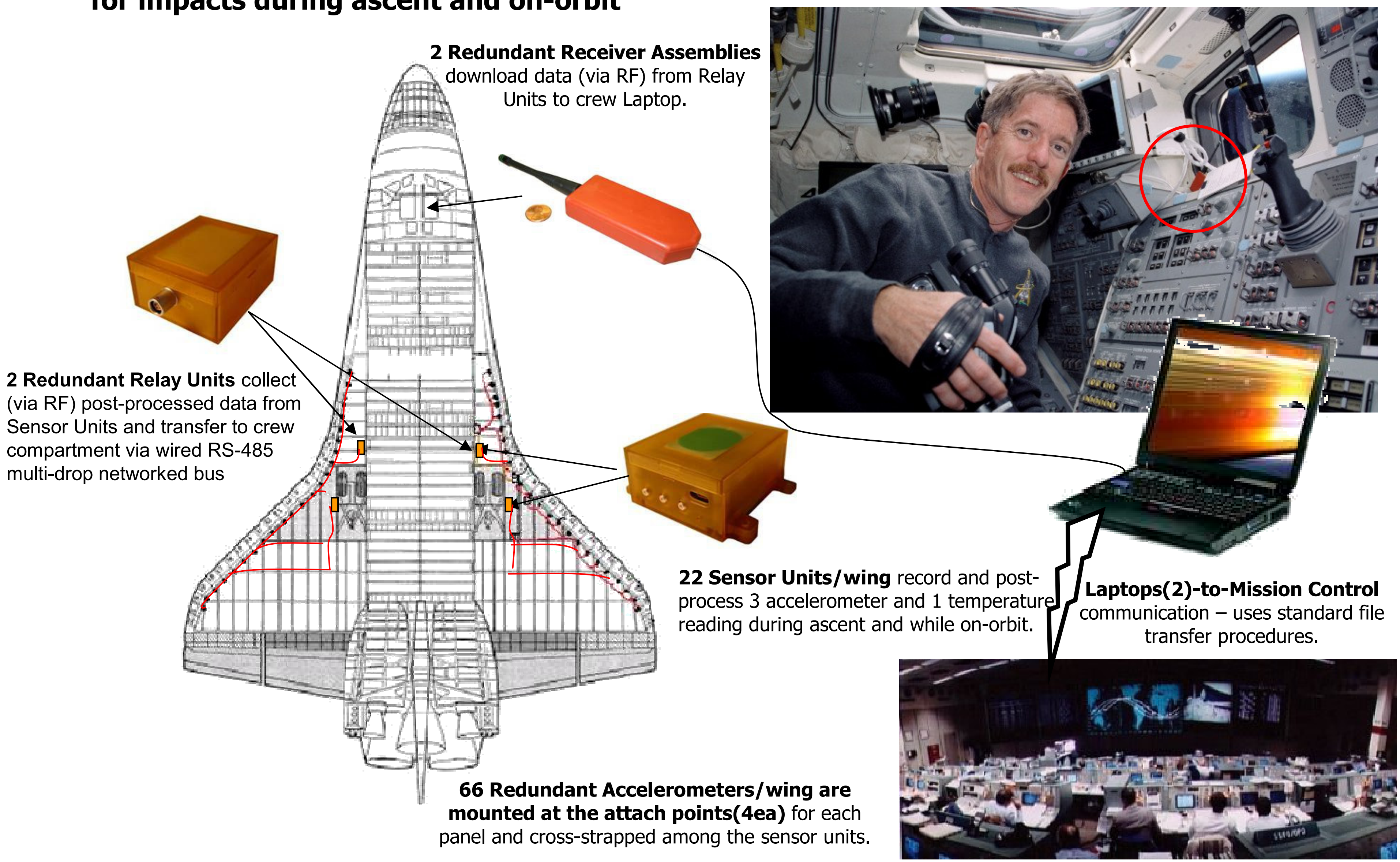
1. **Design in accessible Structural Zones with resource interfaces** for vehicle power, data, commanding and time synchronization. An area for mounting avionics in the zone would be established. Access requirements may be driven by any assembly level or mission phase.
2. **Develop and certify a suite of modular instrumentation** and sensors to augment standard wired instrumentation that can accommodate anticipated measurement types.
3. **Use a weight and resource allocation** for modular instrumentation, if standard instrumentation needs cannot be justified.
4. **As the system design, test and analyses mature** system managers bring forward specific sensor and measurement requirements.
5. **Instrumentation and System Integration Trade-offs** can then be performed using the different types of wired, fiber-optic, wireless, sensor-tag and non-contact tools to accomplish the measurement.
6. **"Second Tier" requirements** Are developed for instrumentation systems, structure and vehicle interfaces tailored according to the integrated needs for each zone.

New Technology Transitions have always caused concern…

1930's	Vacuum-driven instruments; early aircraft radios; vacuum-controlled autopilots; 14 volt DC systems; HF radio
1940 's	DC electrical autopilots; 28 volt DC systems; VHF radio; electrical cockpit instruments; 115VAC electrical autopilots; vacuum tube controls; LORAN; radio direction finders and altimeters; hydraulic flight control; jet propulsion
1950's	Solid state (transistor logic) controls; airborne computers for G&N and weapon system control; stability augmentation; UHF radio; TACAN; MLS
1960's	Integrated circuits; fly-by-wire (Mercury, Gemini, Apollo); digital flight control (Apollo)
1970's	Redundant data bus flight control (Shuttle; USAF 680J project); CRT displays
1980's	Liquid crystal displays; Global Positioning System (GPS); auto-land
1990's	Photonics; GPS attitude control; **Stand-alone wireless instrumentation sensor networks for Space Applications**
2000's	**Wireless Zones in Spacecraft, Wireless Sensor Networks in critical applications, Wireless Flight Control, long range active/passive RFID sensors, and… <u>New System Engineering to accommodate</u> "<u>Fly-by-Wireless</u>"**

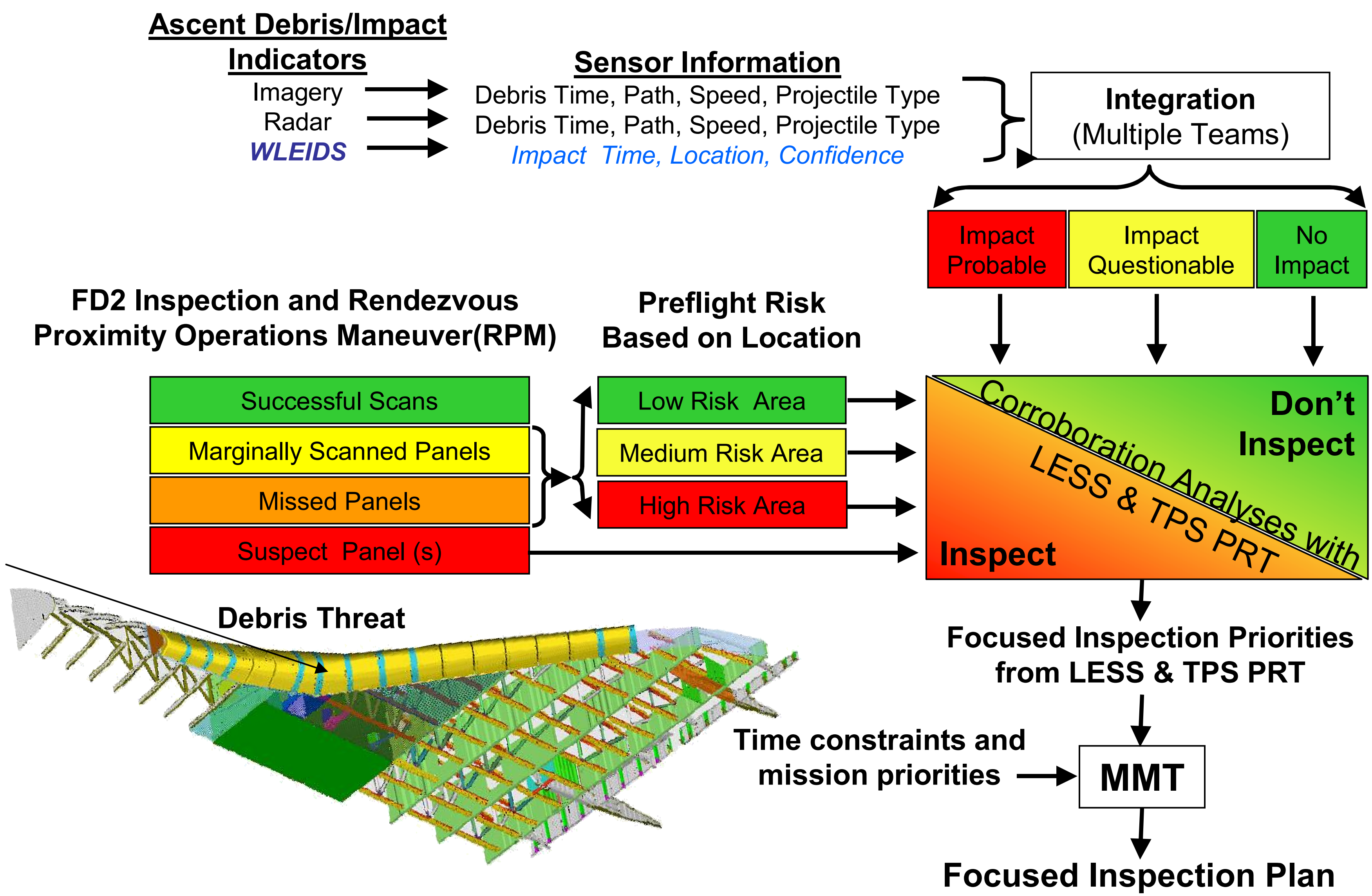
Wing Leading Edge Impact Detection System using Enhanced Wide-band Micro-TAU (STS-114 & Subs)

Monitors Shuttle Orbiter Wing Leading Edge for impacts during ascent and on-orbit



WLEIDS Purpose: Ascent Impact Indicator

Used to influence TPS inspection priorities & planning

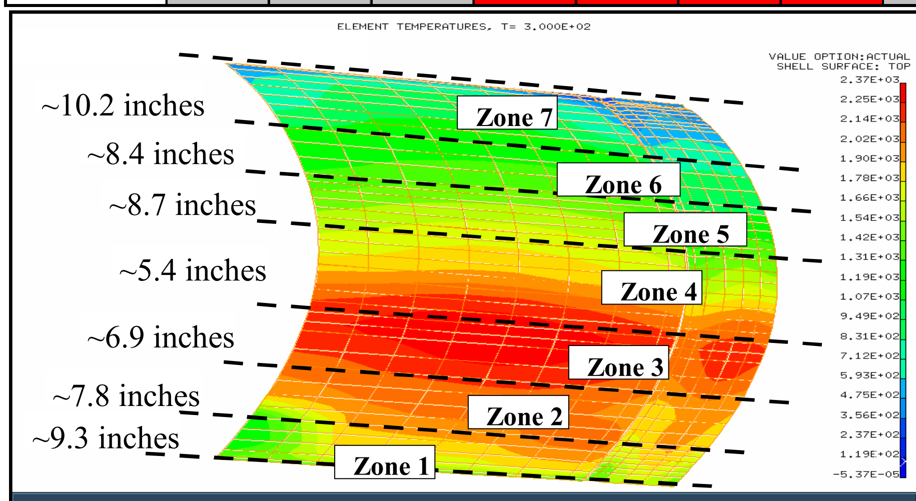


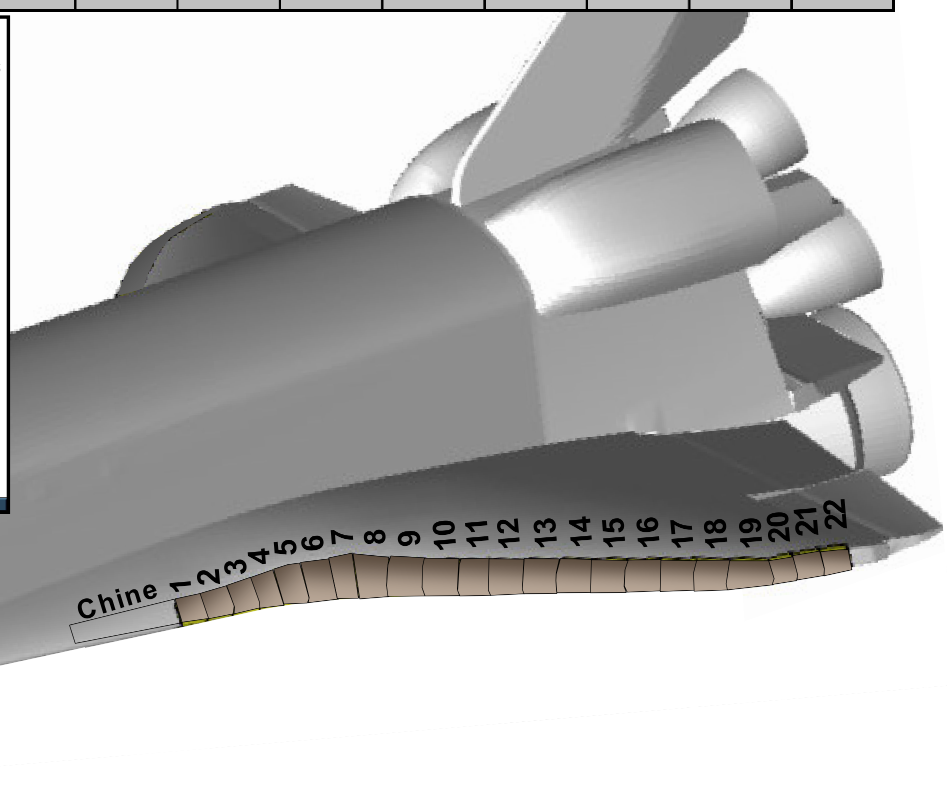
Wing Leading Edge Re-Entry Risk: RCC Max Coating Loss (No Substrate Loss Allowed)

ISS Hvy Wt Fwd CG EOM Entry Trajectory

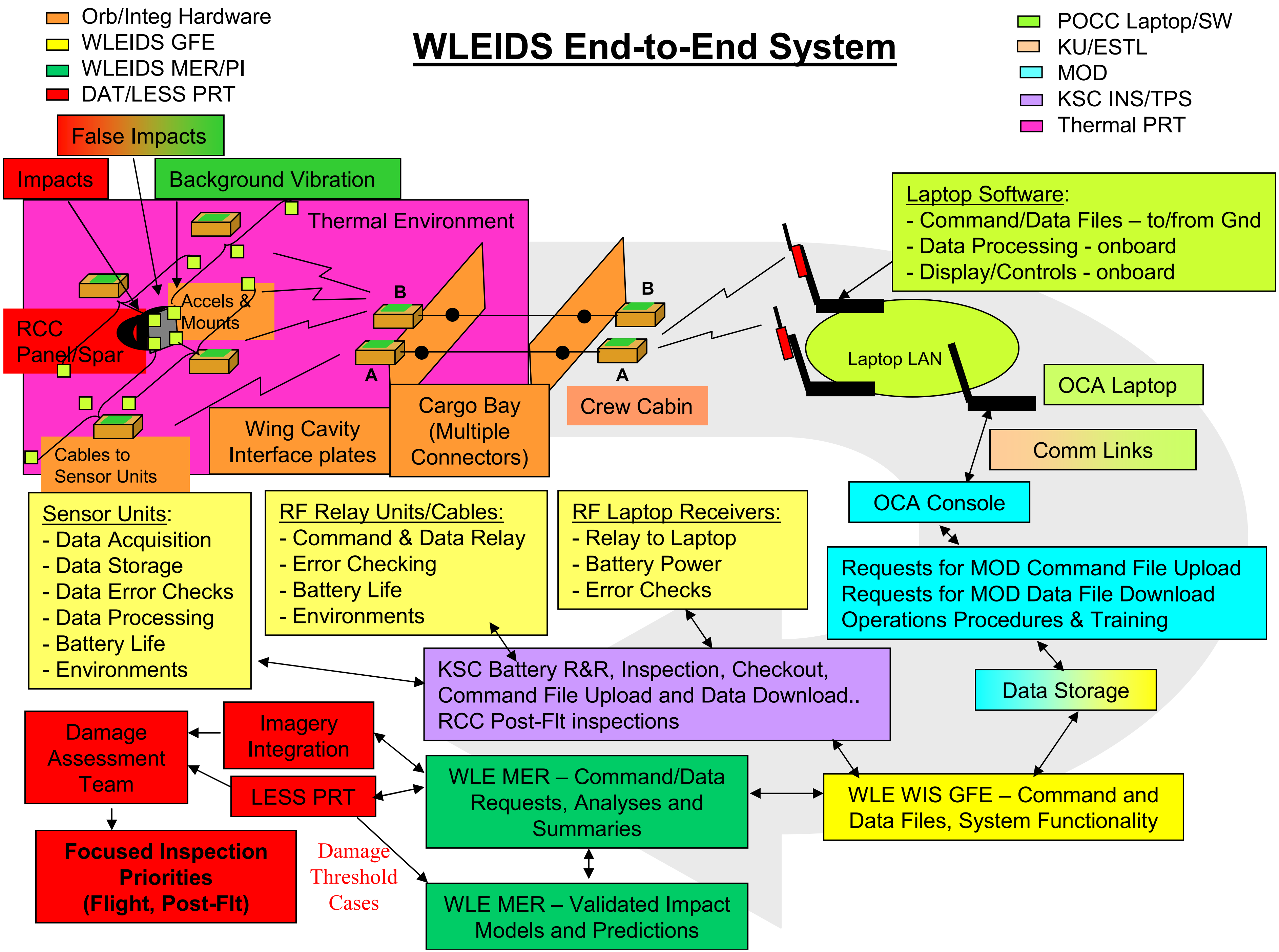
Damage Diameter in Inches:

Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Panel(s)	1-4	5	6	**7**	8	**9**	10	11	12	13	**14**	15	16	17	18	**19**-22
Zone 7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Zone 6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Zone 5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zone 4	N/A	N/A	N/A	0.16	0.13	0.08	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Zone 3	N/A	N/A	N/A	0.16	0.08	0.08	0.13	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Zone 2	N/A	N/A	N/A	0.16	0.08	0.08	0.16	0.16	0.16	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zone 1	N/A	N/A	N/A	0.16	0.16	0.16	0.16	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A



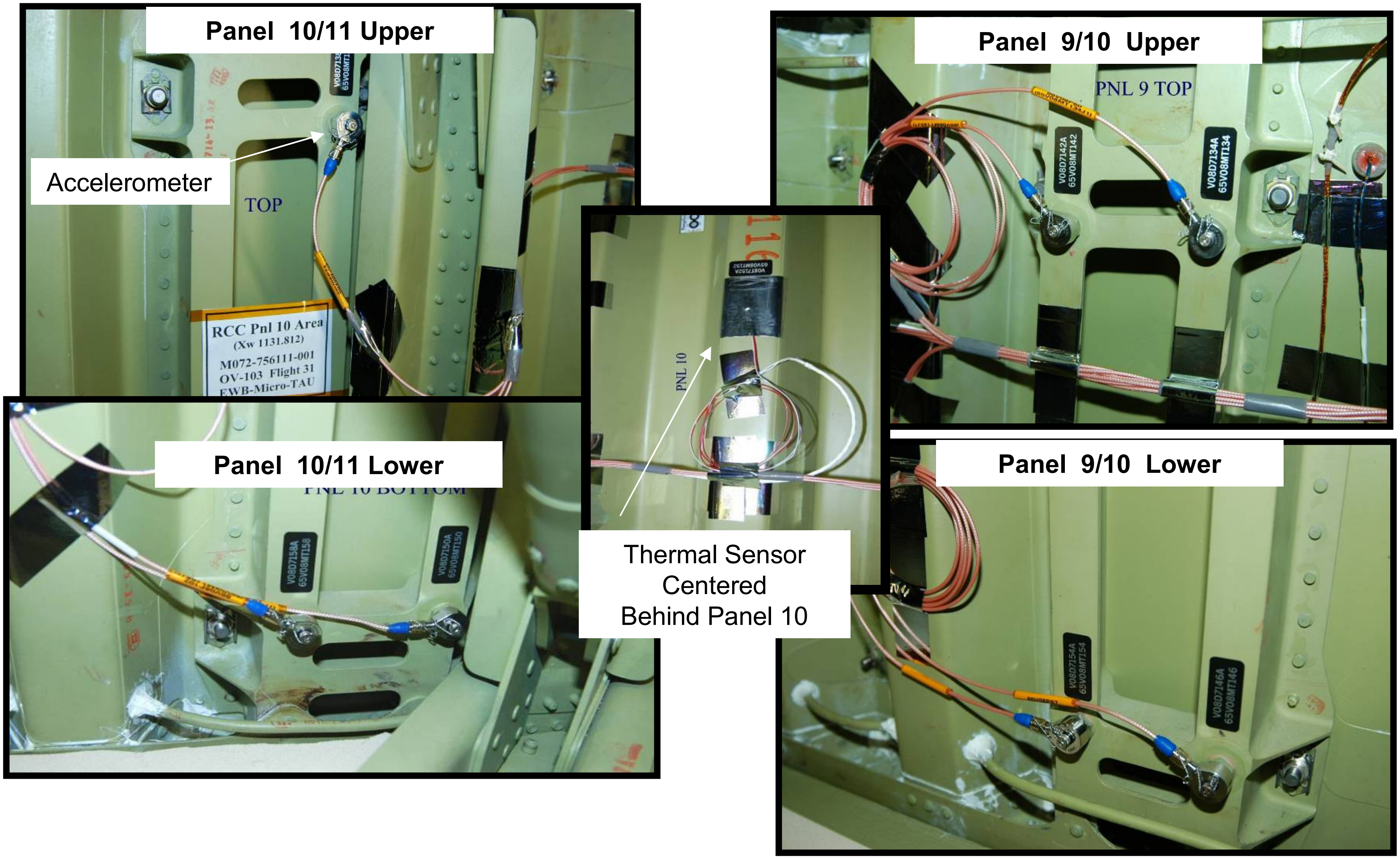


WLEIDS End-to-End System



WLEIDS System Overview:
Accelerometer Flight Installation

Accelerometers installed behind WLE spar near the upper/lower attach bolts for RCC Panel assemblies



Photographs looking forward inside port wing

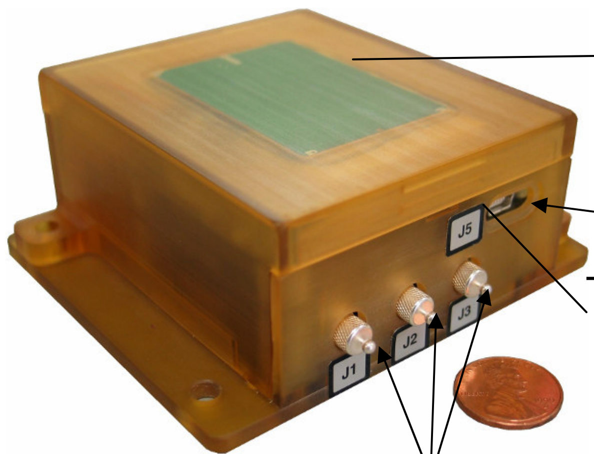
WLEIDS System Overview: GFE Hardware

Enhanced Wide-band Micro-Triaxial Accelerometer Unit (EWB Micro-TAU)

Sensor Unit

Relay Unit

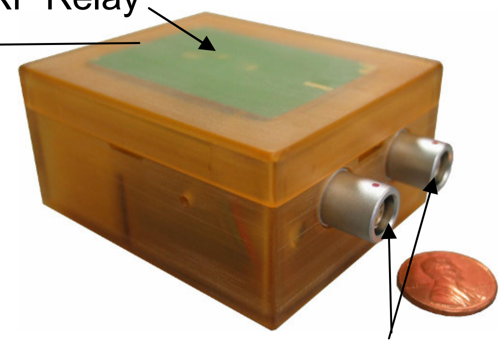
Patch Antennas for RF Relay



USB Port

Temperature Channel

Accelerometer Channels

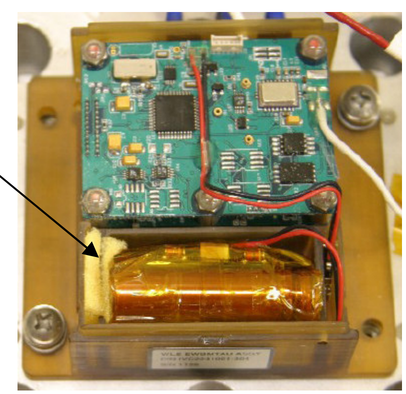


Relay Unit 485 Connectivity to Crew Cabin (wired)

Original Plan:
Lithium BCX C-cell Battery (low temps but too hazardous)

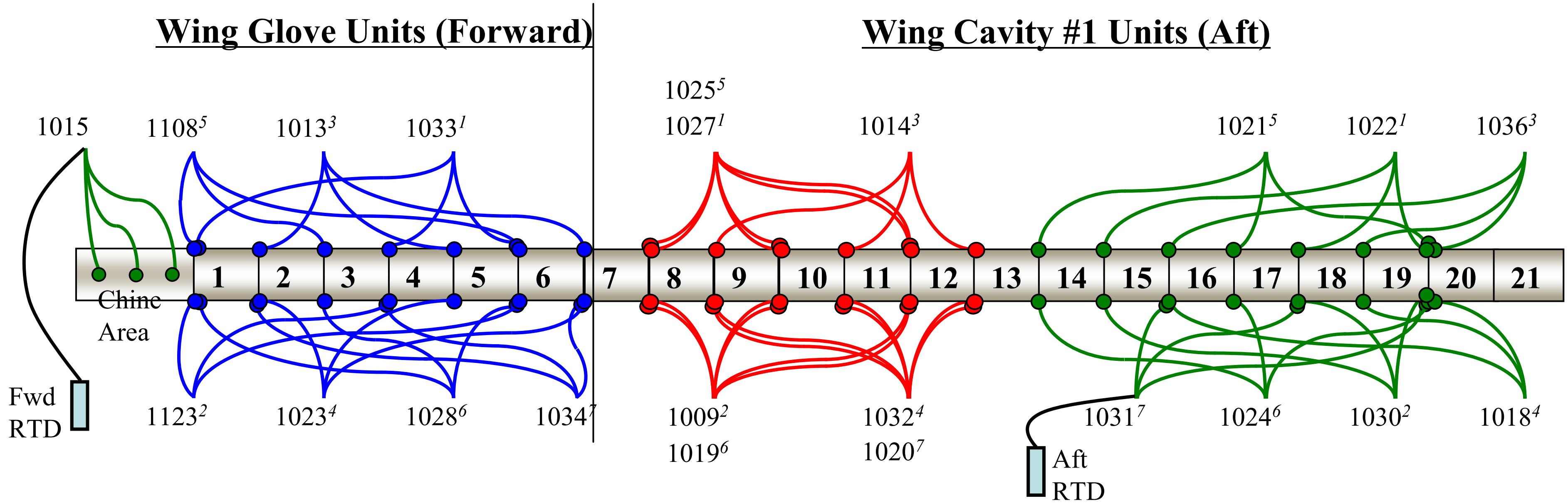
Current Config:
Two L91 AA LiFeS2 cells (dies at 0 deg F)

In Work: Add Voltage Regulator (dies at -40F)

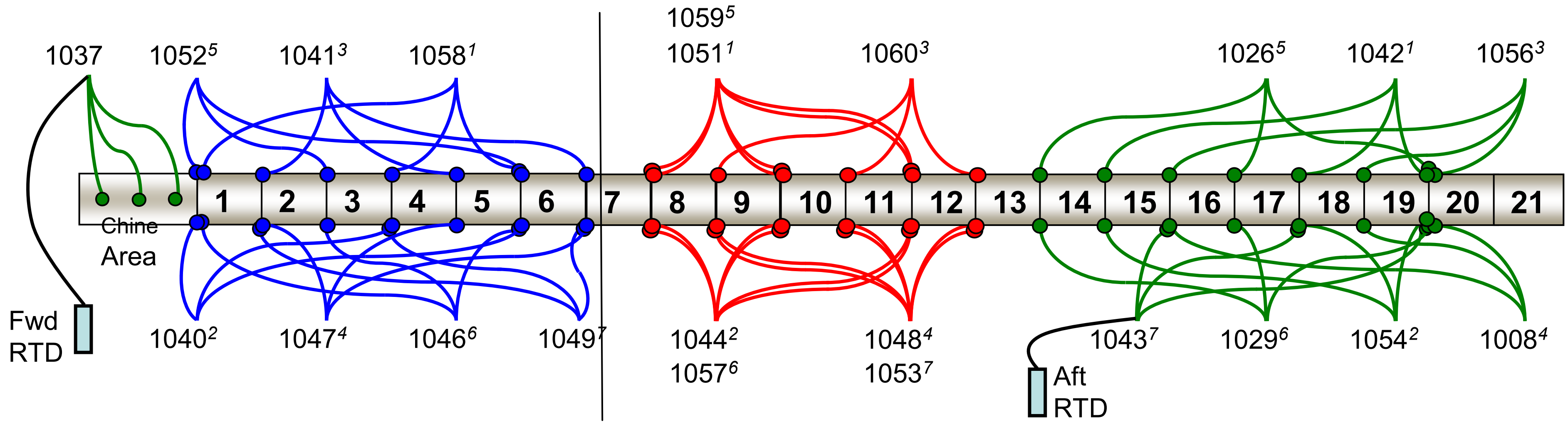


Accelerometer to Sensor Unit Cross-Strapping

STS-121 Port Wing Accelerometer – Sensor Unit Configuration



STS-121 Starboard Wing Accelerometer – Sensor Unit Configuration



WLEIDS System Overview: Sensor Unit Installation

(A Compromise of “the Vision” for Safety & Operations)

Sensor Unit installation went from flexible (individually located & oriented near sensors) boxes attached with RTV, to two groups of sensor units bolted in rigid patterns on uniquely designed plates, creating high G-loads & reduced communication reliability.

Rationale:

- Avoid Li-BCX Explosive Hazard at high temps if hole develops in wing RCC/Tile
- Ease of battery replacement – near wheel well access panel
- Avoid critical hazard if hardware comes loose in the wing
- Avoid risk of damaging sensitive struts in the wing

Forward Sensor Unit Group
8 sensor units

RF Relay Unit A

Aft Sensor Unit Group
14 sensor units

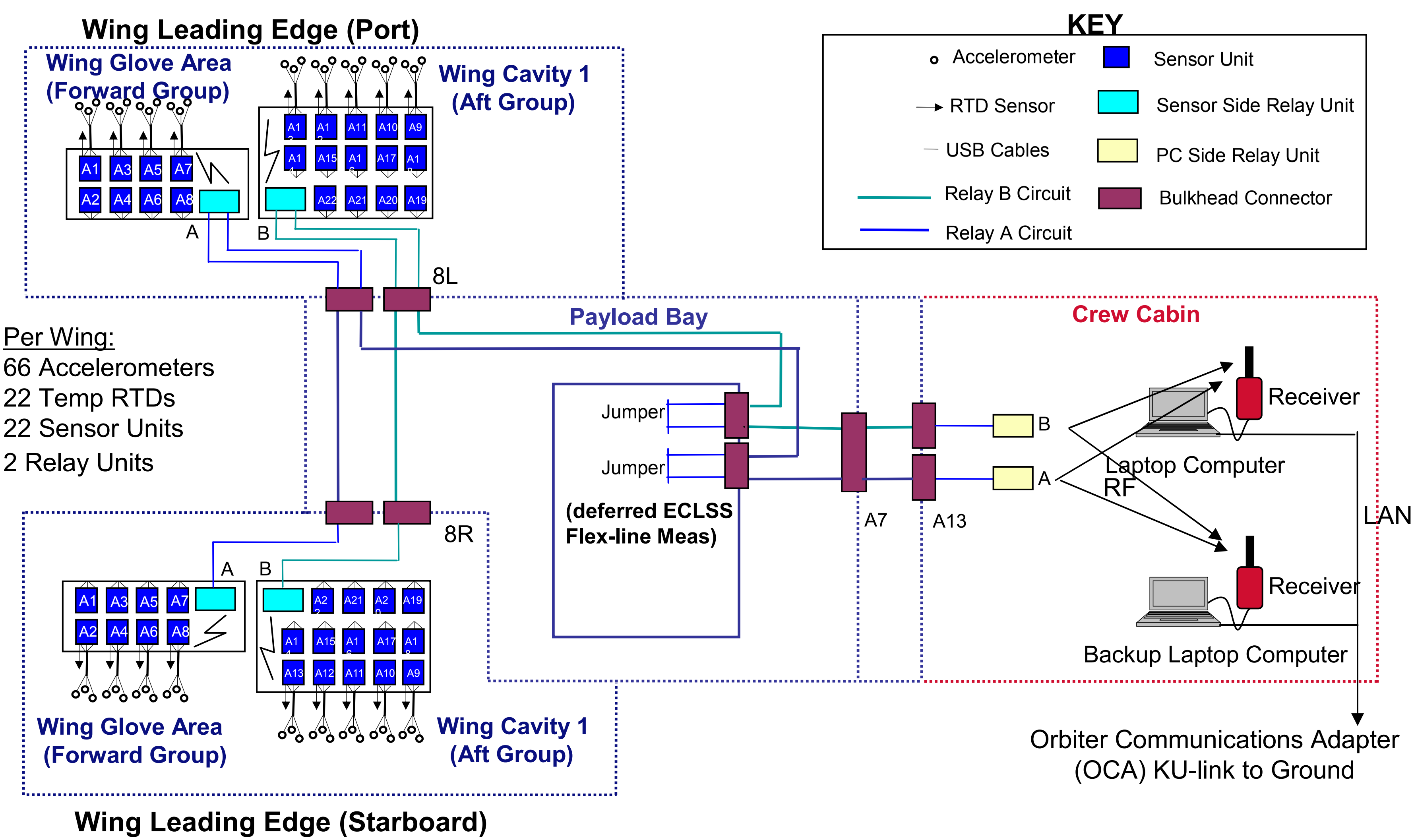
RF Relay Unit B

Inside the crew cabin
2 Cabin Relay Units

Cabin Relay Unit (A & B) communicates with wing Relay Unit A or B and sends data to laptop

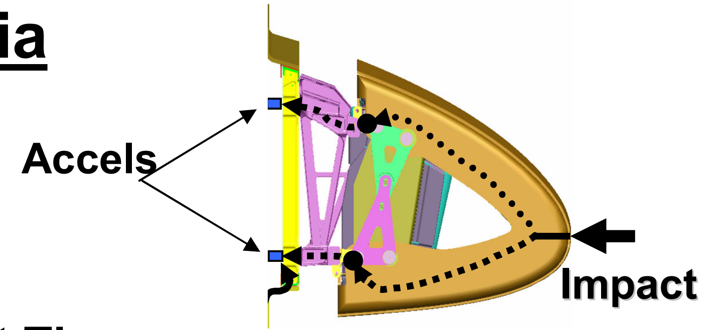
WLEIDS System Overview: Vehicle Wiring Diagram

- Sensor Units can communicate with Cabin via Relay path A or B



Per Wing:
66 Accelerometers
22 Temp RTDs
22 Sensor Units
2 Relay Units

WLEIDS Ascent Impact Criteria



1. <u>Significant transient relative magnitude</u> - Get Time

   (Look for sudden, elevated real transient events above background)

2. <u>Localized response distribution</u> - Get all Sensor Channels involved

   (Distinguish localized response from global events and data anomalies)

3. <u>Elevated high frequency content</u> – Confirm Impact Signature

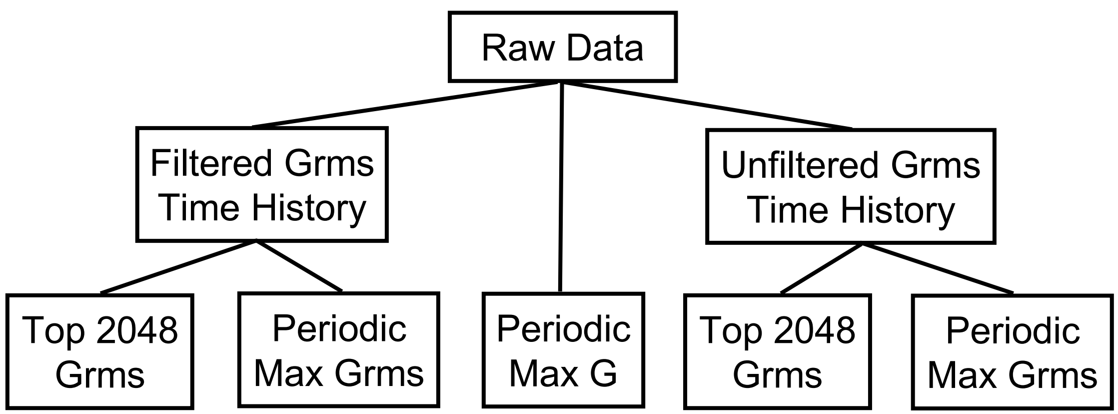
   (Distinguish energy in higher frequencies compared to background)

4. <u>Shock signal characteristics</u> – Confirm Impact Signature

   (Distinguish unusual responses from previous experience in test/flight)

WLEIDS Ascent Data Analysis: File Type Overview

Data Processing Structure

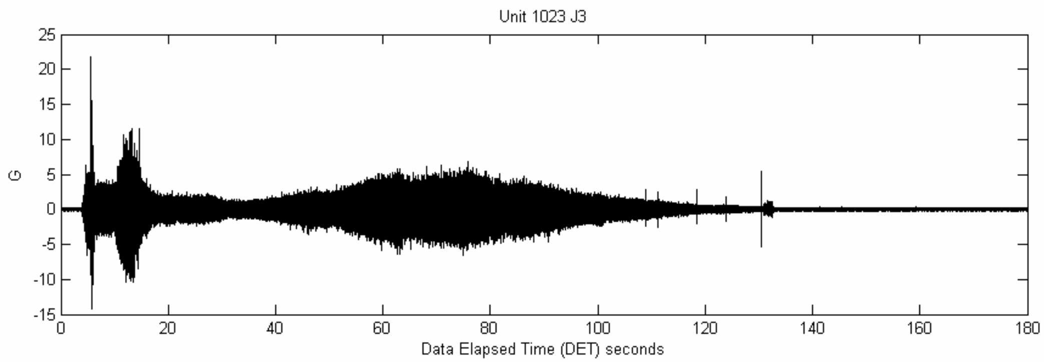


Summary file download order

1) Filtered Periodic Max Grms
2) Unfiltered Periodic Max Grms
3) Periodic Max G
4) Filtered Top 2048 Grms
5) Unfiltered Top 2048 Grms

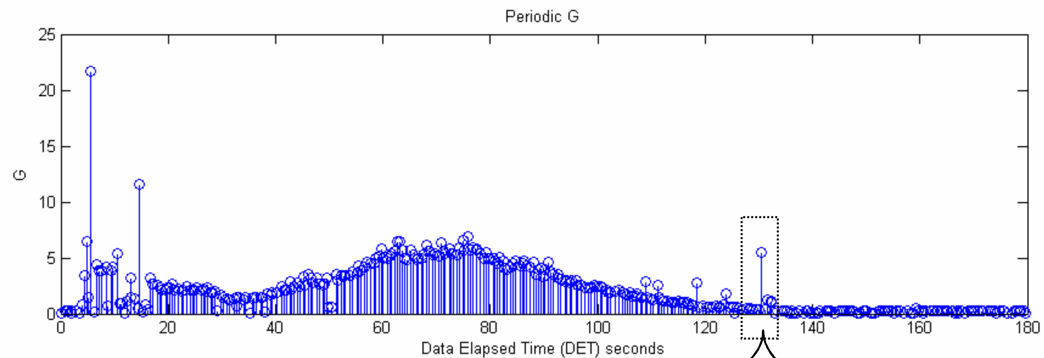
- All of these files are created internal to each sensor unit immediately after the ascent data take and can be requested for download after the crew sets up the WLES laptop
  – Raw data
    - Most definitive indication of impacts
    - Would take 88 days to download the entire raw data file from all sensor units via RF
    - Prefer to download at least one, half second window for all events for quantitative evaluation of impact criteria
  – Grms Time Histories
    - Intermediate step between raw data and summary files that utilize a Grms calculation
    - Small portions can be downloaded, but points are chosen more effectively in summary files
    - Filtering helps eliminate some of the low frequency response of the vehicle and accentuates the impact response
  – Summary files
    - Used to create an initial list of events that will be classified using additional downloads and the impact criteria
    - Possible to confirm a probable impact based on these files alone if downloads are not available
    - All periodic files will be analyzed prior to first written report

WLEIDS Ascent Data Analysis: File Types



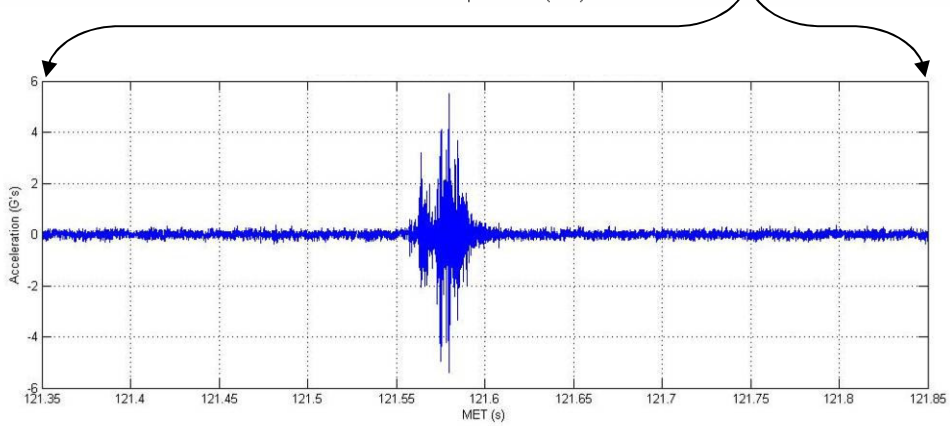
Raw Data:

- 20,000 samples per second
- Half seconds of raw data can be selected for download based on analysis of summary files



Periodic G:

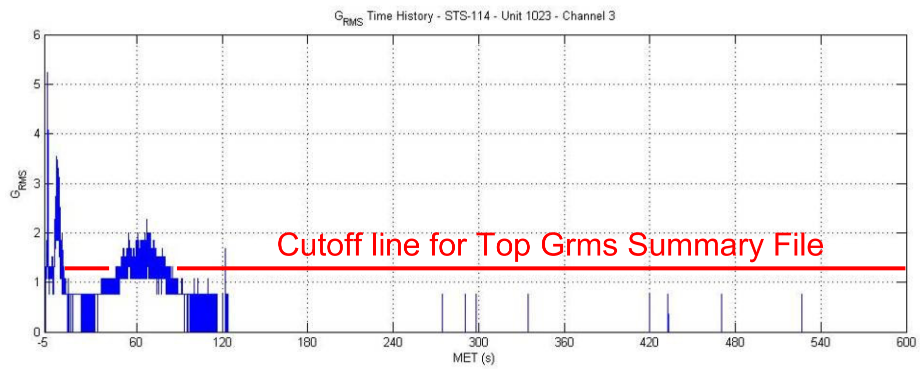
- File split into 1,200 ½-second time periods
- Top G point in each period is returned
- Best for identifying impacts near the noise floor
- Third download for STS-121



Half Second G Time History:

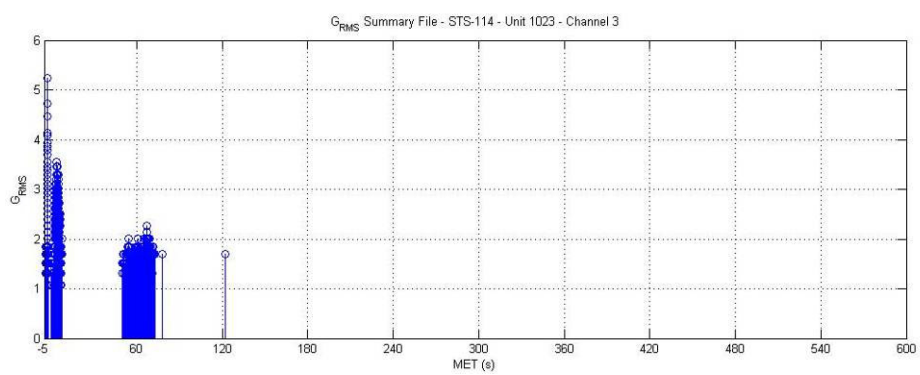
- Used to investigate points of interest
- Can be requested from any file type

WLEIDS Ascent Data Analysis: File Types



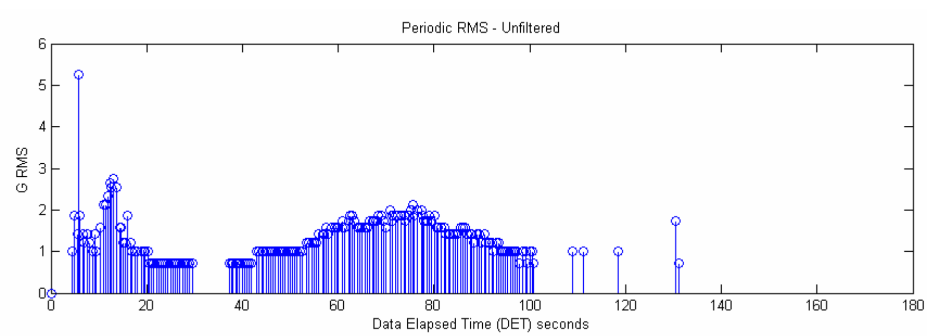
Grms Time History:

- 256 point RMS windows with 50% overlap
- Processed twice:
  - High pass filter at 312.5 Hz (primarily reduces response from global events to accentuate impacts)
  - No filtering
- Current version is significantly affected by large steps in discrete Grms values below 1.2 Grms



Top Grms Summary File:

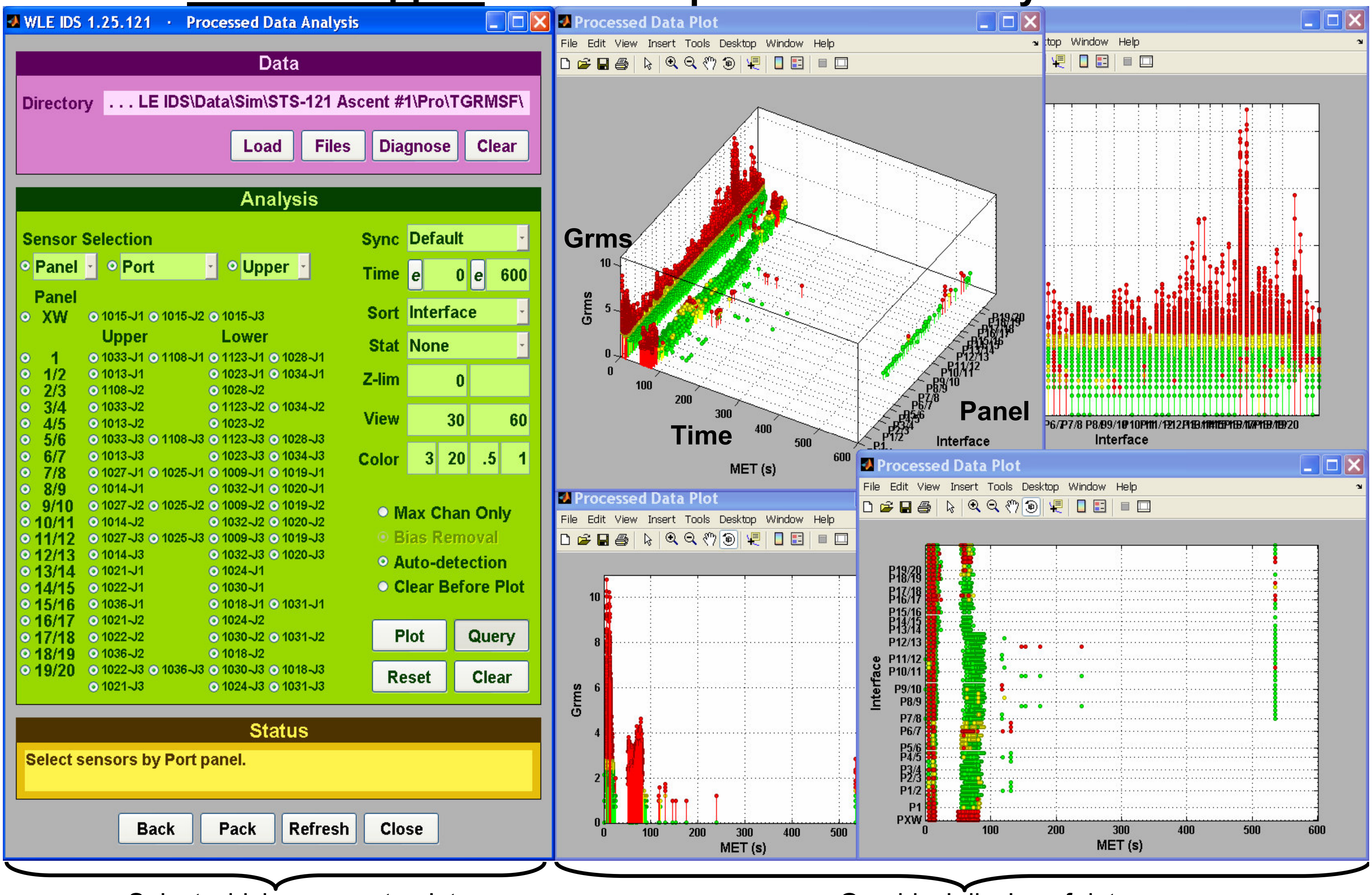
- Created from both Grms time history files
- Top 2,048 points returned
  - High point density around ignition and max Q
  - Value of cutoff line may change for each flight
- File without filtering is same as STS-114



Periodic Grms Summary File:

- Created from both Grms time history files
- File split into 1,200 ½-second time periods
- Top Grms point in each period is returned

Mission Support: Ascent Impact Detailed Analysis Tool

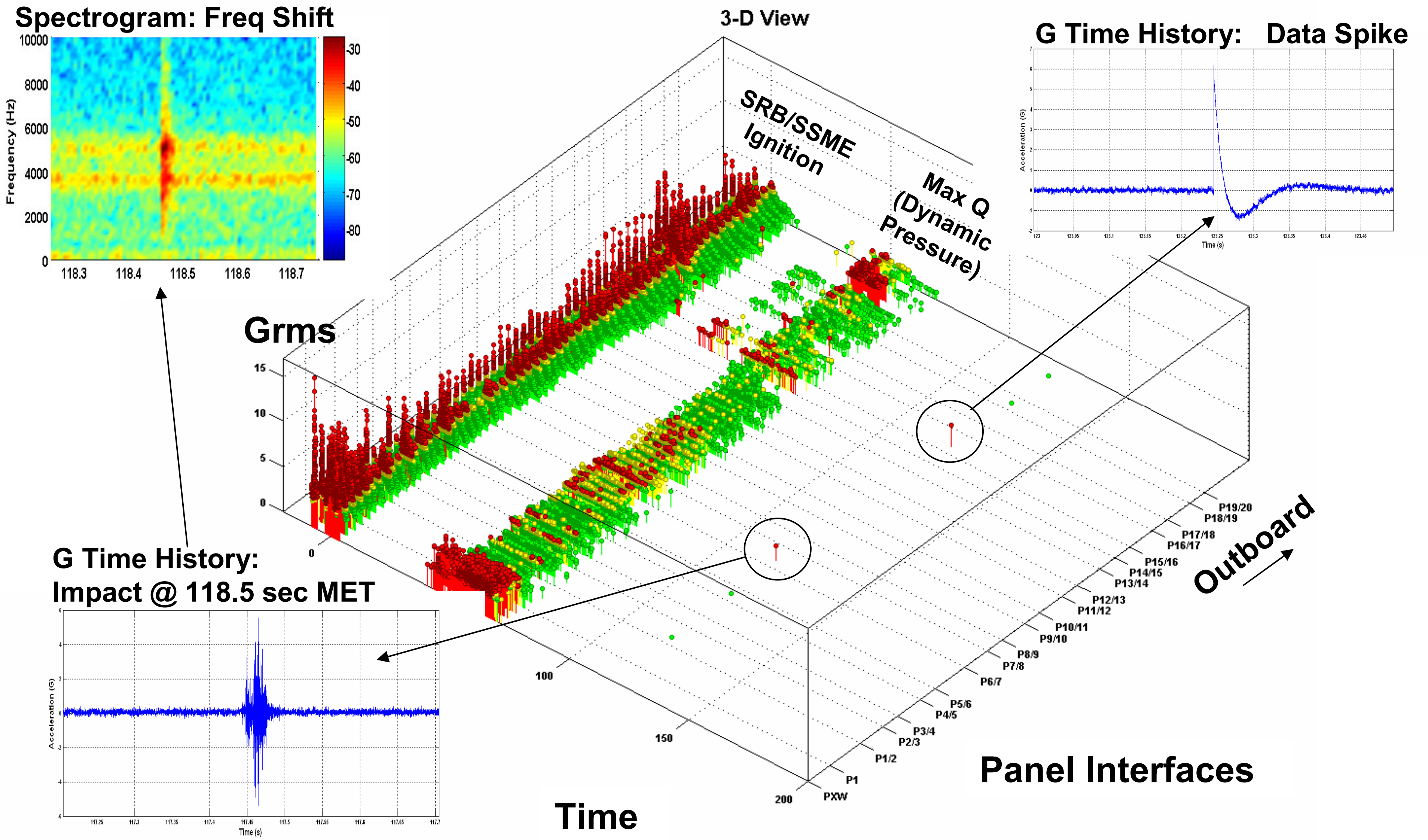


Select which sensors to plot

Graphical display of data

STS-114 Ascent Data Analysis: Mission Tools

Half second time history downloads used to distinguish between real impact events and data anomalies

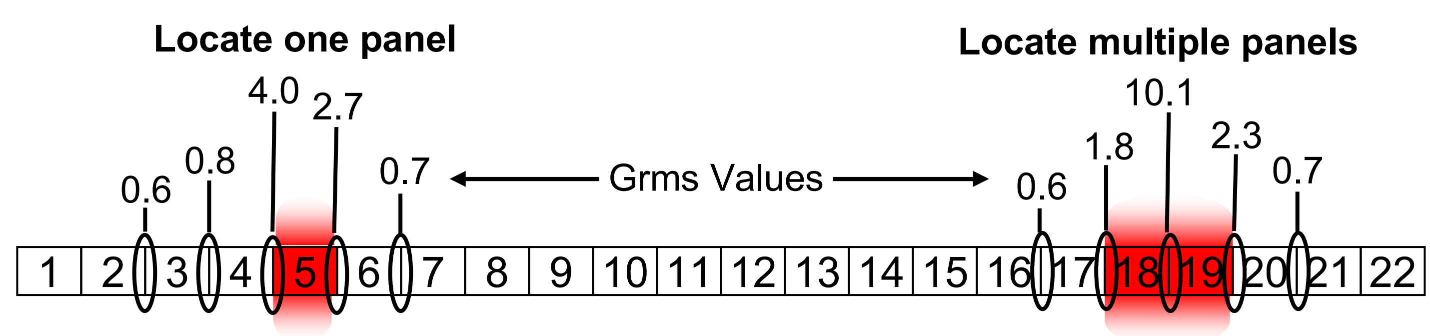


<u>Ascent Data Analysis</u>: Determine Impact Location

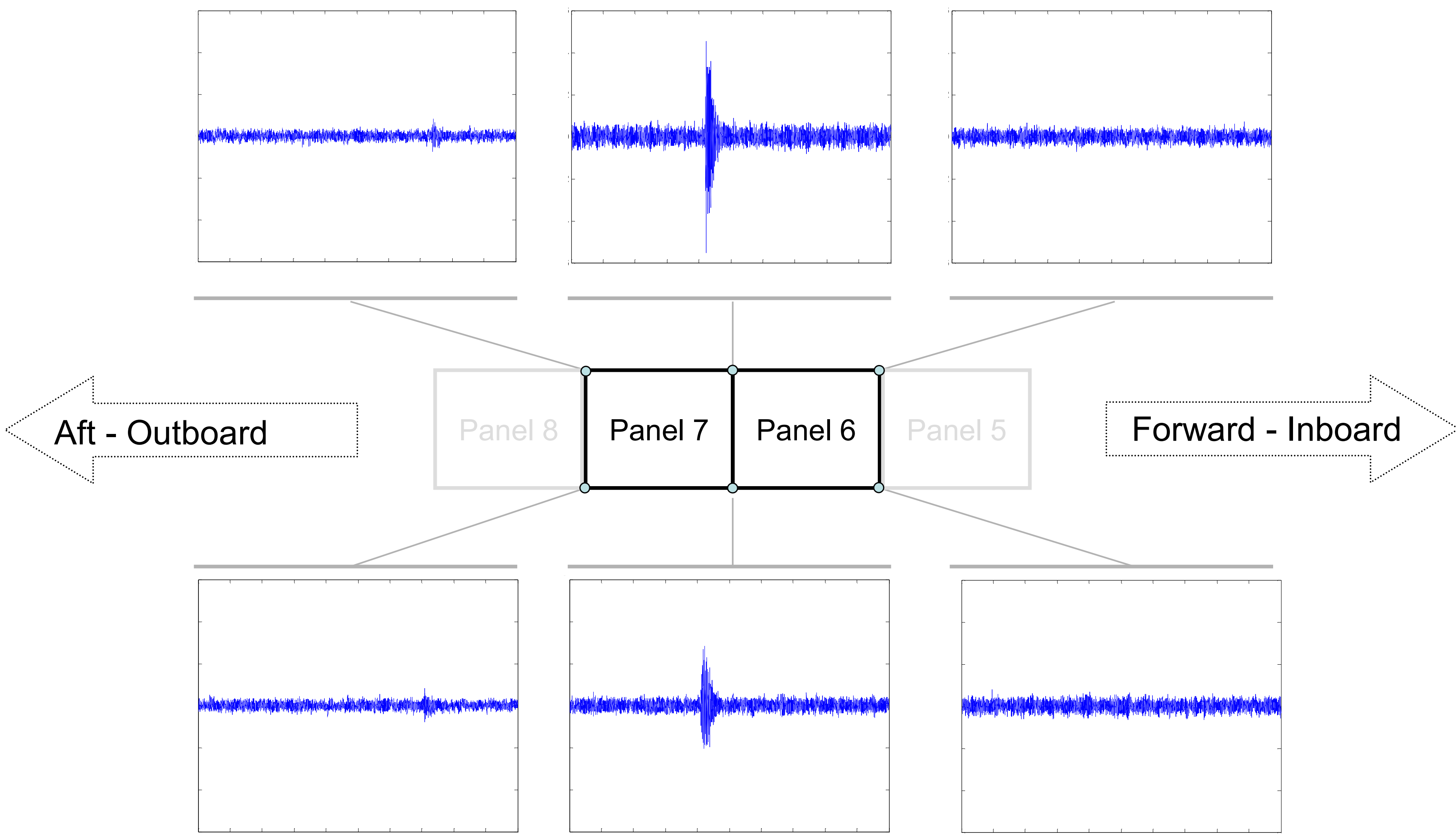
- Large response on only one interface
  - report adjacent panels to the interface
- Equally large response on two or more interfaces
  - report range of panels between the interfaces

- Cannot distinguish impact location on the panel (upper or lower surface or apex)
- Location includes T-seals either side of panel reported
  - Cannot distinguish between an impact to RCC Panel versus T-seal
- Location includes an undefined region on the tile acreage behind the reported panels
  - Cannot distinguish between an impact to RCC surface and a Tile surface

Example:

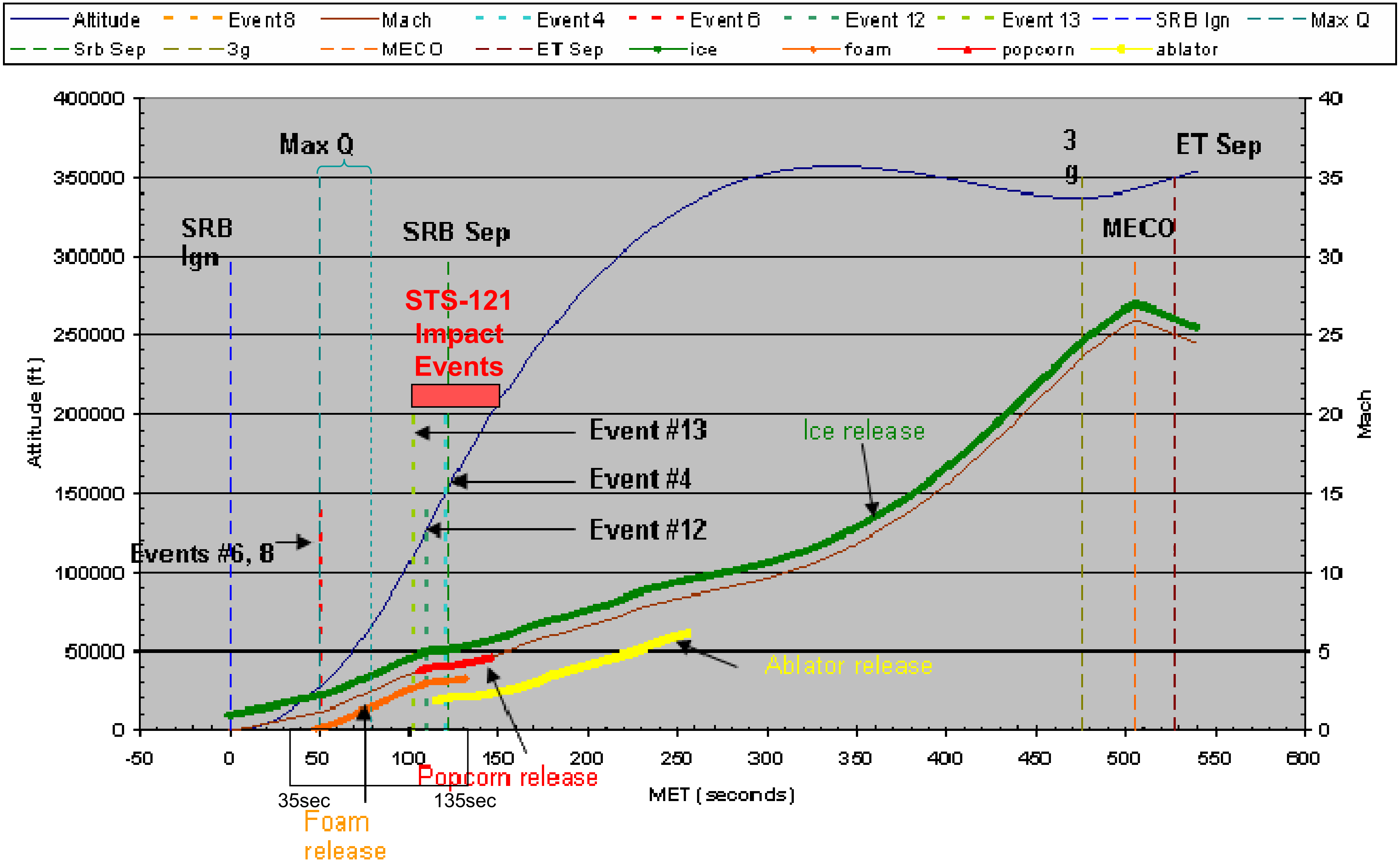


STS-114 Ascent Data Analysis: Panel 6/7 Hit
Impact Location: Time History Plots

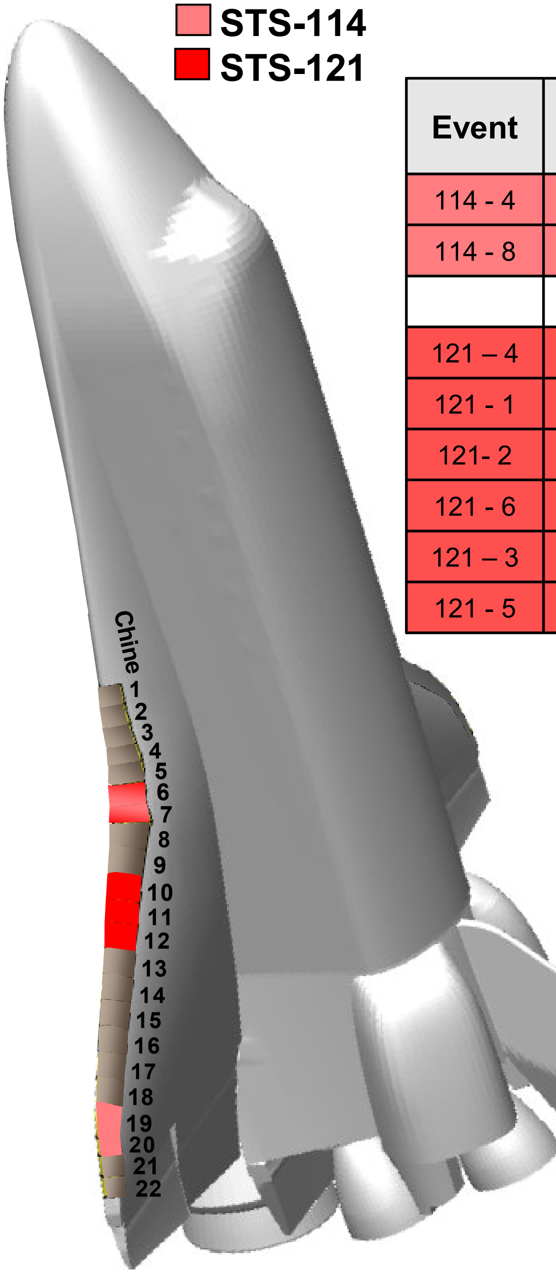


Observed Events vs Typical Shuttle Ascent Profile

Note: **STS-114 – post-flight analysis impacts between 35 and 135 sec MET**
STS-121 – In-flight Impacts occurred between 100 and 120 sec MET



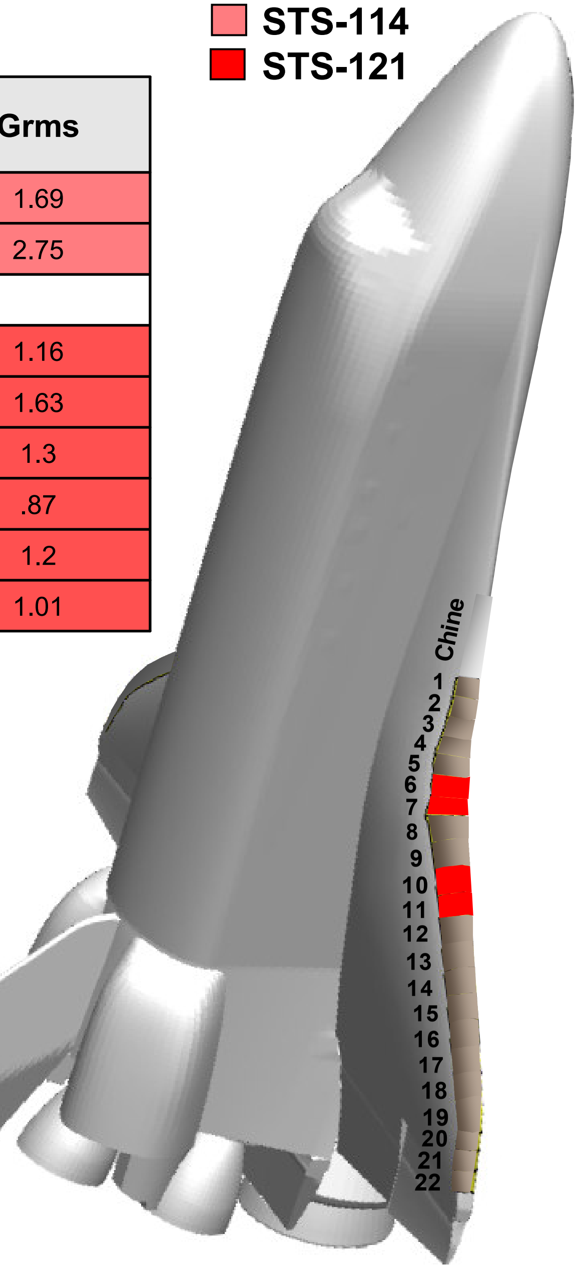
Port
Wing Leading Edge Impacts
STS-114
STS-121



In-Flight Reports

Event	MET (Sec)	Panel	Grms
114 - 4	121.9	Port, 6-7	1.69
114 - 8	50.2	Port 19 -20	2.75
121 – 4	100.25	Starboard, 6-7	1.16
121 - 1	104.41	Port, 6-7	1.63
121- 2	104.11	Starboard, 7	1.3
121 - 6	105.42	Starboard, 10-11	.87
121 – 3	110.47	Port, 6-7	1.2
121 - 5	119.74	Port, 10-12	1.01

Starboard
Wing Leading Edge Impacts
STS-114
STS-121



Challenge: Threshold Level for WLEIDS Impact Reporting

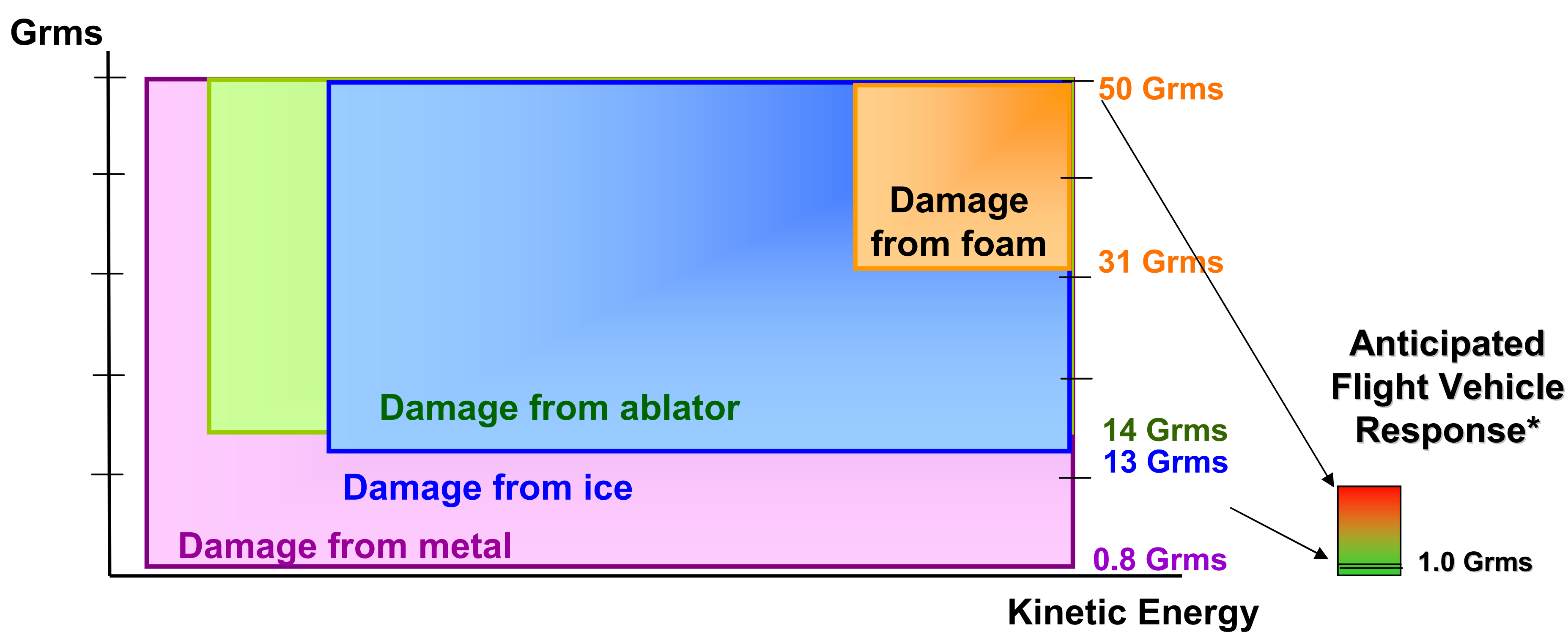
Problem: Analysis routines will likely identify too many non-damaging impacts to be practically addressed. Assessment of STS-114 raw data with these routines showed 146 impacts… with no damage to the RCC surface.

Consider the Variability and Uncertainty in:

1. **Predicted Damage Threshold/Critical Damage Impact Cases from Models**.
   - Conservative based on many months of testing and model validation.
   - Damage Threshold and Critical Damage Cases can be almost the same.
2. **WLEIDS impact test article actual response data and predicted behavior**.
   - Quite variable with impactor, impact location on panel or T-seal.
   - Limited Tests, Air blast effects,
3. **WLEIDS flight data response data versus observed damage**.
   - Changes with Panel #, effect of Orbiter Structure, Changes with MET
   - Keep track of flight impacts to reduce uncertainty, no damage on STS-114.
4. **Selection of a single "best" parameter for use as the threshold**
   - Grms, peak-G, filtered Grms, etc

NOTE: The Impact Threshold level begins conservatively: 1 Grms (unfiltered) and will be refined as more of the above analysis and flight data becomes available.

WLEIDS Impact Test Article Data Trends
RCC Damage Observed

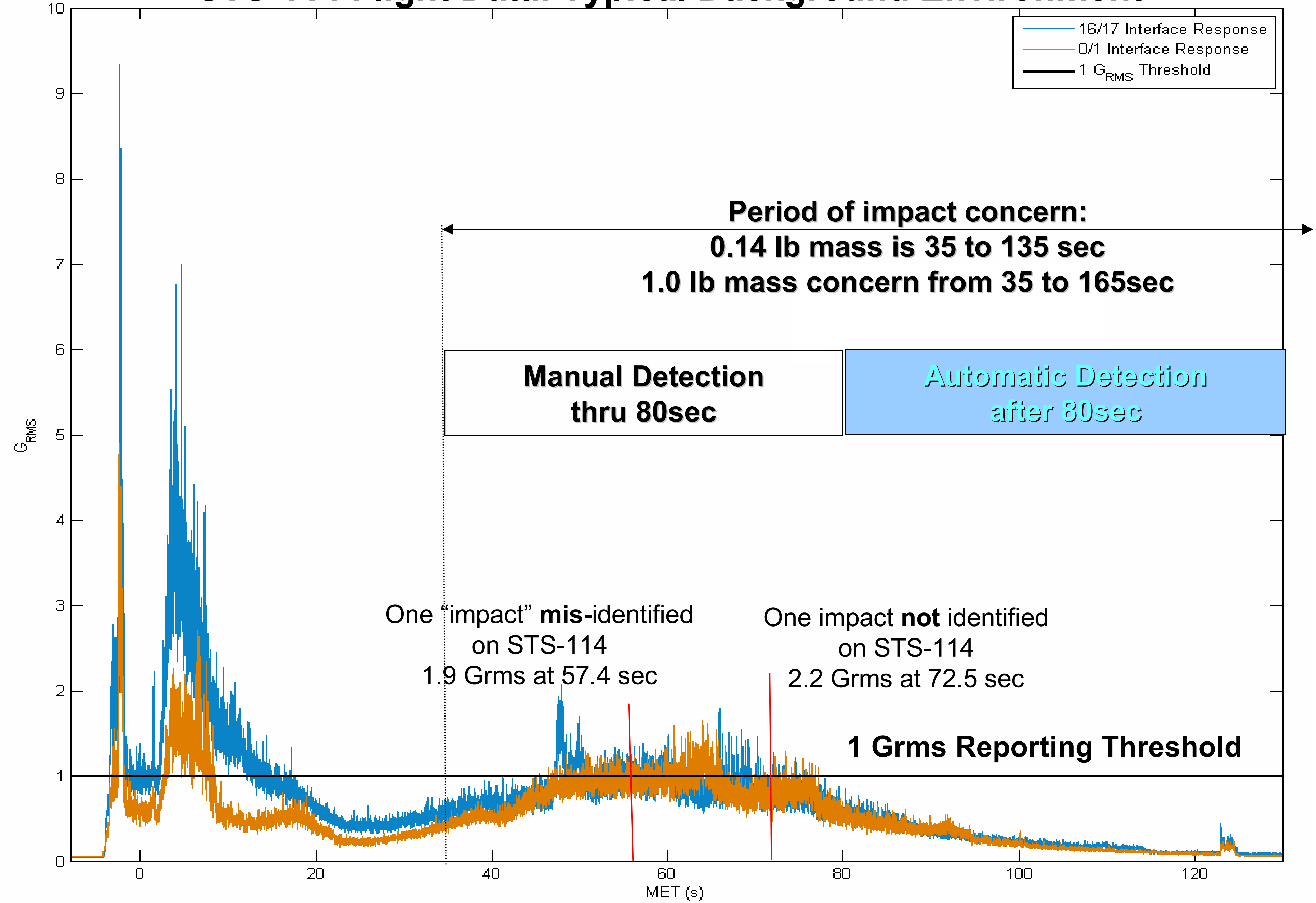


Note: 1.0 Grms: More than 90% of impacts detected from STS-114 data under this value.

0.4 Grms: Background noise floor where events are typically masked.

* Test Data is limited, Impact analyses on validated models are necessary to accurately predict sensor response on the vehicle.

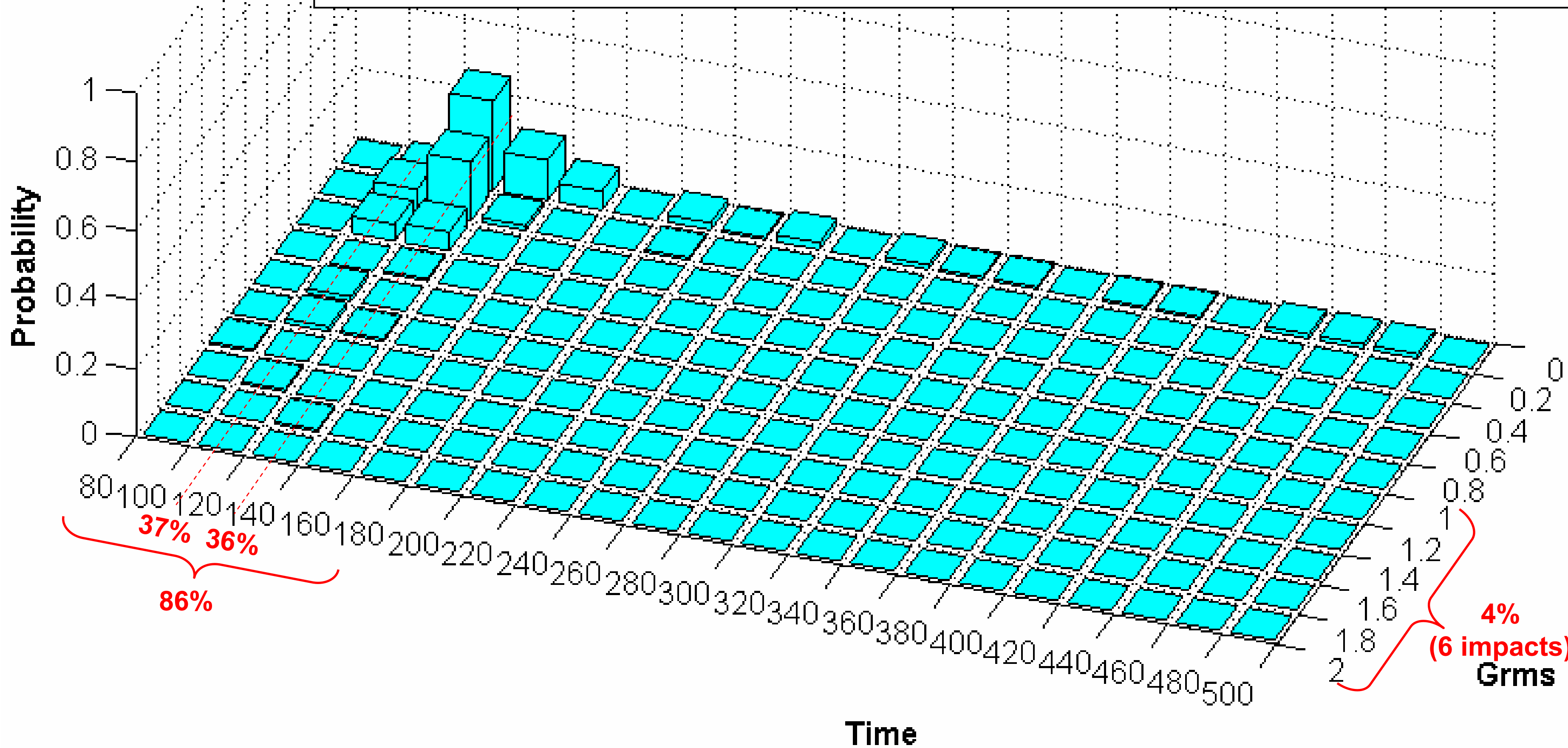
STS-114 Flight Data: Typical Background Environment



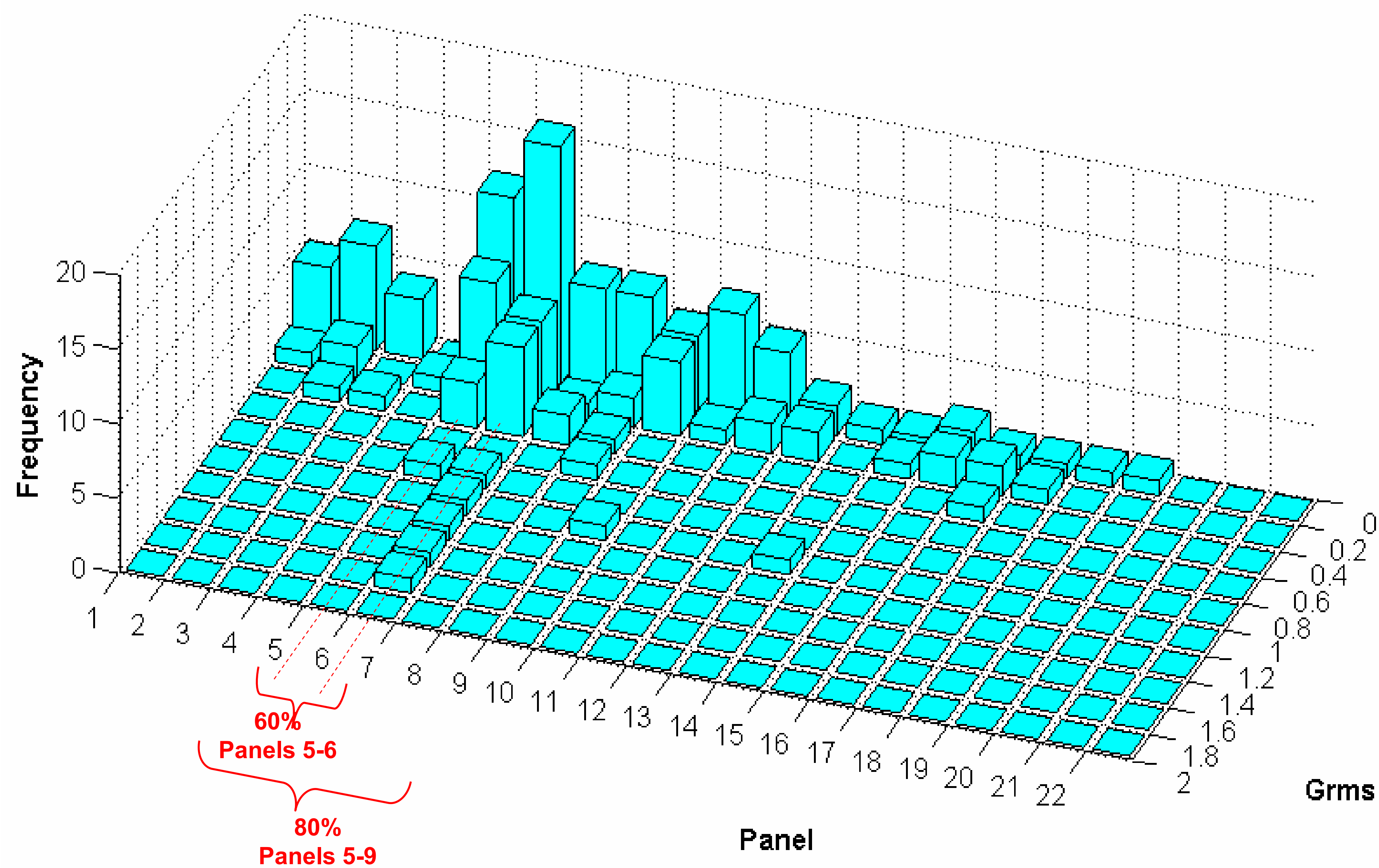
STS-114 Flight Data Analysis: Probability of Impact Magnitude over Time

146 total impacts Auto-detected after MET 80 seconds

- 4% of impacts were above 1 Grms
- 86% of impacts were prior to 180 seconds
- Note: aerodynamically sensitive transport time is 35-165 sec for a 1lb mass

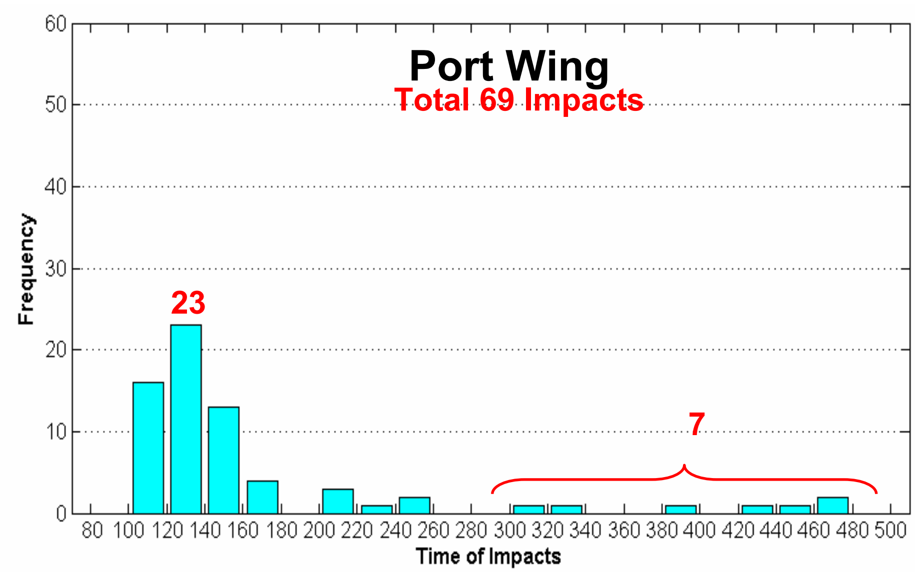


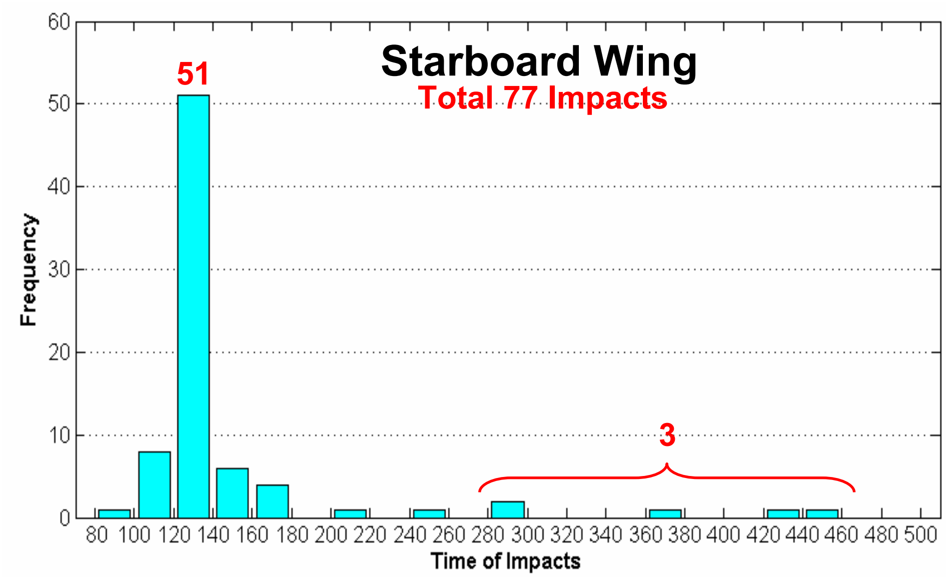
STS-114 Frequency & Magnitude of Impacts by Panel
after 80 seconds MET

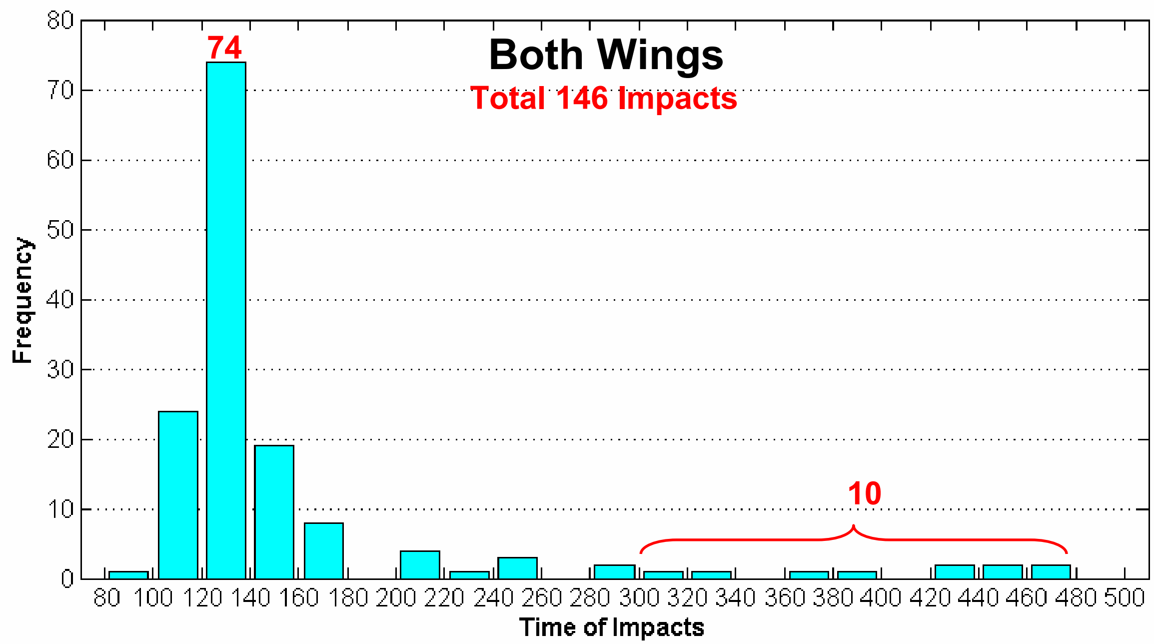


STS-114 Frequency of Impacts over Time

after 80 seconds MET

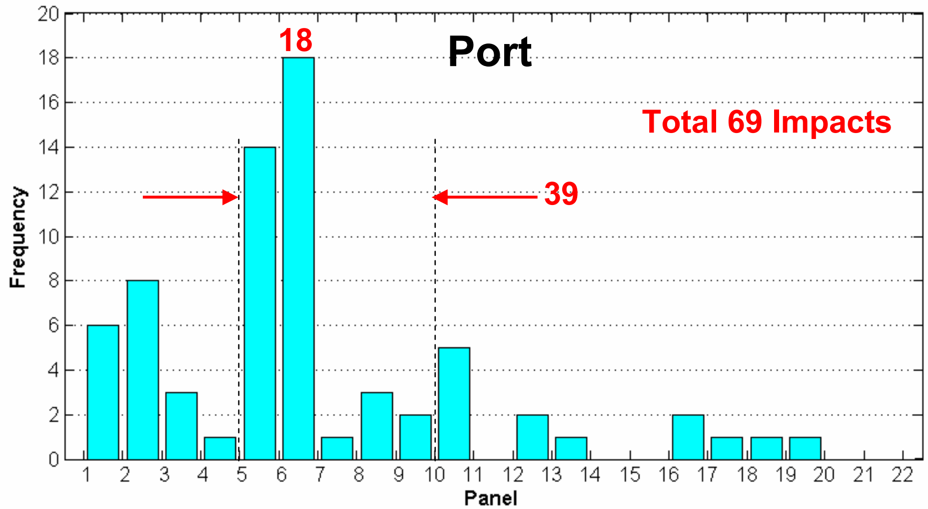


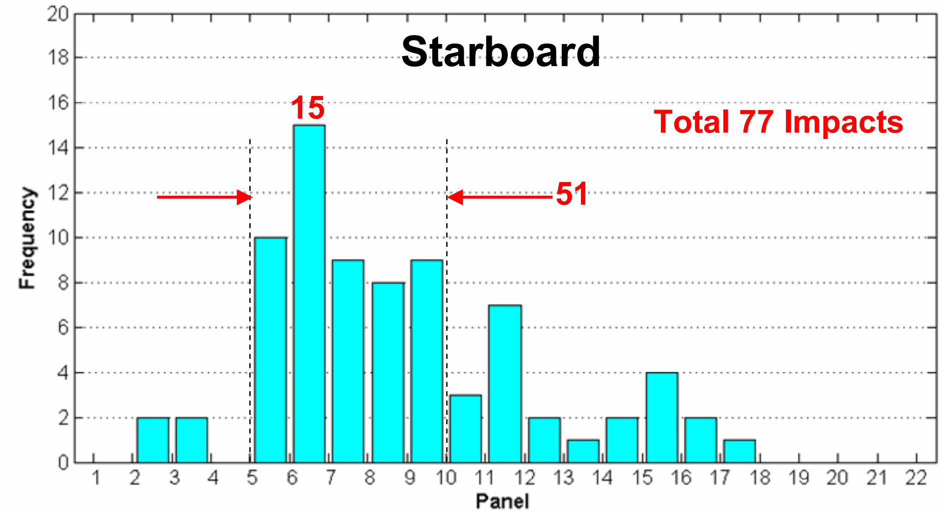


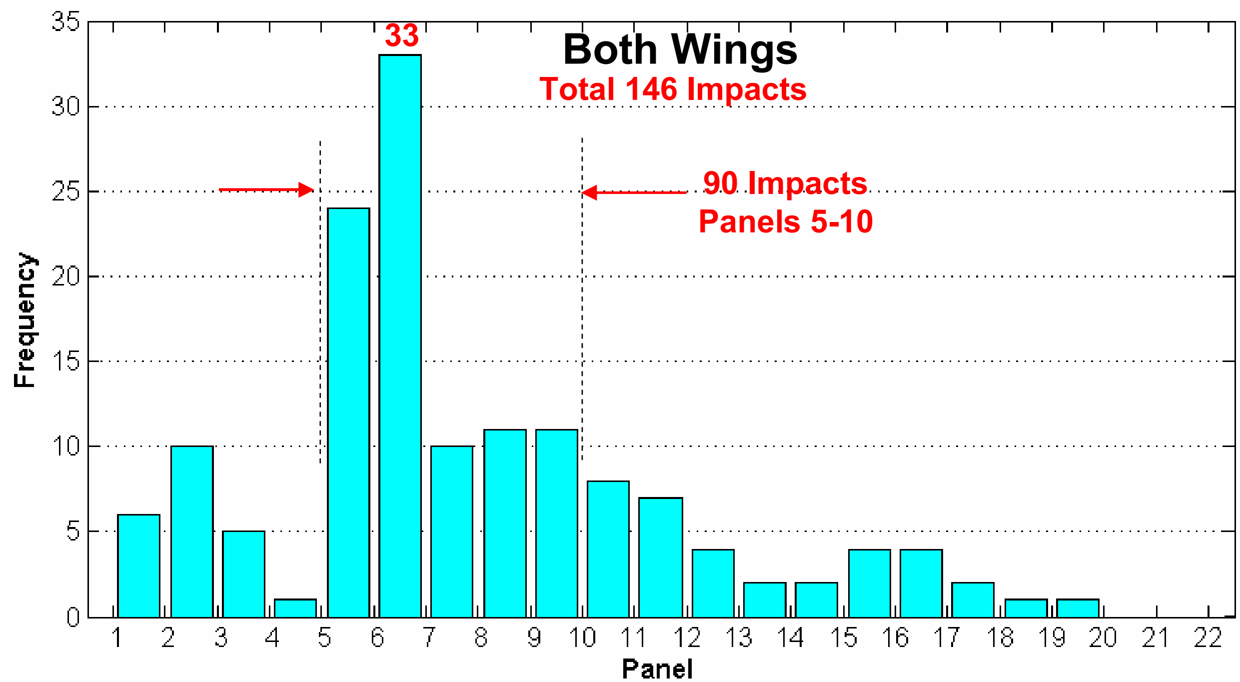


STS-114 Frequency of Impacts by Panel

after 80 seconds MET



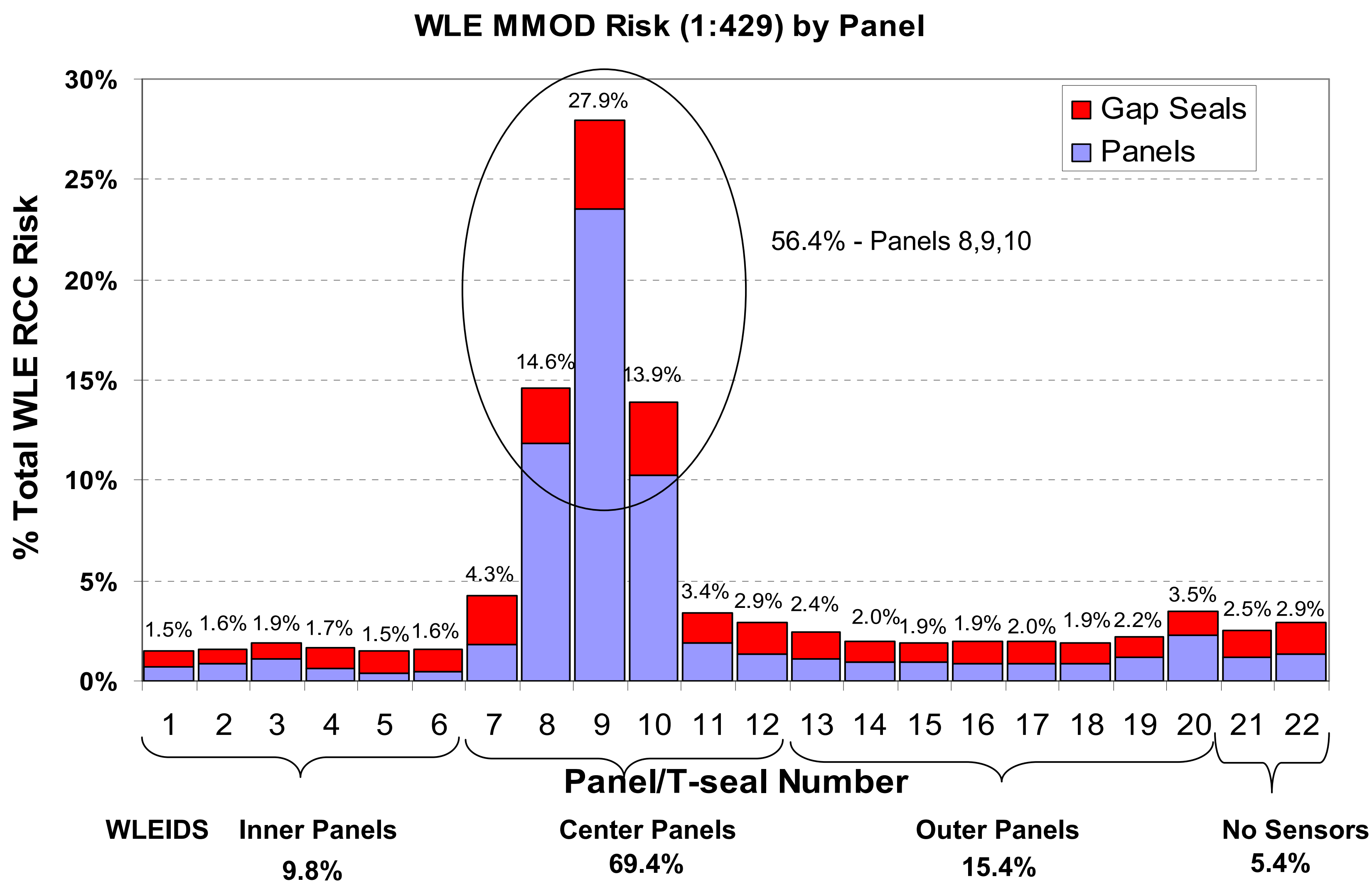




WLEIDS 2nd Purpose: MMOD Impact Indicator

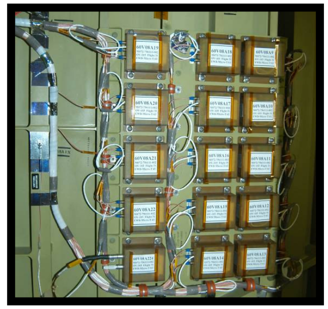
Used to influence TPS Late Inspection priorities & planning

MMOD Risk Breakdown for Wing Leading Edge (STS-114)



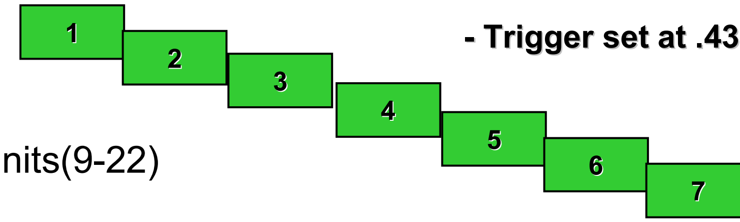
WLEIDS On-Orbit Impact Monitoring

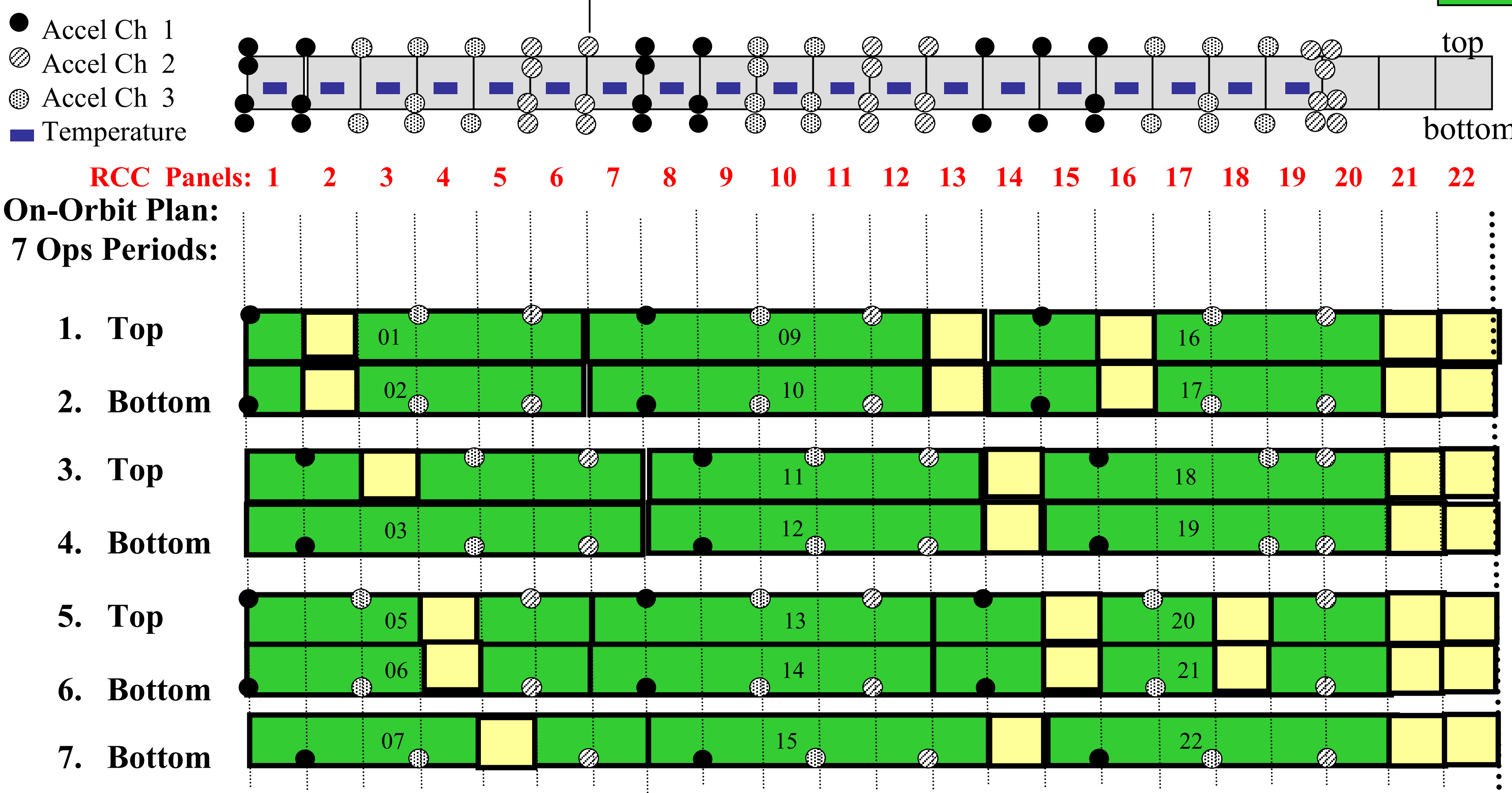
Forward/Inbd Sensor Units(1-8)

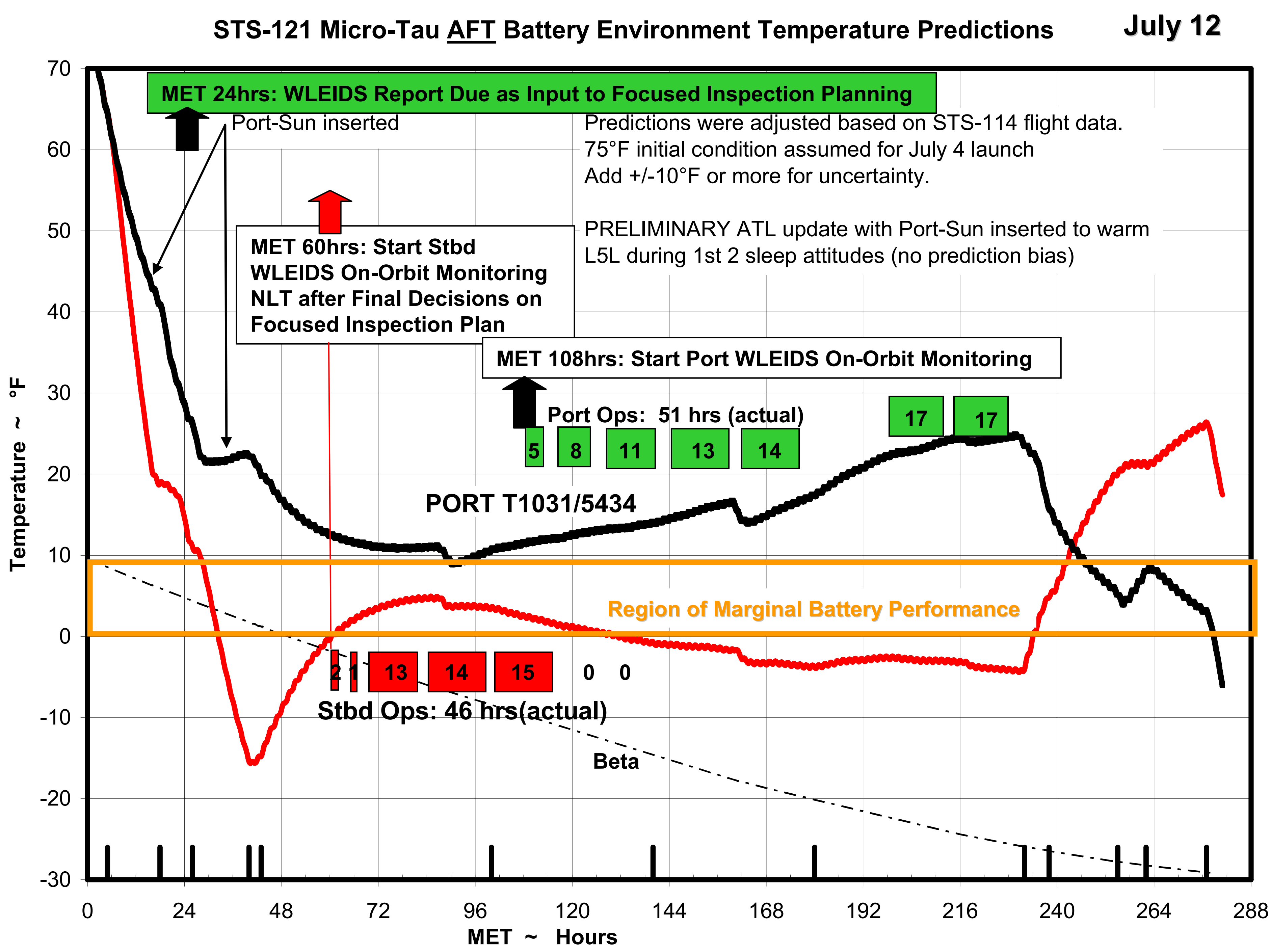


Aft/Outboard Sensor Units(9-22)

- Start after Ascent Assessment Complete
- 7 groups of 3 sensor units each
- Record ½ sec of raw data if triggered
  - Trigger set at .43g's

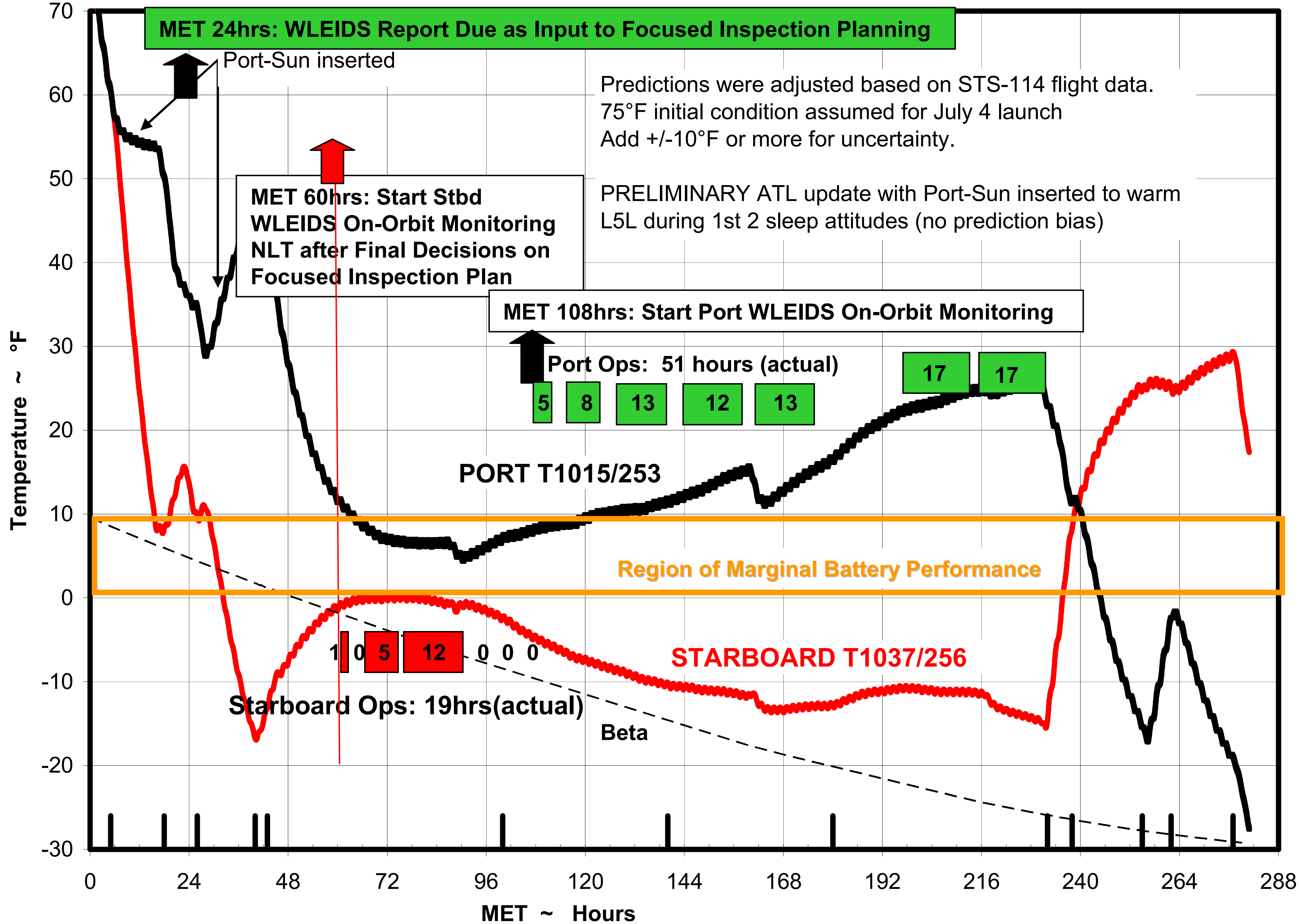






STS-121 Micro-Tau AFT Battery Environment Temperature Predictions
July 12
MET 24hrs: WLEIDS Report Due as Input to Focused Inspection Planning
Port-Sun inserted
Predictions were adjusted based on STS-114 flight data.
75°F initial condition assumed for July 4 launch
Add +/-10°F or more for uncertainty.
PRELIMINARY ATL update with Port-Sun inserted to warm
L5L during 1st 2 sleep attitudes (no prediction bias)
MET 60hrs: Start Stbd WLEIDS On-Orbit Monitoring NLT after Final Decisions on Focused Inspection Plan
MET 108hrs: Start Port WLEIDS On-Orbit Monitoring
Port Ops: 51 hrs (actual)
5
8
11
13
14
17
17
PORT T1031/5434
Region of Marginal Battery Performance
2
1
13
14
15
0
0
Stbd Ops: 46 hrs(actual)
Beta
Temperature ~ °F
MET ~ Hours
70
60
50
40
30
20
10
0
-10
-20
-30
0
24
48
72
96
120
144
168
192
216
240
264
288

STS-121 Micro-Tau FORWARD Battery Environment Temperature Predictions July 12



WLEIDS Ground Impact Tests

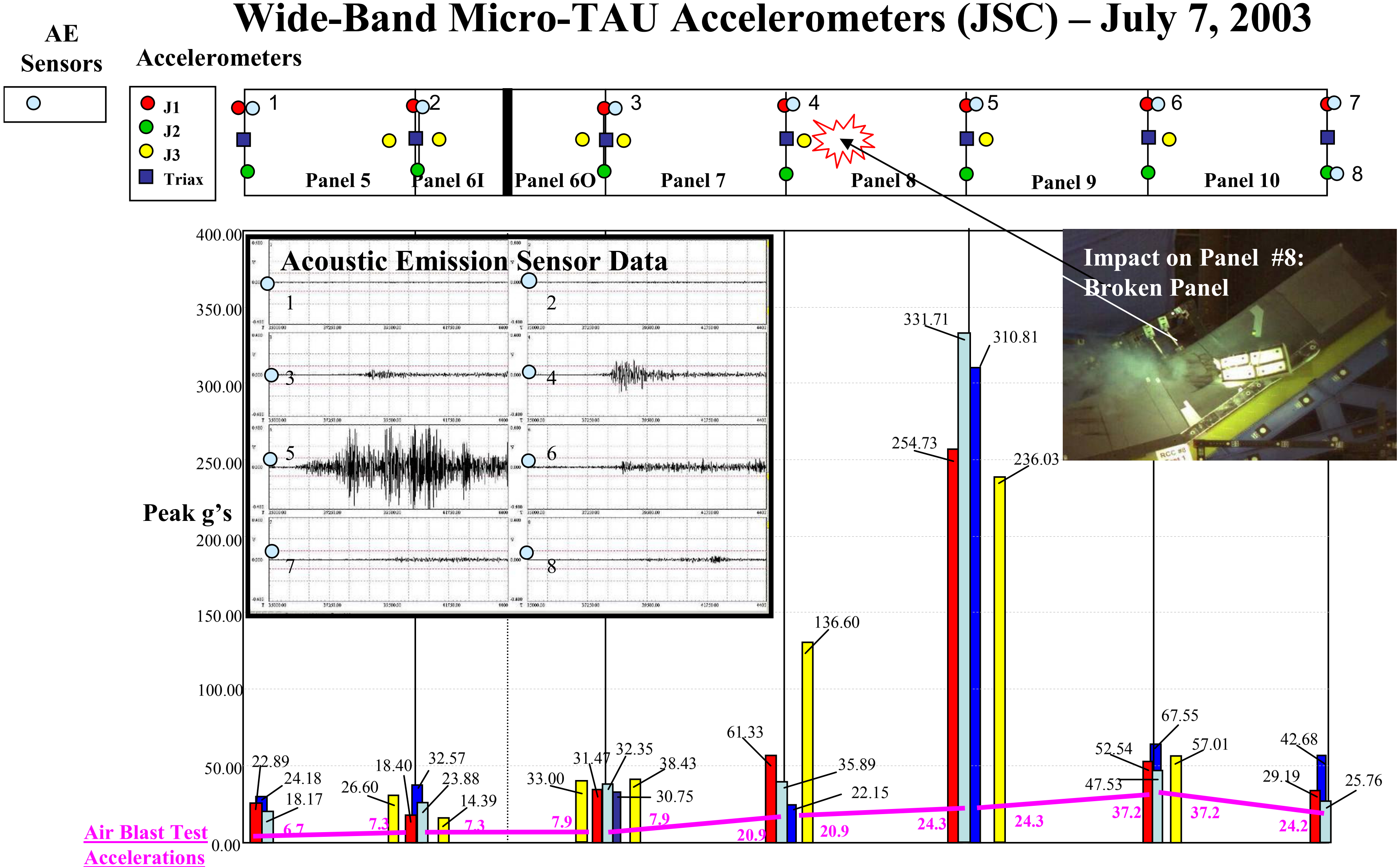
- **STS-107 CAIB investigation thru Sep 2003** – Leading Edge Test Article Impact Tests
  - LESS Test Article design like Columbia, some differences with current Orbiters
  - High accelerometer readings behind the spar and ability to localize what panel the impact occurred on
  - Micro-WIS flight experience provided maturity to be ready in time for STS-114

- **Additional Return-to Flight Impact tests thru Mar 2005:**
  - Larger wing section test article impacts(T-35):
    - Leading Edge RCC: foam, ice, ablator, metal
    - Tile areas: foam and ice
  - Single Panel Leading Edge Test Article (SPLETA) with current configuration
    - Ascent Impactors: Foam, ice, ablator, and metal
    - Hypervelocity
  - Additional foam and ice shots to Panel 9 for validation of RCC damage models

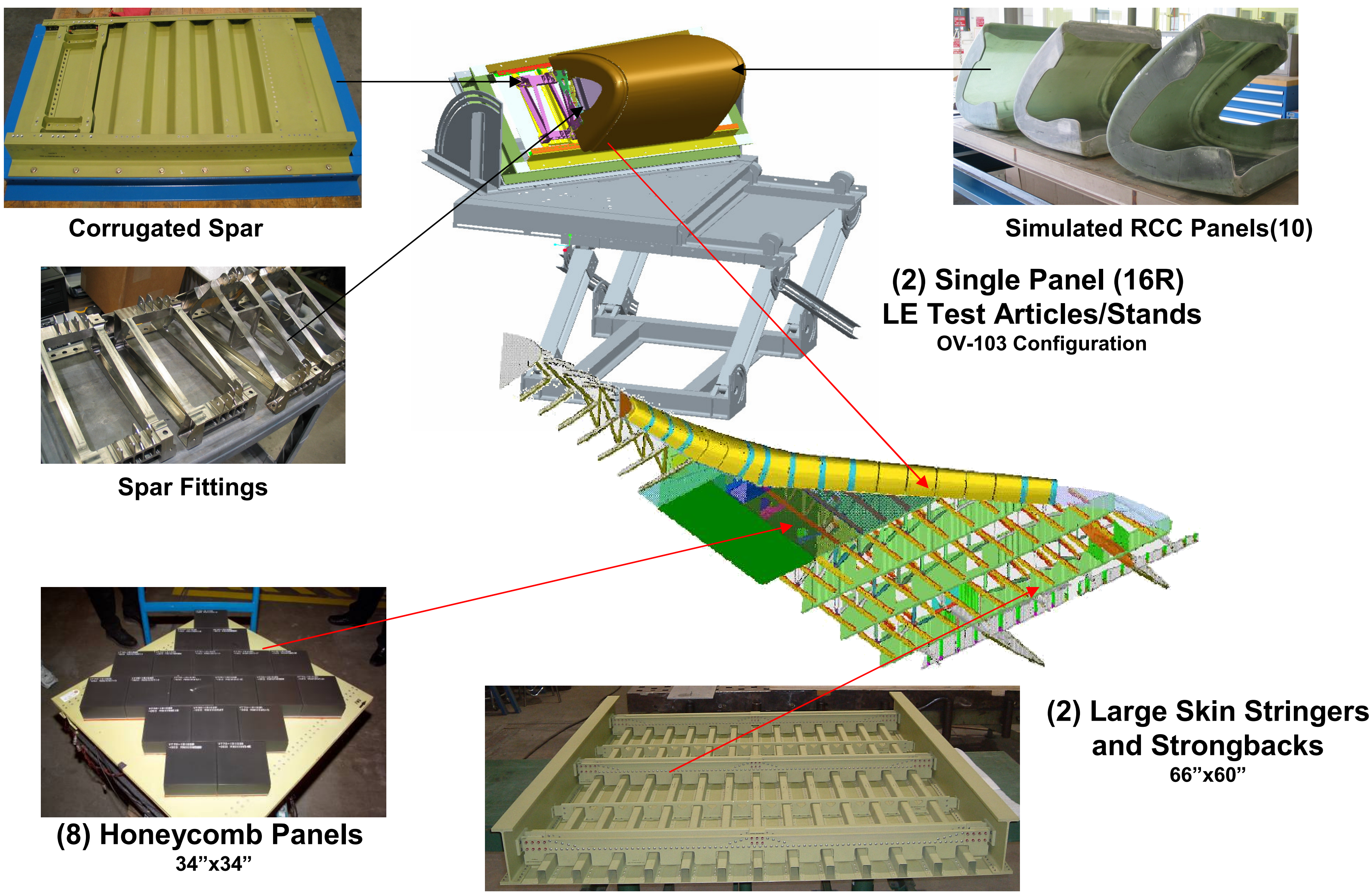
Columbia Accident Investigation

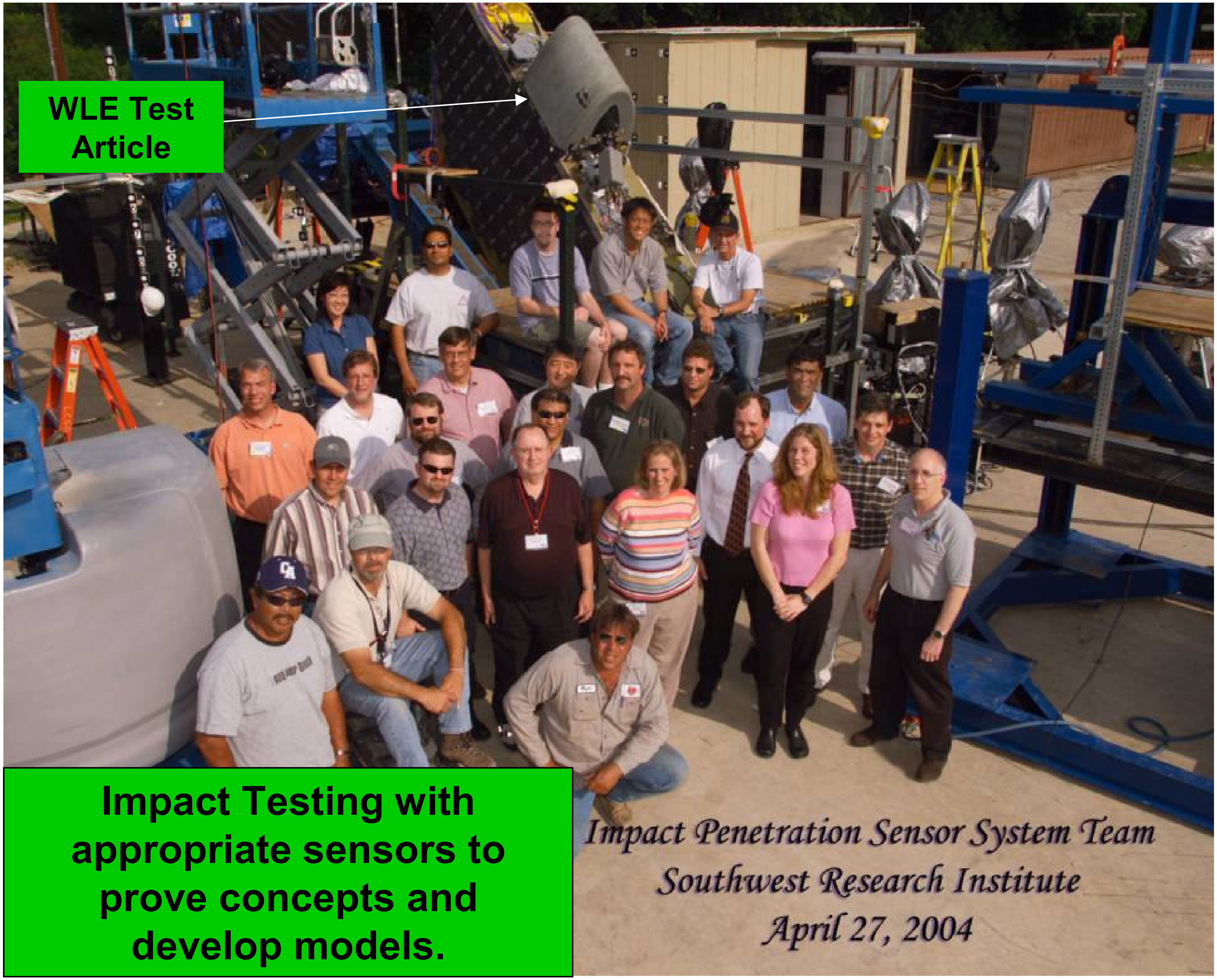
Catastrophic Impact Damage Test on RCC Panel 8

Wide-Band Micro-TAU Accelerometers (JSC) – July 7, 2003



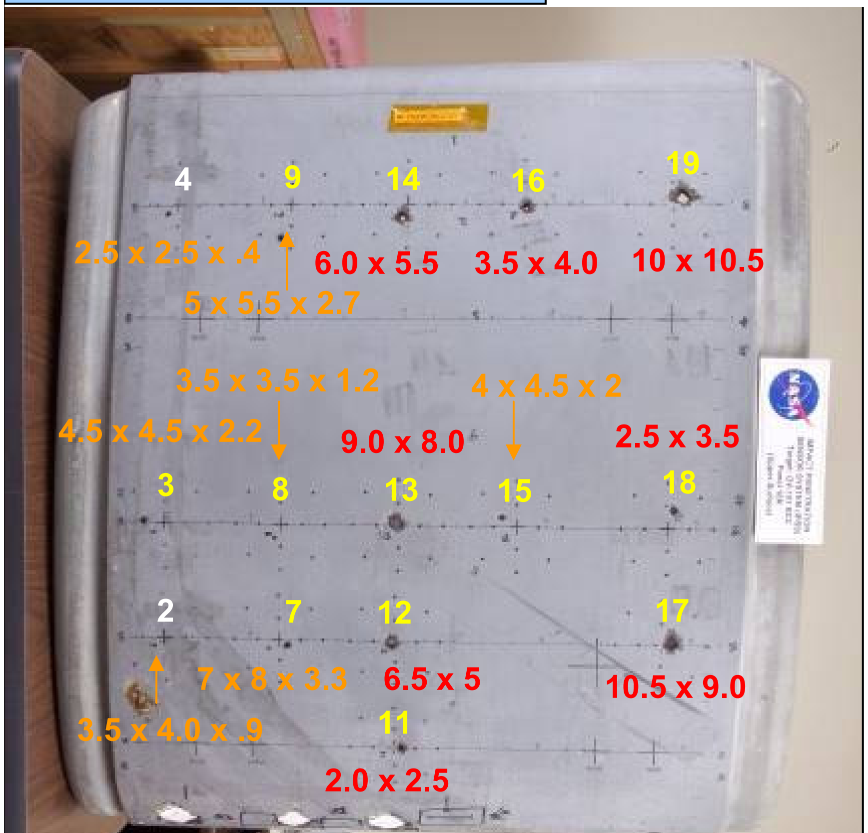
New Test Articles for Impact Sensor Testing

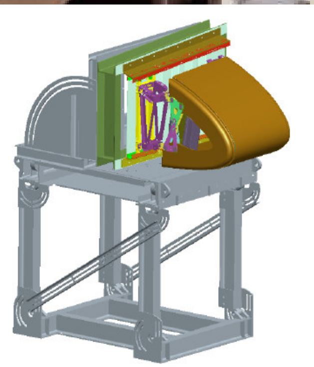



WLE Test Article
Impact Testing with appropriate sensors to prove concepts and develop models.
Impact Penetration Sensor System Team
Southwest Research Institute
April 27, 2004

Hypervelocity Impact Test Results
Damage to RCC Panel 16R

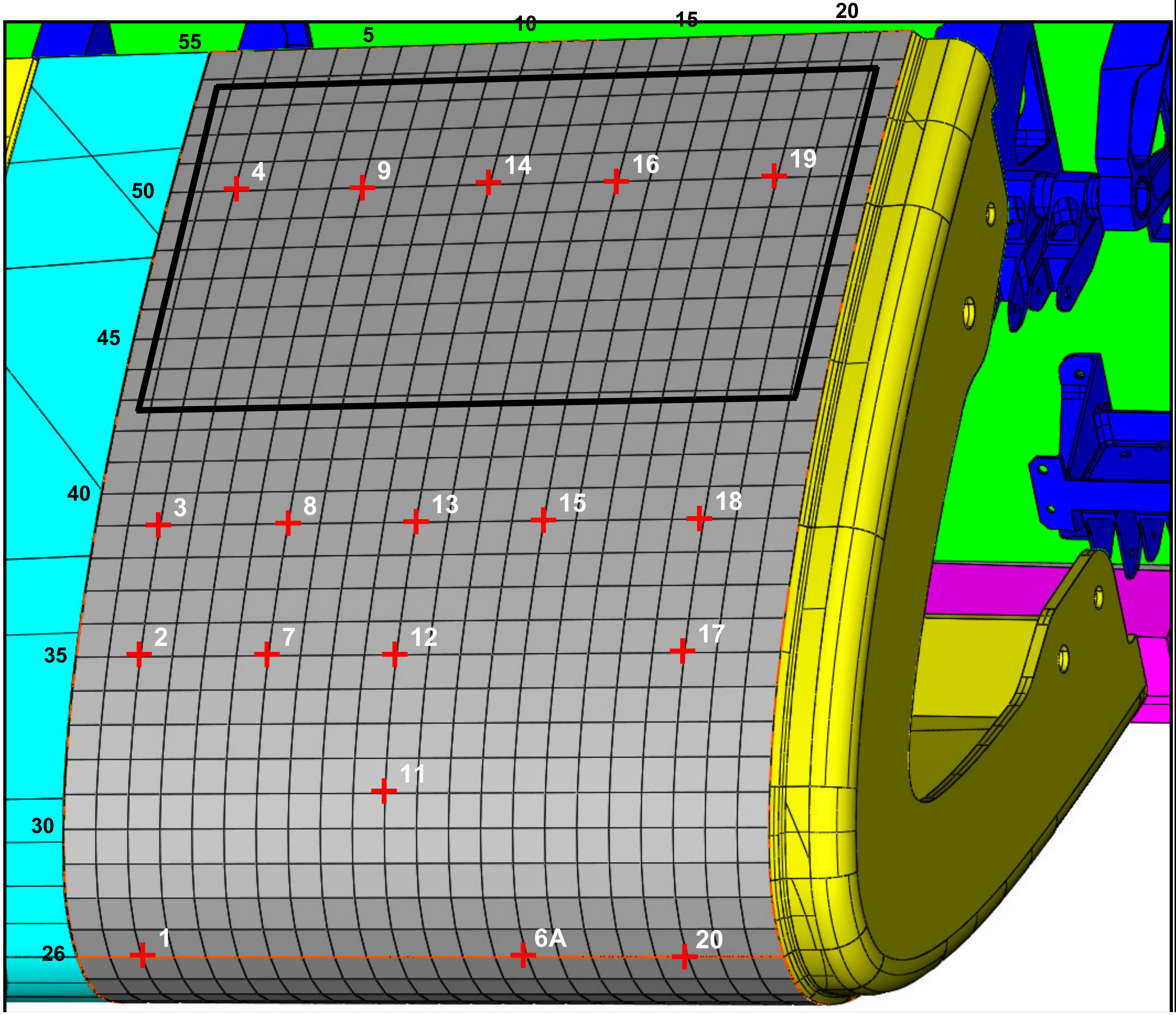
Damage: Coating, Crater, Hole
Length x Width x Depth (in mm)





Note: AE data in separate report

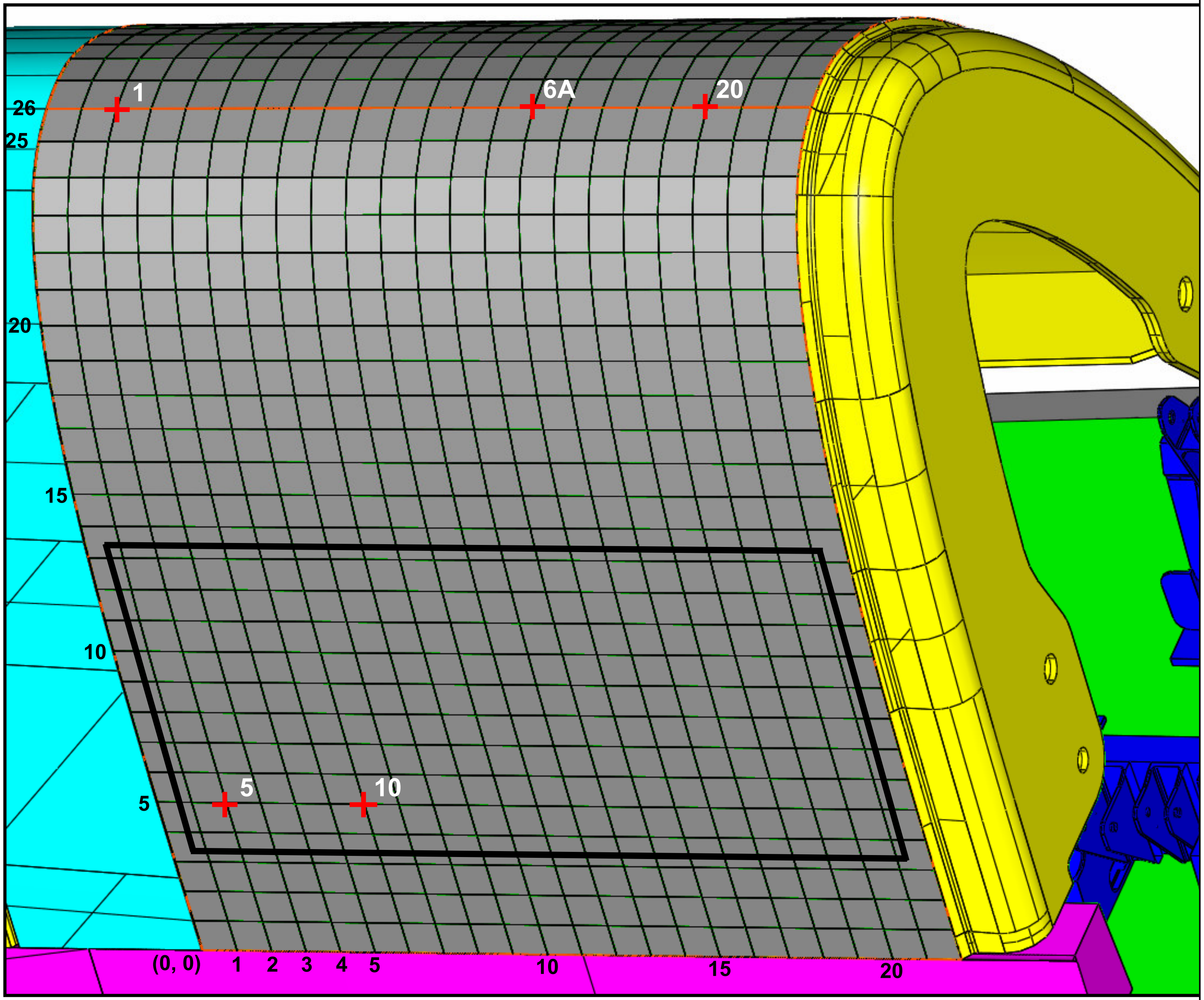
RCC Panel 16R – Upper Surface (Hypervelocity Impact Locations)



Shot #	Size mm	Angle Deg	Peak-G (x) UO / LO	Peak-G (x) UI / LI
1	0.4	90	.55	.53
			.55	.61
2	0.4	60	.70	.52
			.76	.58
3	1.0	45	4.9	2.9
			3.7	3.8
4	0.4	30	.56	.28
			.33	.39
5	0.6	45	1.2	1.1
			1.8	1.2
6A	0.8	90	3.3	2.6
			3.0	3.1
7	1.0	30	4.8	4.5
			5.6	5.5
8	0.6	60	2.0	1.2
			1.5	1.8
9	1.2	30	6.2	4.0
			4.7	5.5
10	0.8	30	2.0	1.7
			2.1	2.0
11	1.2	60	7.1	5.2
			4.7	6.0
12	1.6	45	6.4	7.4
			8.3	9.0
13	2.0	45	6.3	6.1
			5.0	8.2
14	2.0	30	9.3	6.8
			11.2	3.3
15	0.8	60	2.7	2.6
			2.3	3.3
16	1.6	45	9.4	6.5
			7.2	7.0
17	2.4	30	10.1	7.4
			7.9	14.1
18	1.8	60	5.2	3.5
			4.5	5.7
19	2.4	45	9.4	9.5
			8.1	16.4
20	1.0	90	6.4	7.4
			5.0	4.8

Note: AE data in separate report

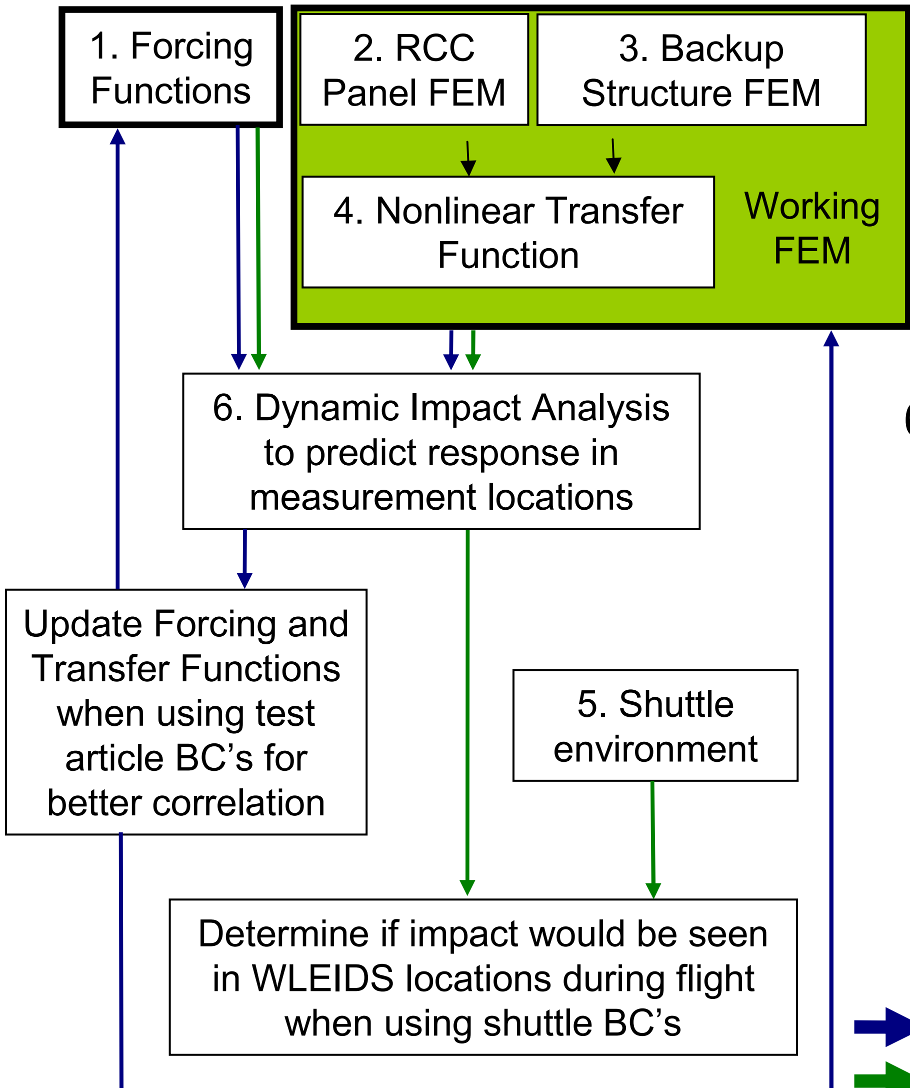
RCC Panel 16R – Lower Surface (Hypervelocity Impact Locations)



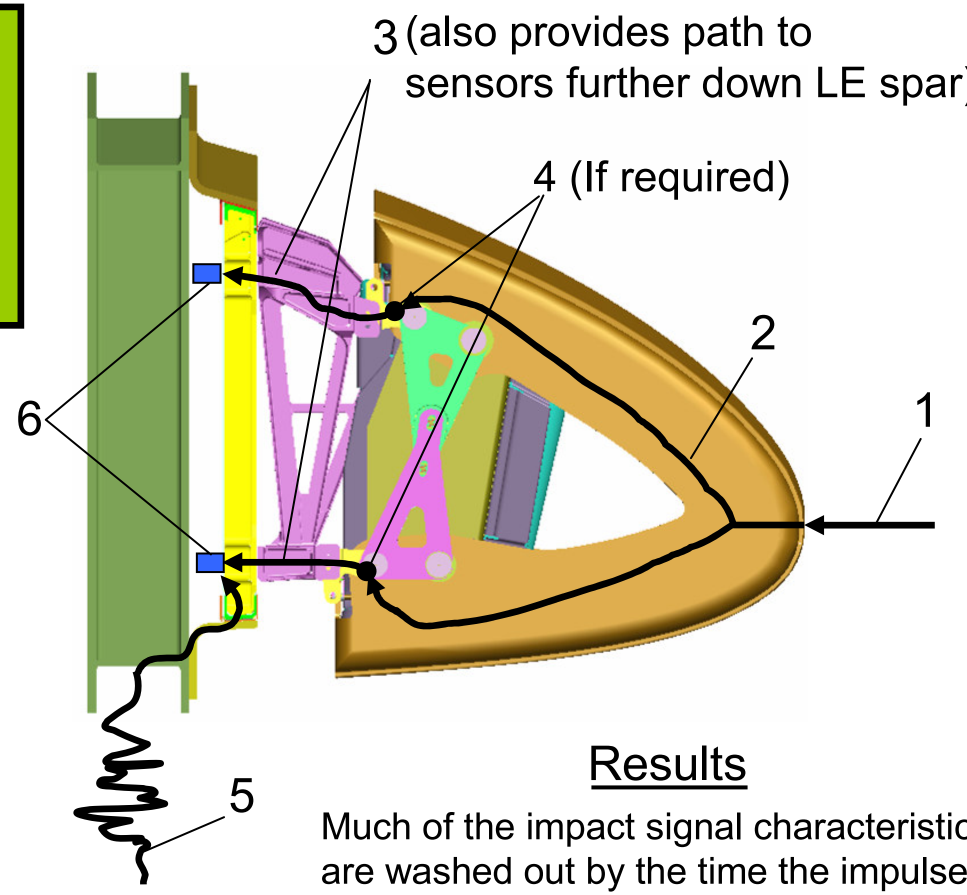
Shot #	Size mm	Angle Deg	Peak-G (x) UO / LO	Peak-G (x) UI / LI
1	0.4	90	.55	.53
			.55	.61
2	0.4	60	.70	.52
			.76	.58
3	1.0	45	4.9	2.9
			3.7	3.8
4	0.4	30	.56	.28
			.33	.39
5	0.6	45	1.2	1.1
			1.8	1.2
6A	0.8	90	3.3	2.6
			3.0	3.1
7	1.0	30	4.8	4.5
			5.6	5.5
8	0.6	60	2.0	1.2
			1.5	1.8
9	1.2	30	6.2	4.0
			4.7	5.5
10	0.8	30	2.0	1.7
			2.1	2.0
11	1.2	60	7.1	5.2
			4.7	6.0
12	1.6	45	6.4	7.4
			8.3	9.0
13	2.0	45	6.3	6.1
			5.0	8.2
14	2.0	30	9.3	6.8
			11.2	3.3
15	0.8	60	2.7	2.6
			2.3	3.3
16	1.6	45	9.4	6.5
			7.2	7.0
17	2.4	30	10.1	7.4
			7.9	14.1
18	1.8	60	5.2	3.5
			4.5	5.7
19	2.4	45	9.4	9.5
			8.1	16.4
20	1.0	90	6.4	7.4
			5.0	4.8

WLEIDS Modeling Approach

General Approach



General Approach Applied to SPLETA



Results

Much of the impact signal characteristics are washed out by the time the impulse reaches the measurement locations and is combined with the shuttle background

Test correlation iterations on test article model

Flight predictions on Orbiter wing model

WLEIDS Risk/Confidence Assessment: Evaluating End-to-End System to Meet Program Goals

1. Clarify Program Goals, Requirements and Intended use of WLEIDS

2. Clarify Roles and Responsibilities for the End-to-End WLEIDS System

3. Assess the end-to-end baseline capability to meet Program Goals (examples):
   - Capability: System operations, functionality, performance, prediction models/tools
   - Detectability: Quantify using new algorithms, impact criteria
   - Availability: Predict Performance of battery/system versus temperature - models
     Time to produce answers needed for mission decision-making
   - Reliability/Safety:
     - System Reliability/Redundancy, System Operations, Verifications, Validations
     - GFE System Hardware: Analysis, testing, flight performance
     - Data Handling
     - Models and Analytical tools
     - Supporting Tests and Test data
     - End-to-End Reliability/PRA (software, firmware, filters, algorithms, models, etc.)
   - Assess Personnel Influence on System Confidence.

4. Peer review critical end-to-end baseline capability(1-3)

5. Provide ongoing status of end-to-end confidence based on key metrics and completion of selected analyses.

WLEIDS Risk Assessment & Mitigation
Ascent Impact Reporting

Crew Availability to set-up and reset locked-up laptop before Sensor Units get cold.

- Training and Prioritization in flight plans should help.

Communication (KU Band) Availability for command up-link and data down-link.

- Early set-up of WLEIDS laptop gives more opportunity.
- Orbiter Interface Unit(OIU) is an option to by-pass the laptop.

Cold Wing may prevent communications with Sensor Units even with nominal operations.

- Mission priorities drive this – pre-dock attitudes can be adjusted if needed.
- Voltage Regulator upgrade is very important to enable data access longer.

Low probability GFE failures* that could limit data download: Relay unit failure, RF fail “on” saturation.

Data and Command File Errors may mis-label or result in wrong data down-loaded.

- Training and Procedures as a team are the solution.

Threshold levels of reporting may leave out lower probability impacts.

- Models to correlate impact data indicators and real damage are lacking.
- Accumulation of flight data and correlation with other sensors/inspections.

Communication of report, data and completeness to management and other teams.

- Continuous Improvement in Team reports, reporting and training is needed.

*** Not concerned in general with WLEIDS GFE performance: WLE Panels have high levels of redundant sensors cross-strapped to separate units, data is separately stored, awaiting redundant RF down-load.**