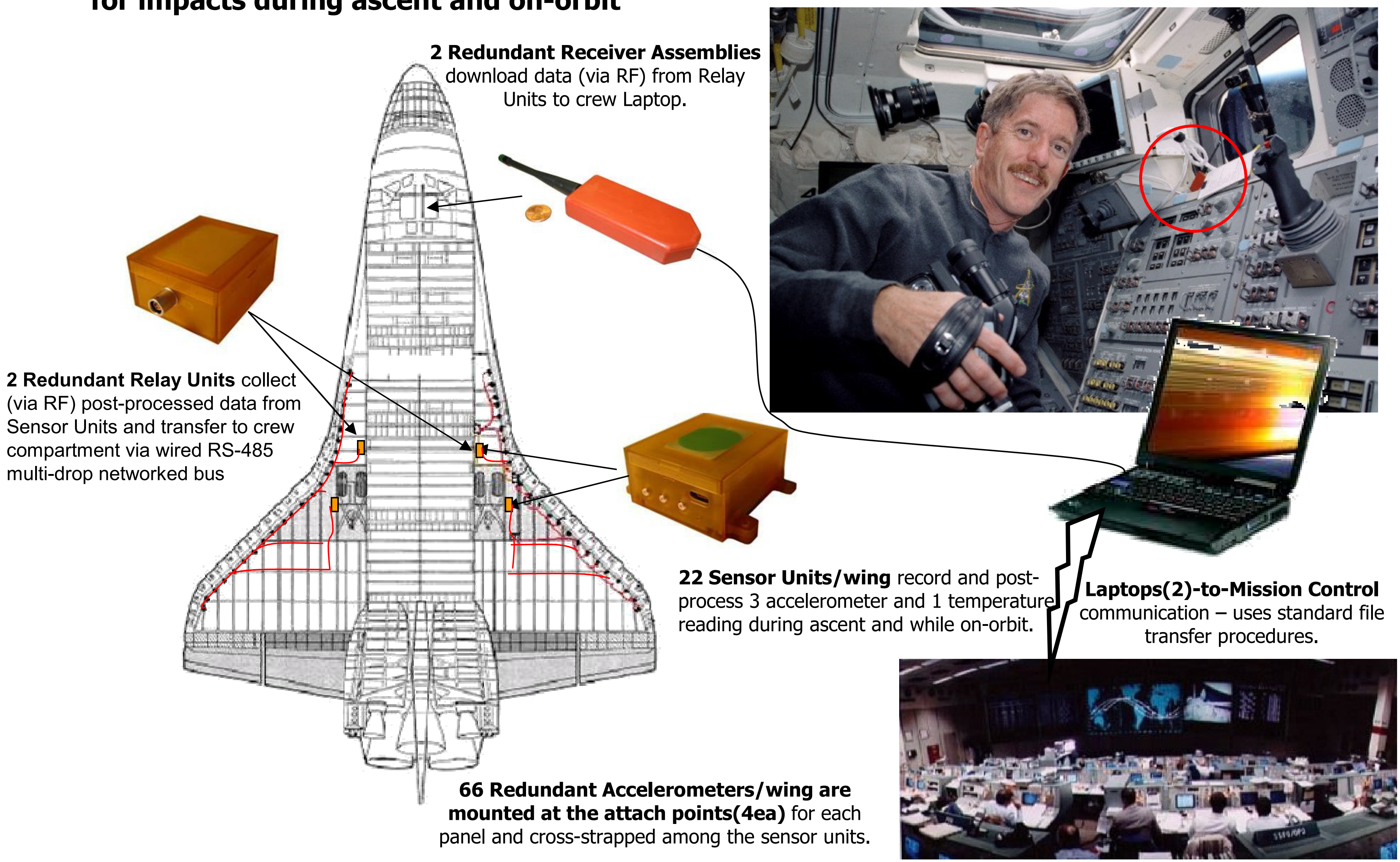
Wing Leading Edge Impact Detection System using Enhanced Wide-band Micro-TAU (STS-114 & Subs)

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

Ascent Debris/Impact Indicators

- Imagery → Debris Time, Path, Speed, Projectile Type
- Radar → Debris Time, Path, Speed, Projectile Type
- *WLEIDS* → *Impact Time, Location, Confidence*

Sensor Information

Debris Time, Path, Speed, Projectile Type
Debris Time, Path, Speed, Projectile Type
Impact Time, Location, Confidence

→ **Integration** (Multiple Teams)

Impact Probable	Impact Questionable	No Impact

FD2 Inspection and Rendezvous Proximity Operations Maneuver(RPM)

- Successful Scans
- Marginally Scanned Panels
- Missed Panels
- Suspect Panel (s)

Preflight Risk Based on Location

- Low Risk Area
- Medium Risk Area
- High Risk Area

Corroboration Analyses with LESS & TPS PRT

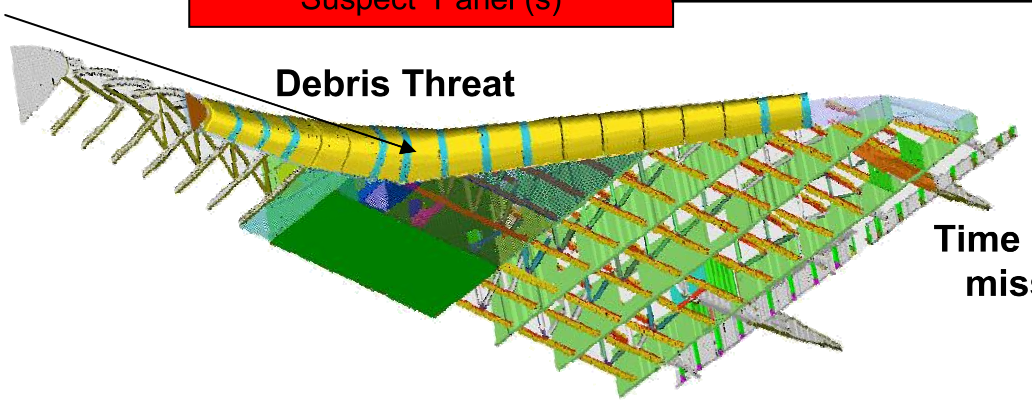
Don't Inspect

Inspect

Focused Inspection Priorities from LESS & TPS PRT

Time constraints and mission priorities → **MMT**

Focused Inspection Plan

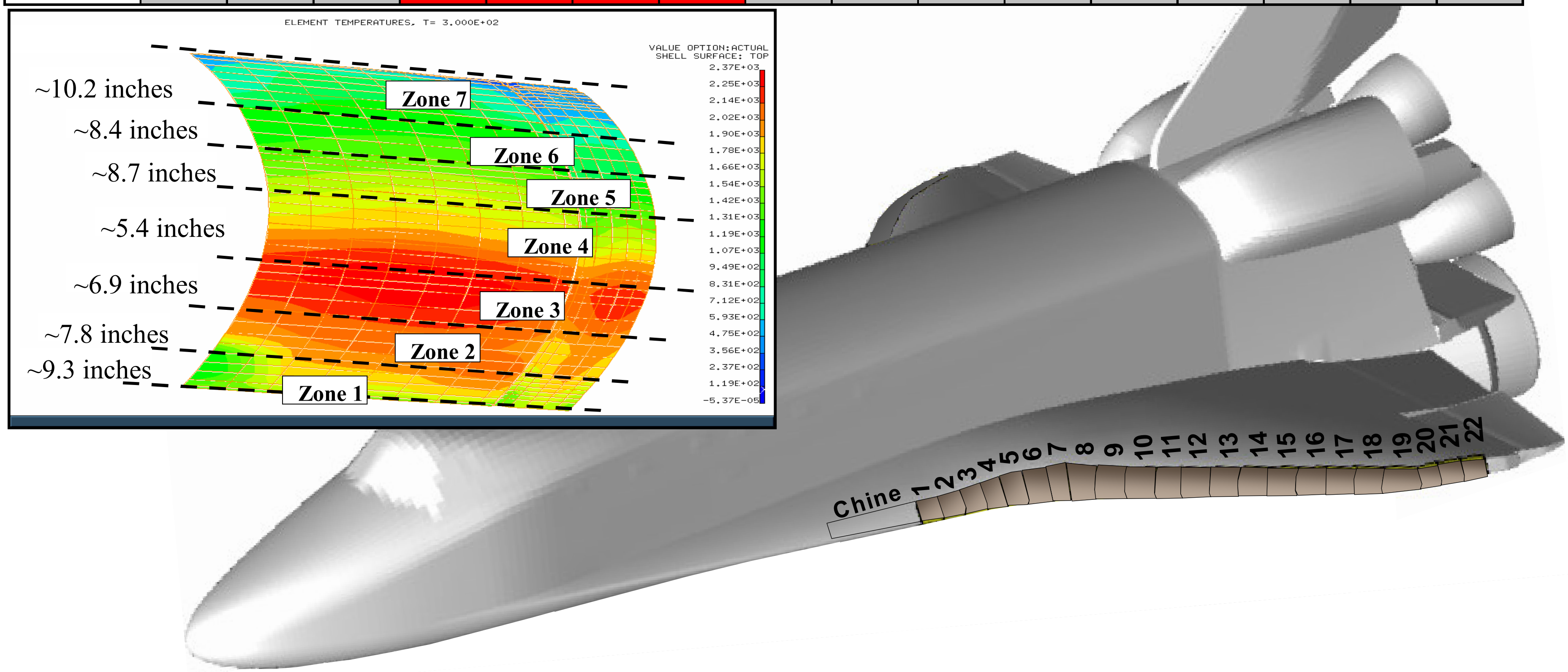


<u>Wing Leading Edge Re-Entry Risk</u>: RCC Max Coating Loss (No Substrate Loss Allowed)

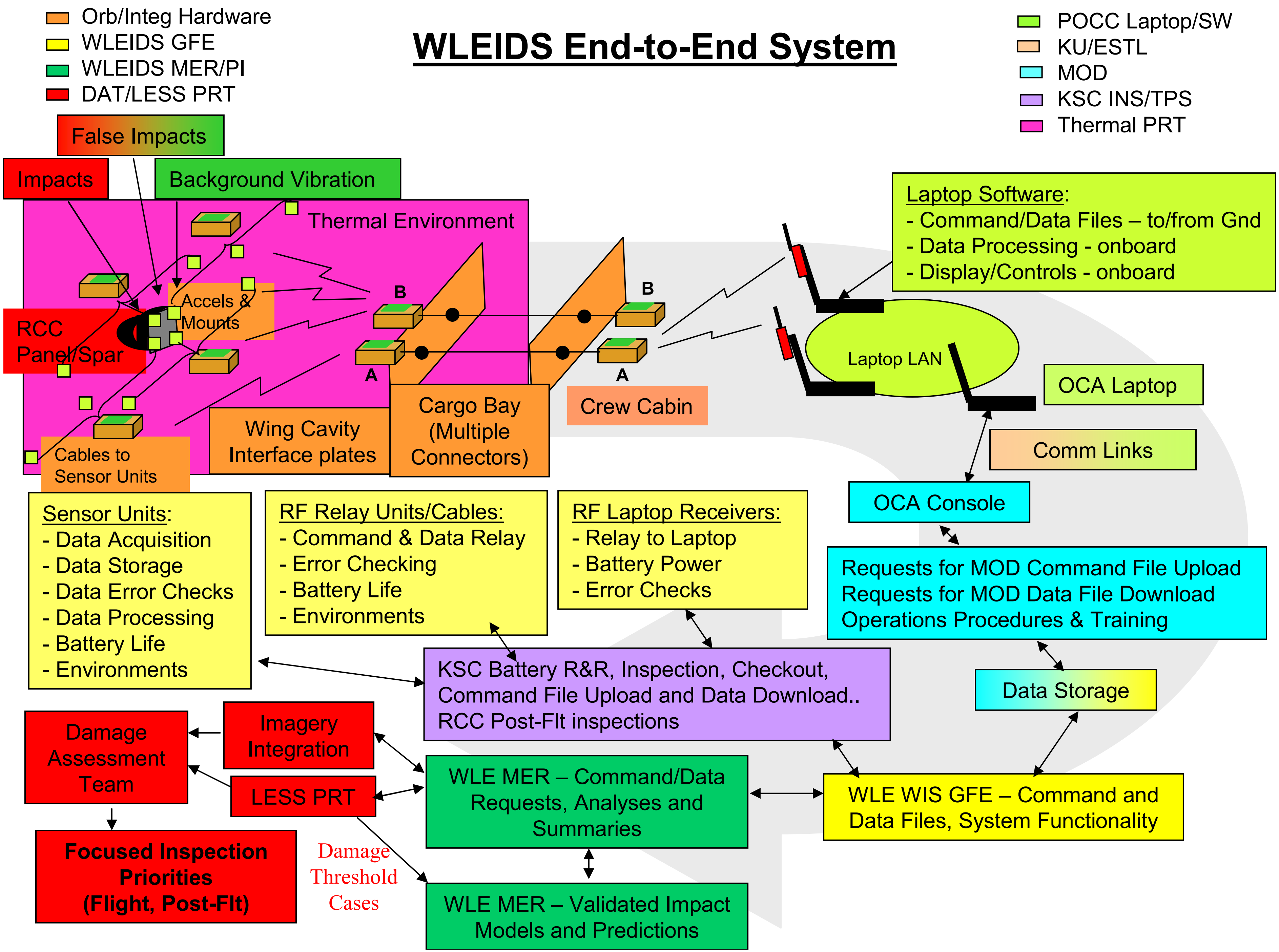
ISS Hvy Wt Fwd CG EOM Entry Trajectory

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

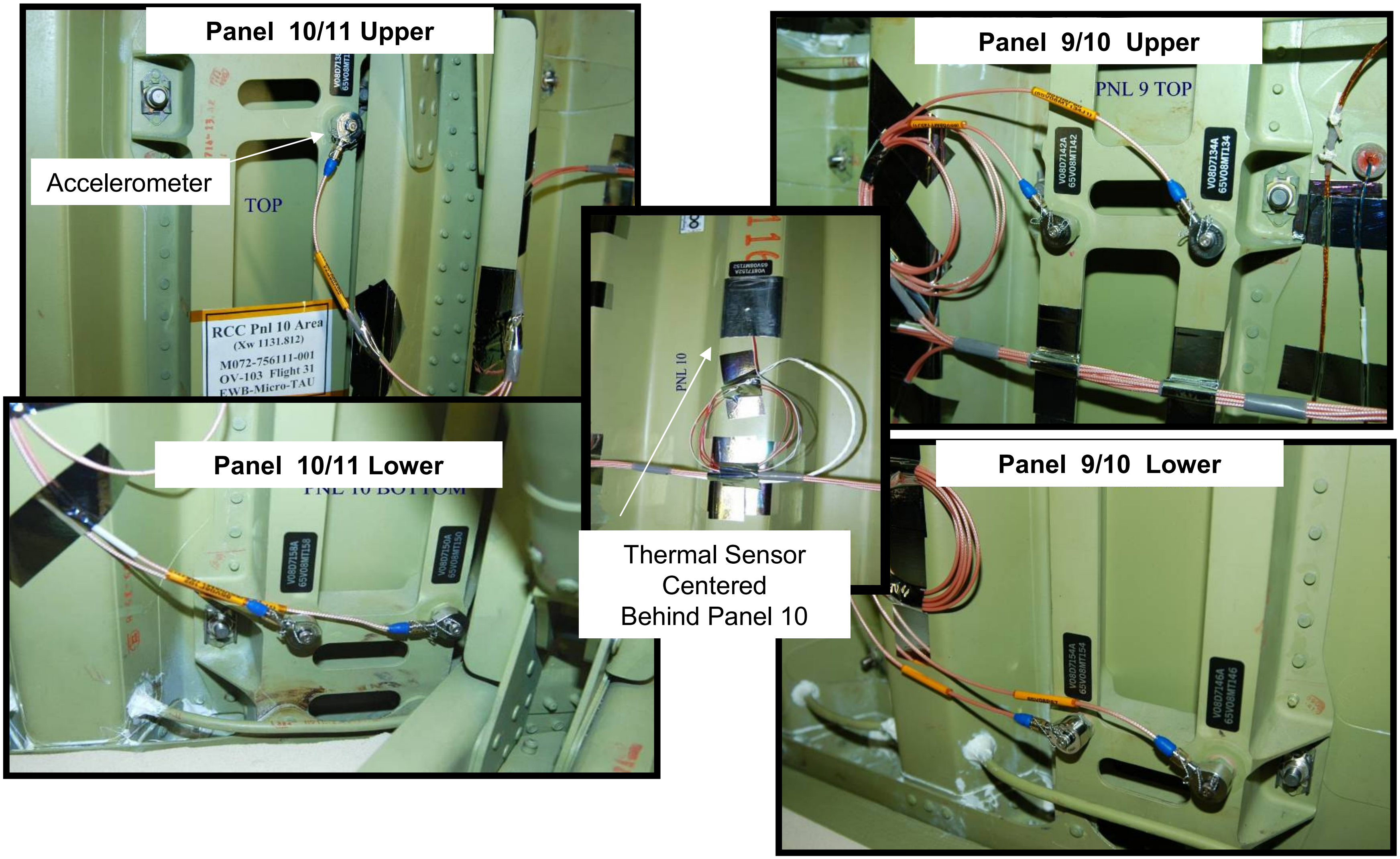


WLEIDS End-to-End System



WLEIDS System Overview:
Accelerometer Flight Installation

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

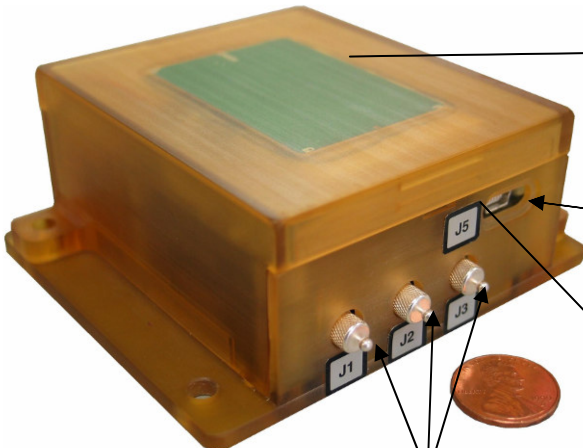


Photographs looking forward inside port wing

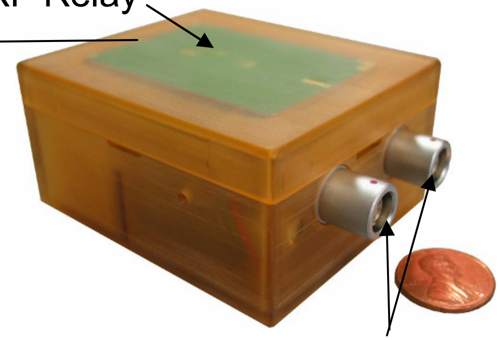
WLEIDS System Overview: GFE Hardware

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

Sensor Unit



Relay Unit



Patch Antennas for RF Relay

USB Port

Temperature Channel

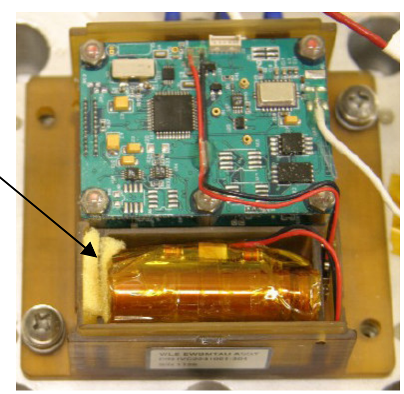
Accelerometer Channels

Relay Unit 485 Connectivity to Crew Cabin (wired)

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

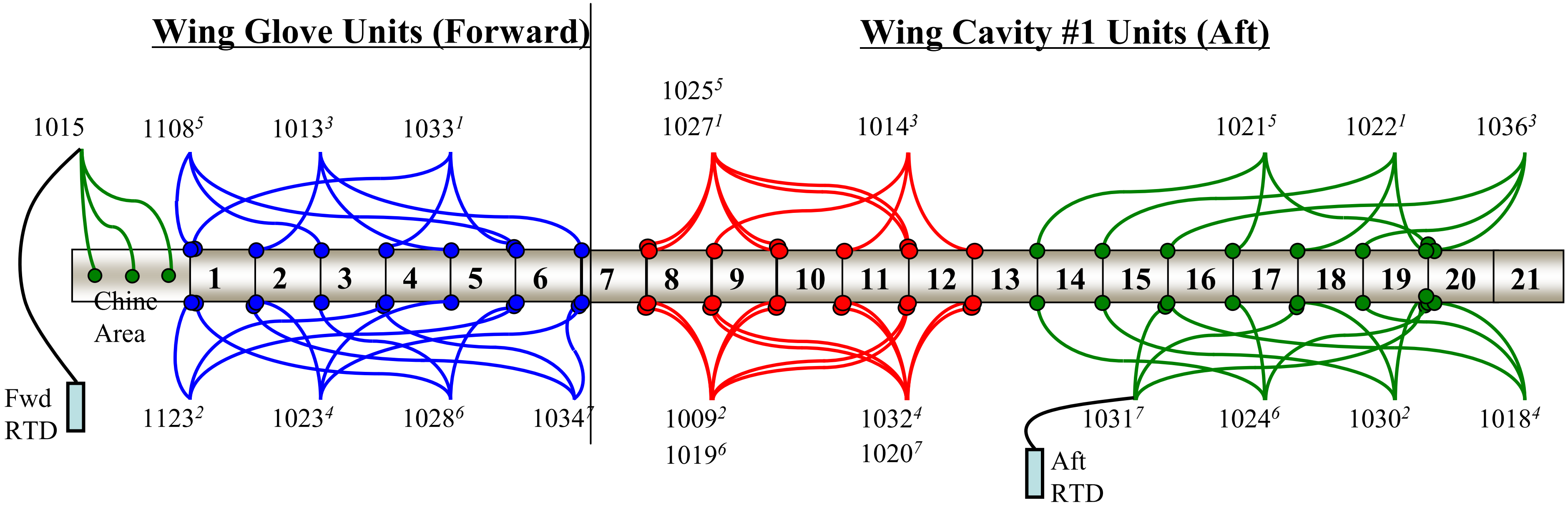
Current Config: Two L91 AA LiFeS2 cells (dies at 0 deg F)

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

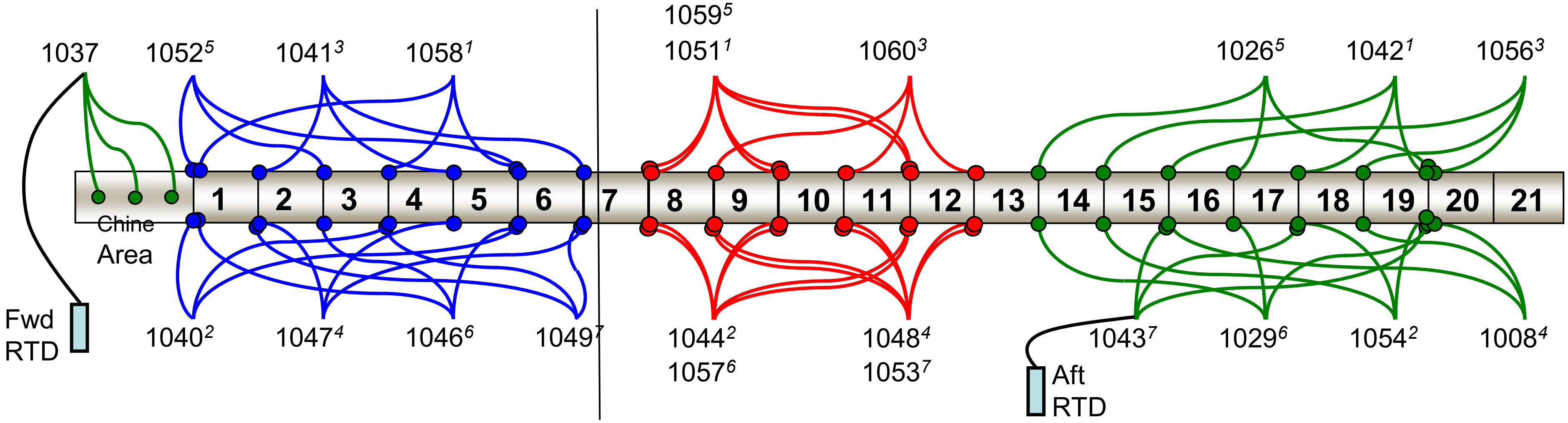


Accelerometer to Sensor Unit Cross-Strapping

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

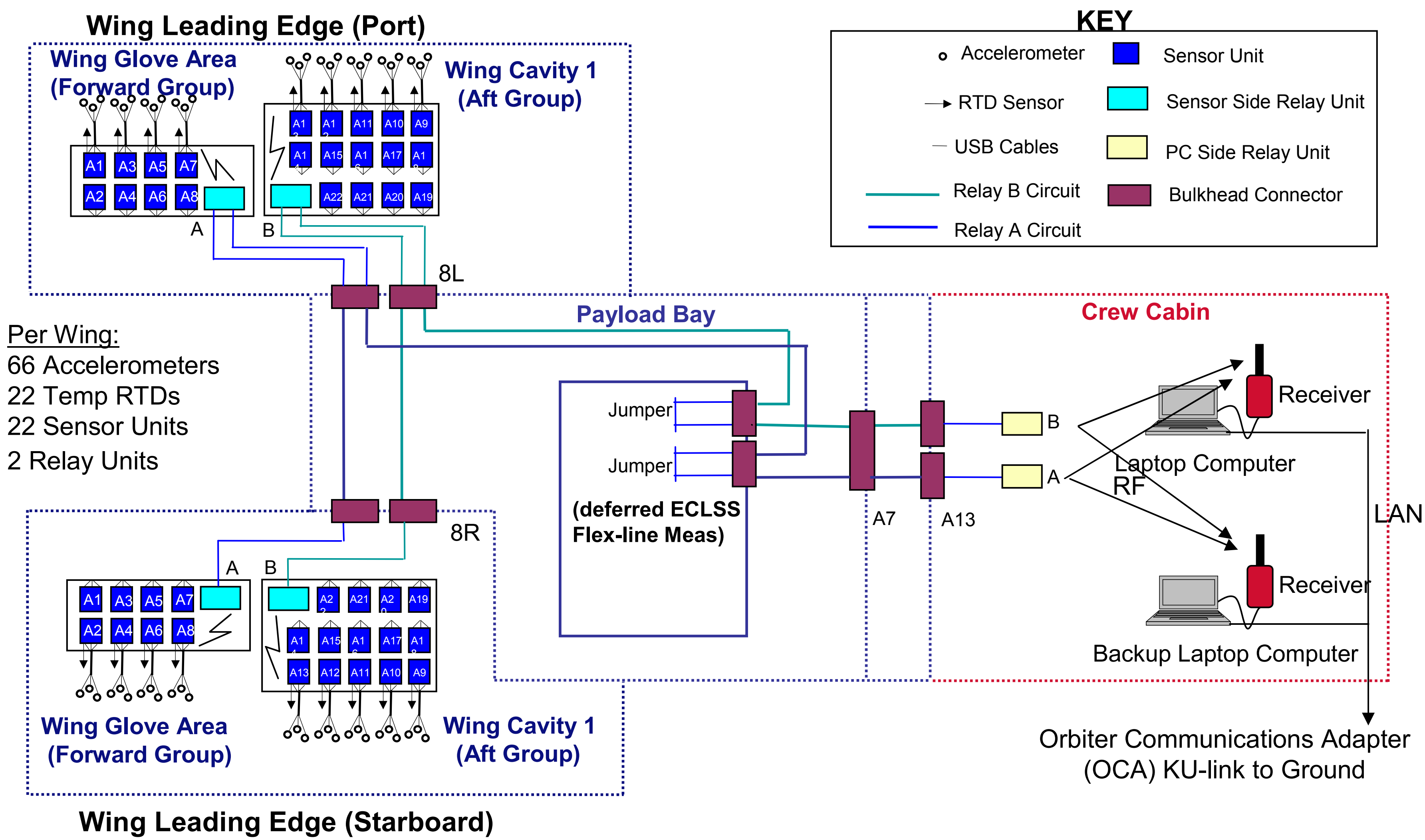
Inside the crew cabin

2 Cabin Relay Units

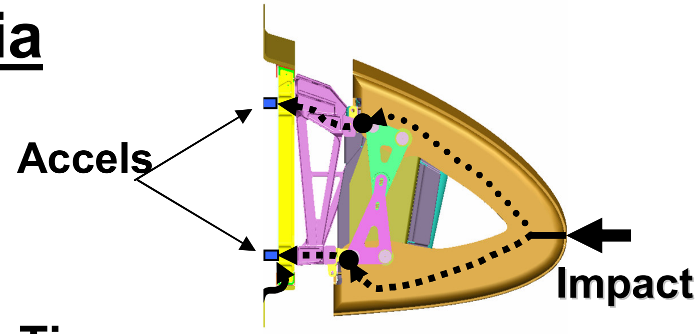
Cabin Relay Unit (A & B) communicates with wing Relay Unit A or B and sends data to laptop

WLEIDS System Overview: Vehicle Wiring Diagram

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



WLEIDS Ascent Impact Criteria



1. Significant transient relative magnitude - Get Time

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

2. Localized response distribution - Get all Sensor Channels involved

   (Distinguish localized response from global events and data anomalies)

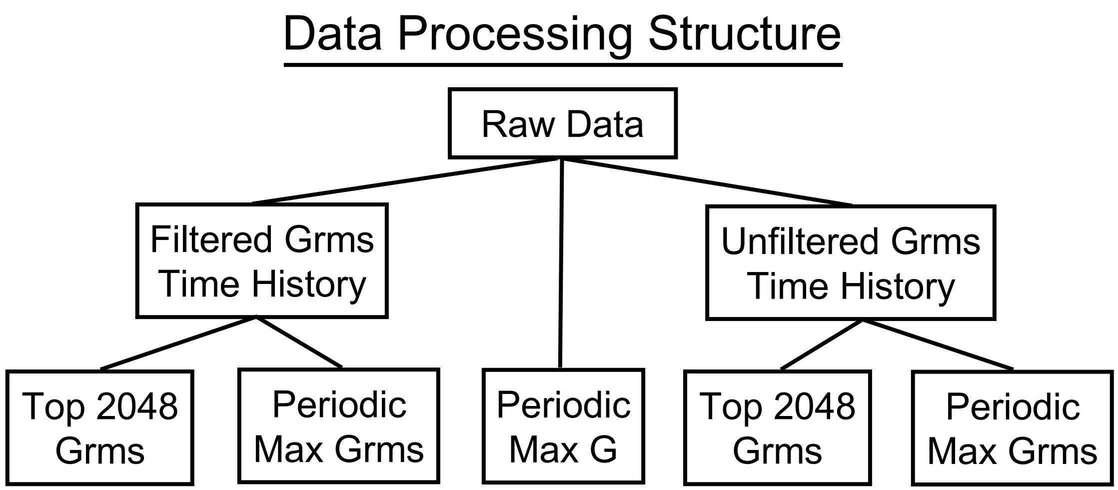
3. Elevated high frequency content – Confirm Impact Signature

   (Distinguish energy in higher frequencies compared to background)

4. Shock signal characteristics – Confirm Impact Signature

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

WLEIDS Ascent Data Analysis: File Type Overview

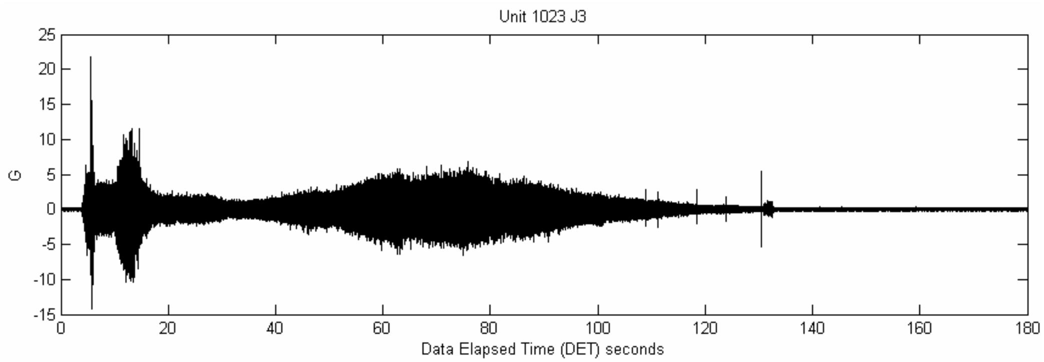


Summary file download order

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

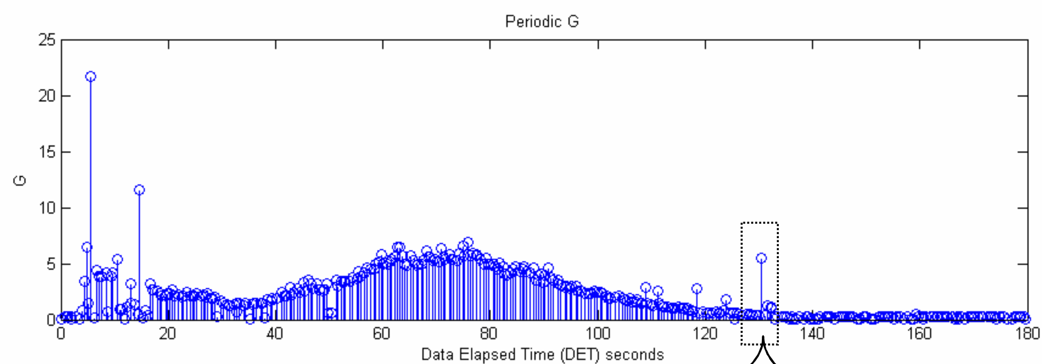
- All of these files are created internal to each sensor unit immediately after the ascent data take and can be requested for download after the crew sets up the WLES laptop
  - Raw data
    - Most definitive indication of impacts
    - Would take 88 days to download the entire raw data file from all 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



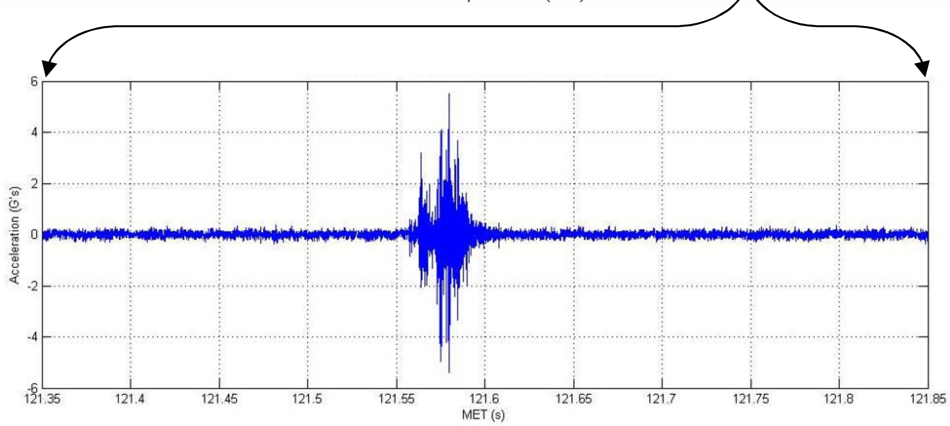
Raw Data:

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



Periodic G:

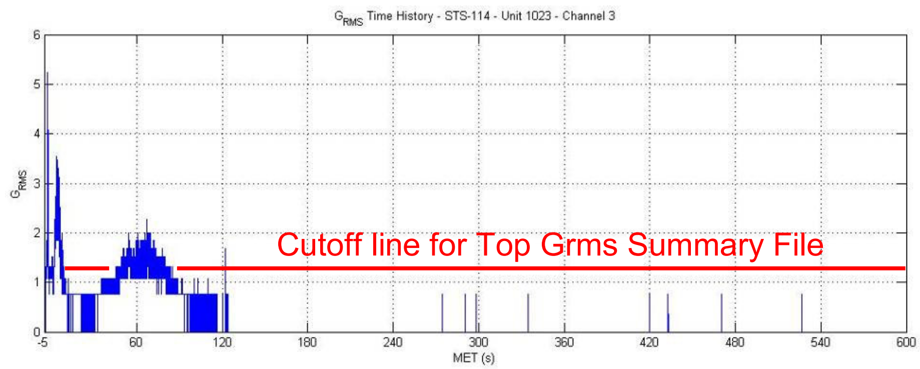
- File split into 1,200 ½-second time periods
- Top G point in each period is returned
- Best for identifying impacts near the noise floor
- Third download for STS-121



Half Second G Time History:

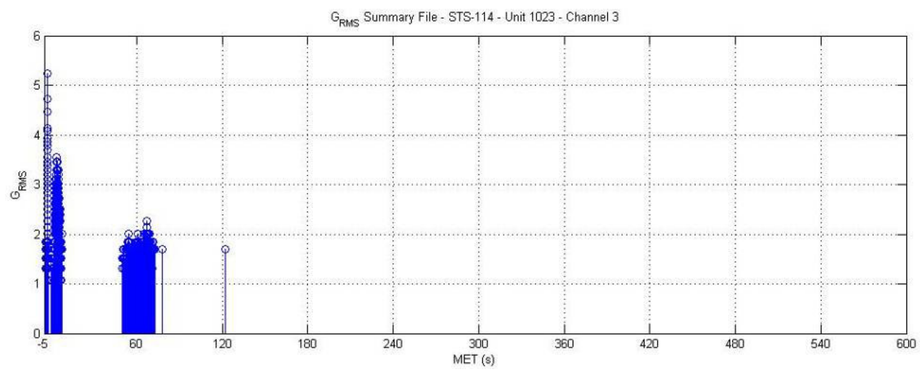
- Used to investigate points of interest
- Can be requested from any file type

WLEIDS Ascent Data Analysis: File Types



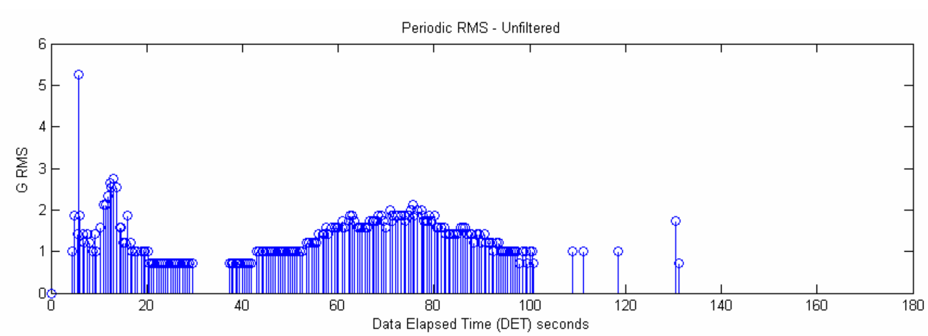
Grms Time History:

- 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:

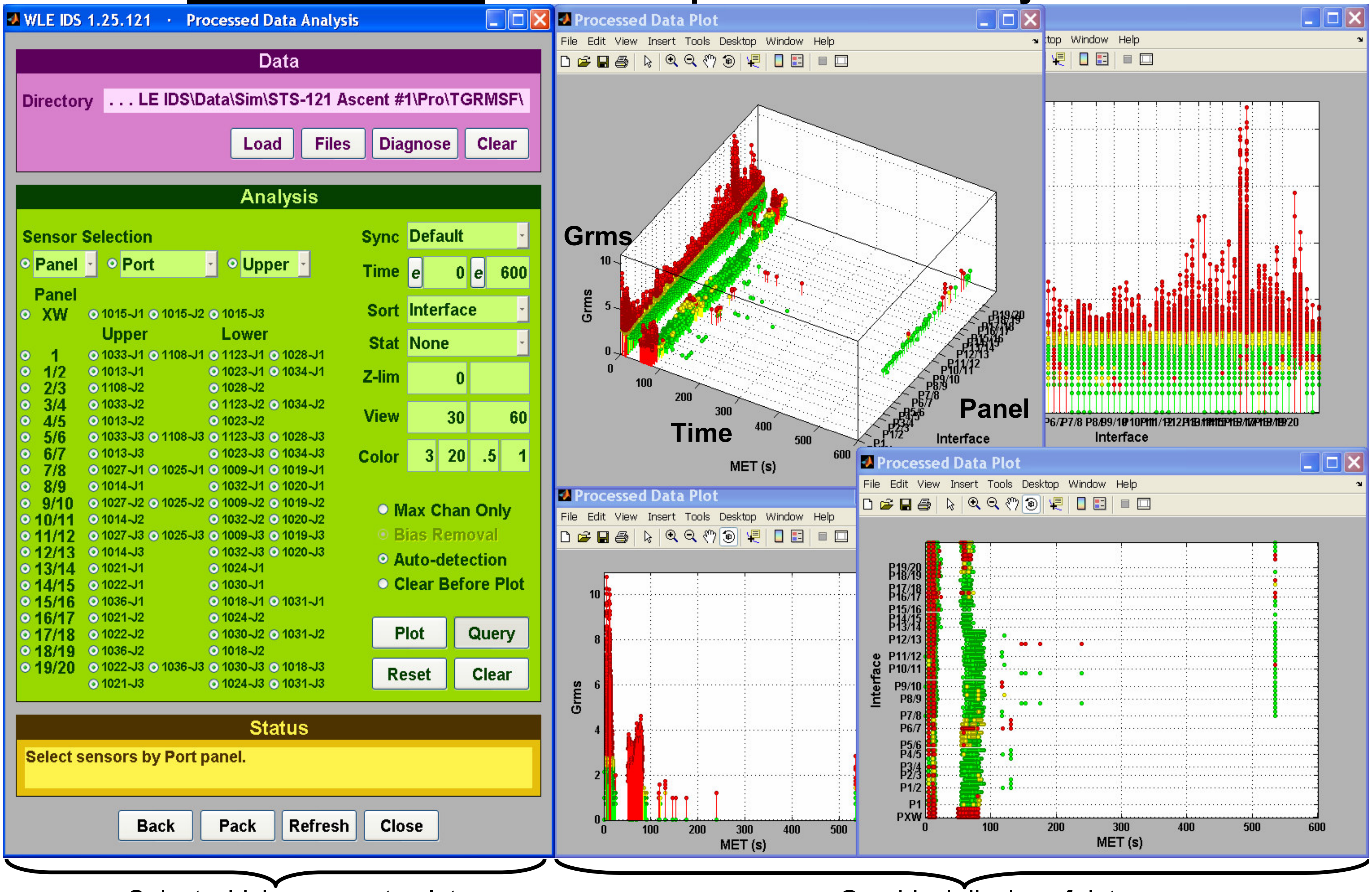
- Created from both Grms time history files
- Top 2,048 points returned
  - High point density around ignition and max Q
  - Value of cutoff line may change for each flight
- File without filtering is same as STS-114



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

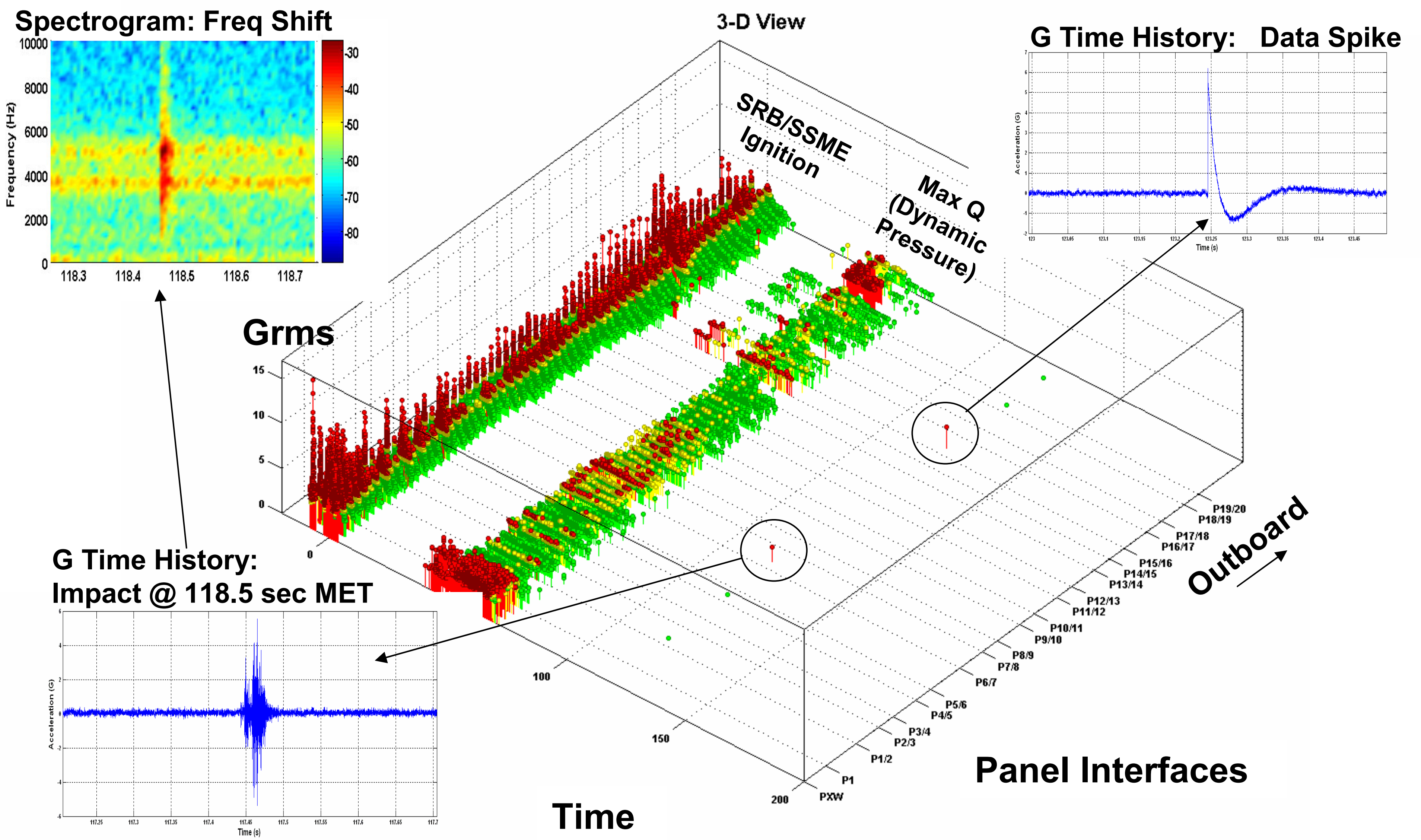


Select which sensors to plot

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

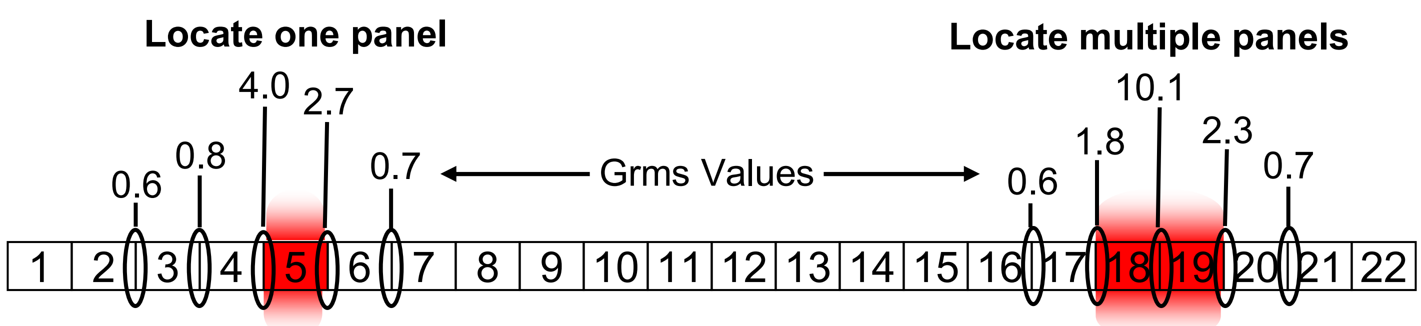


<u>Ascent Data Analysis</u>: Determine Impact Location

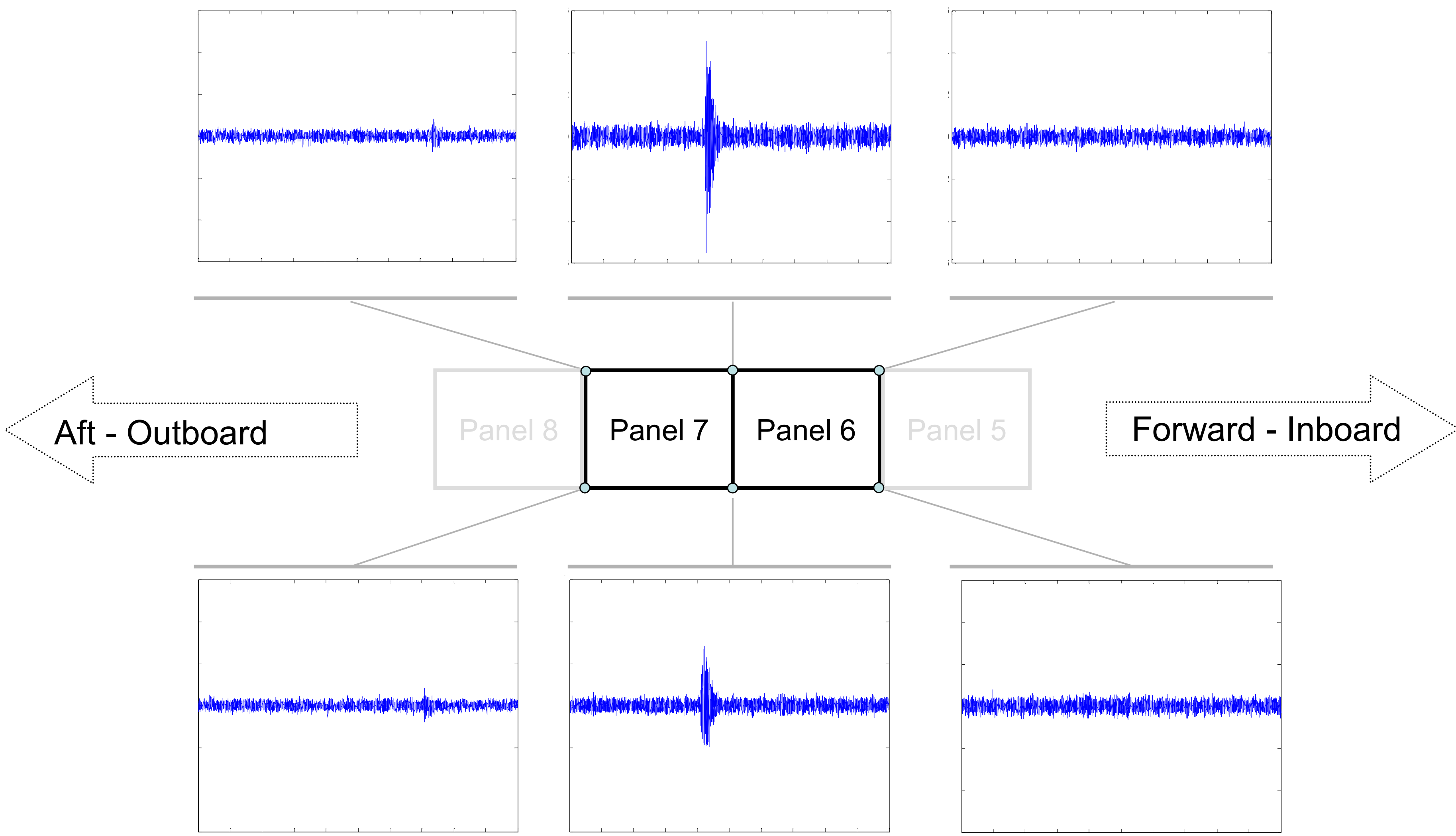
- Large response on only one interface
  - report adjacent panels to the interface
- Equally large response on two or more interfaces
  - report range of panels between the interfaces

- 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:

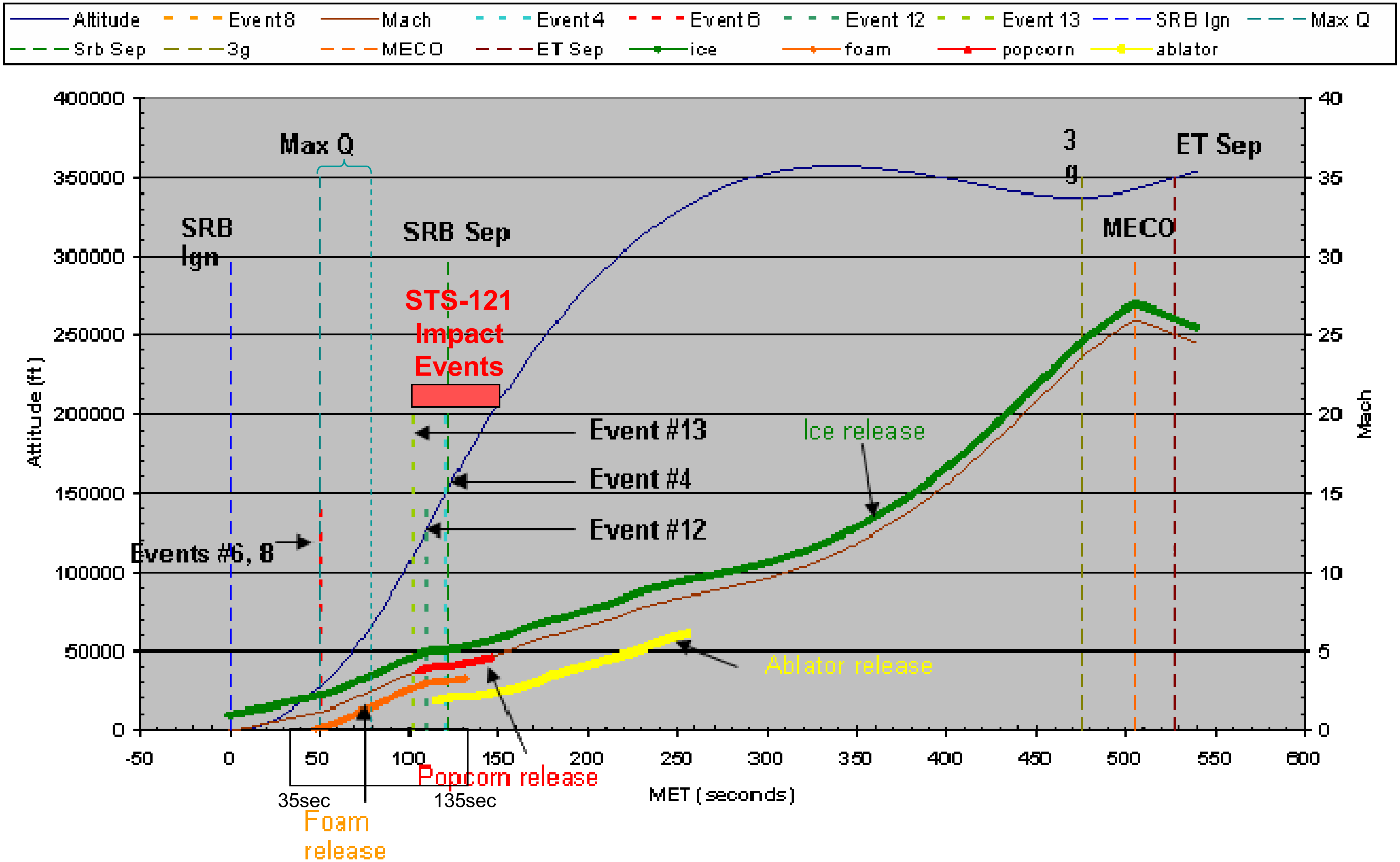


STS-114 Ascent Data Analysis: Panel 6/7 Hit Impact Location: Time History Plots



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

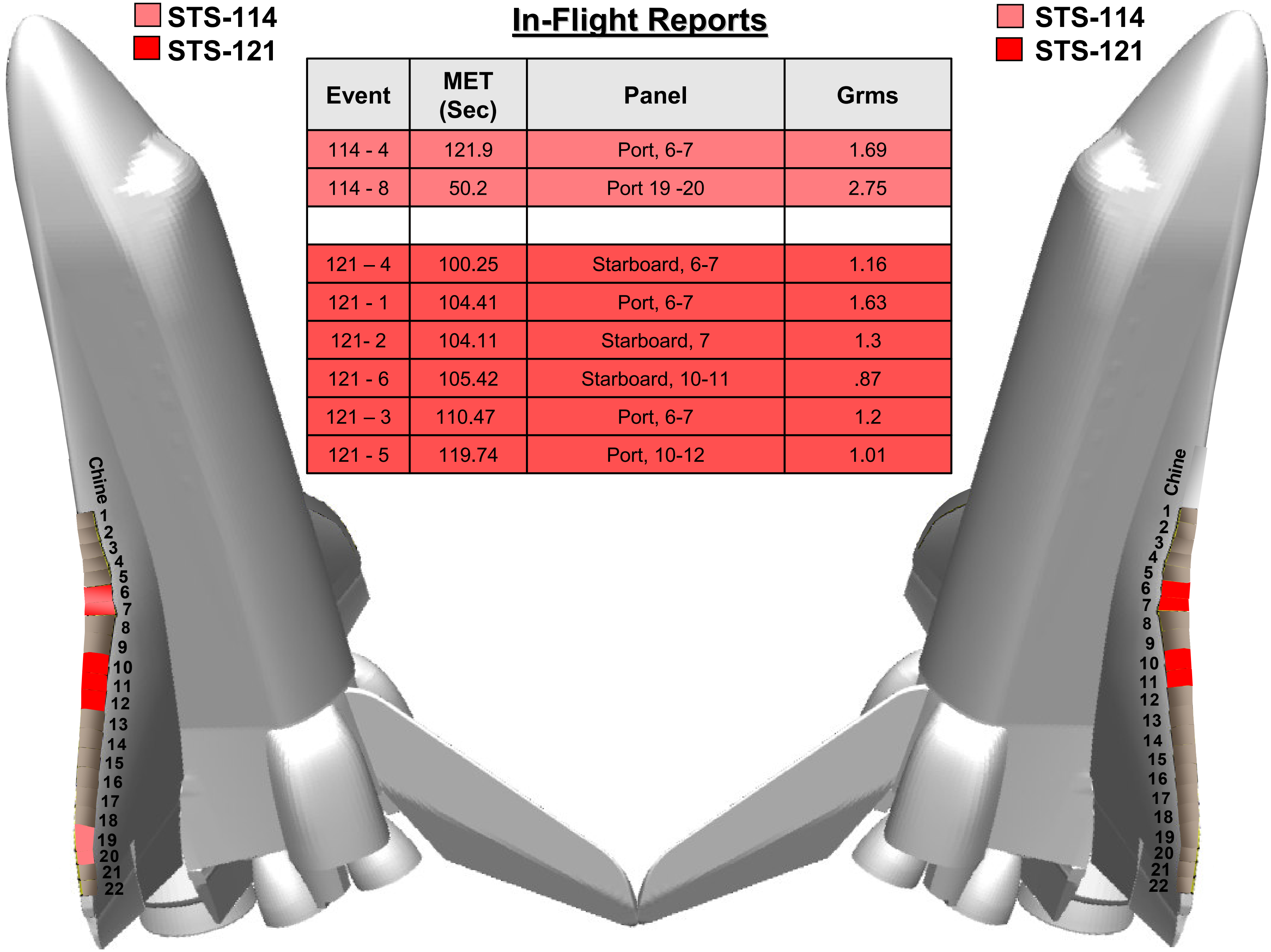
In-Flight Reports

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

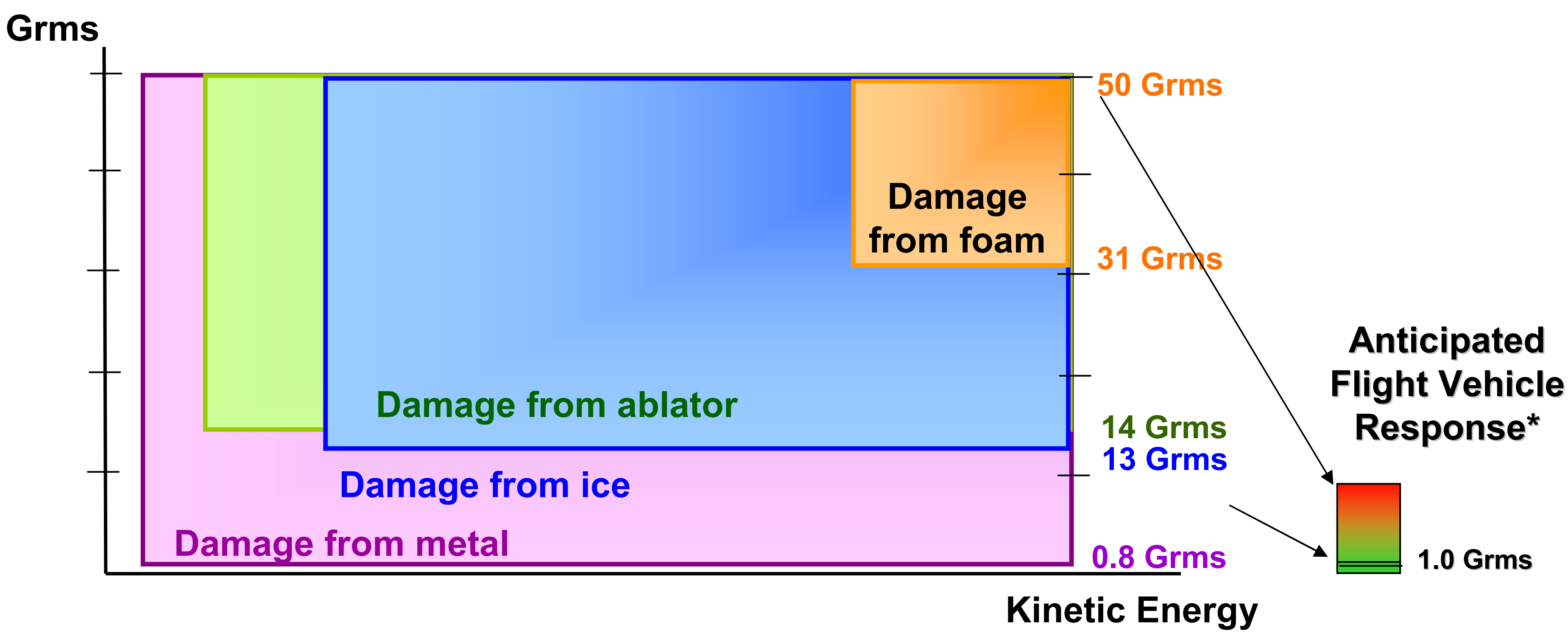
Problem: Analysis routines will likely identify too many non-damaging impacts to be practically addressed. Assessment of STS-114 raw data with these routines showed 146 impacts… with no damage to the RCC surface.

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.

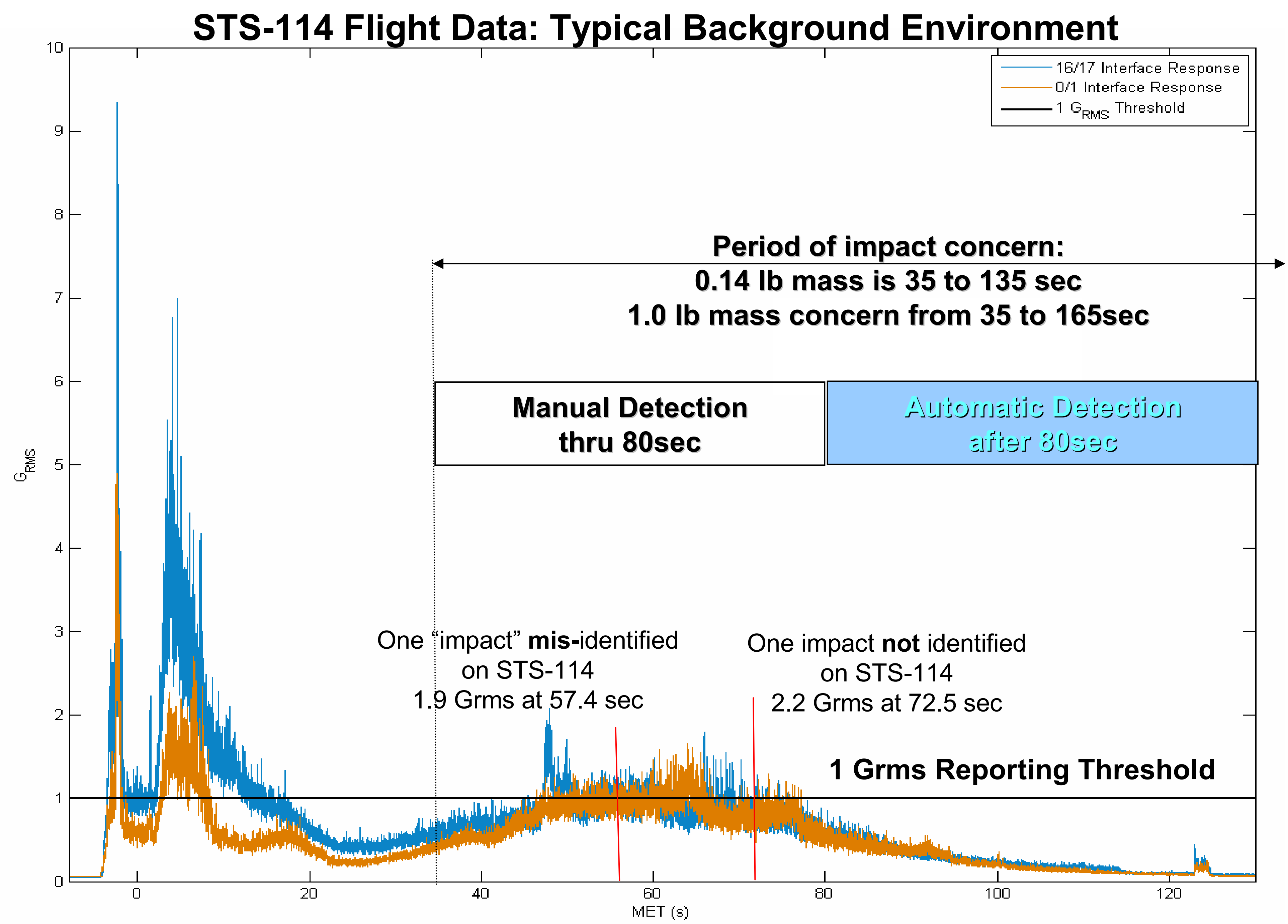
WLEIDS Impact Test Article Data Trends
RCC Damage Observed



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.

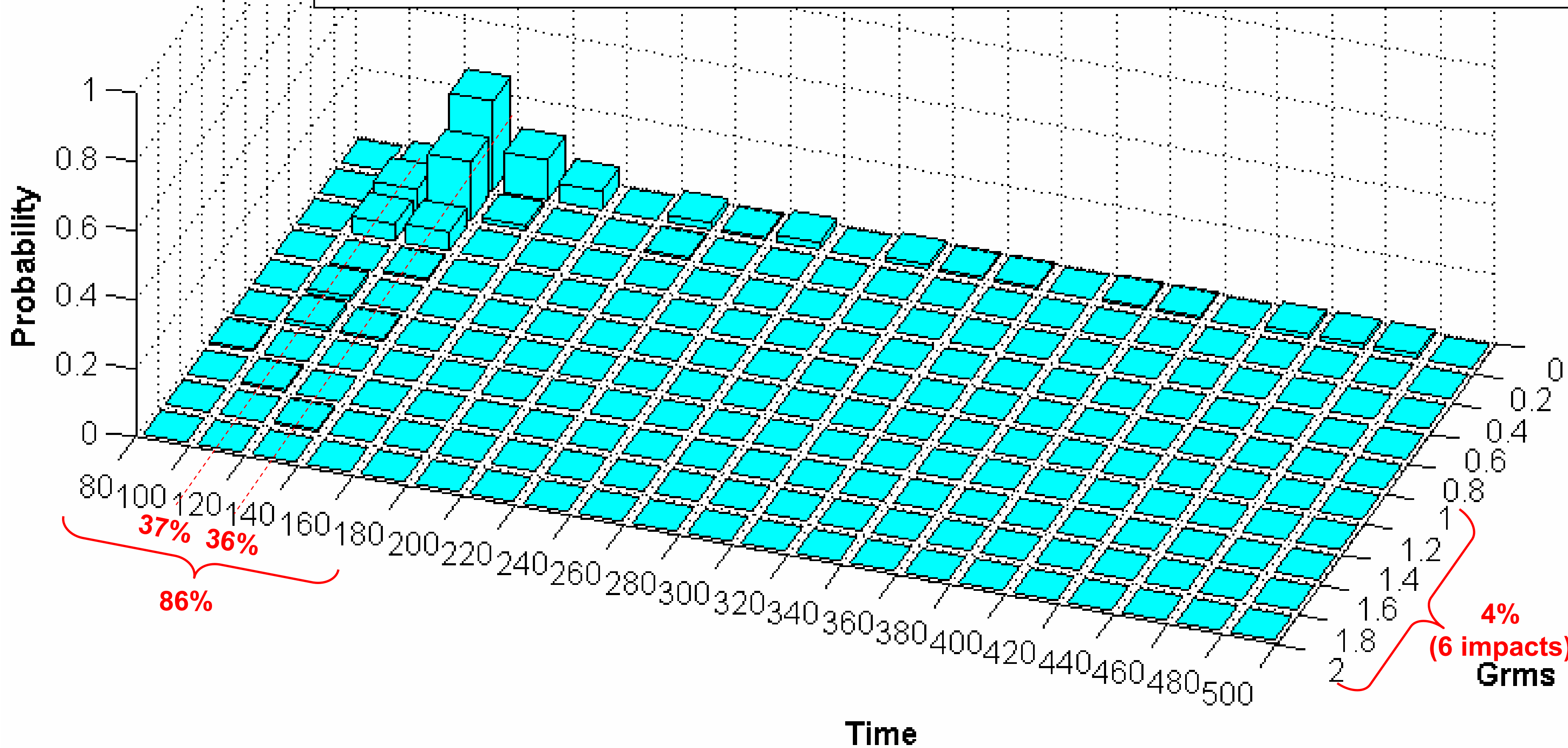
*** Test Data is limited, Impact analyses on validated models are necessary to accurately predict sensor response on the vehicle.**


STS-114 Flight Data: Typical Background Environment
16/17 Interface Response
0/1 Interface Response
1 G_{RMS} Threshold
Period of impact concern:
0.14 lb mass is 35 to 135 sec
1.0 lb mass concern from 35 to 165sec
Manual Detection
thru 80sec
Automatic Detection
after 80sec
One "impact" mis-identified
on STS-114
1.9 Grms at 57.4 sec
One impact not identified
on STS-114
2.2 Grms at 72.5 sec
1 Grms Reporting Threshold
G_{RMS}
MET (s)
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120

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

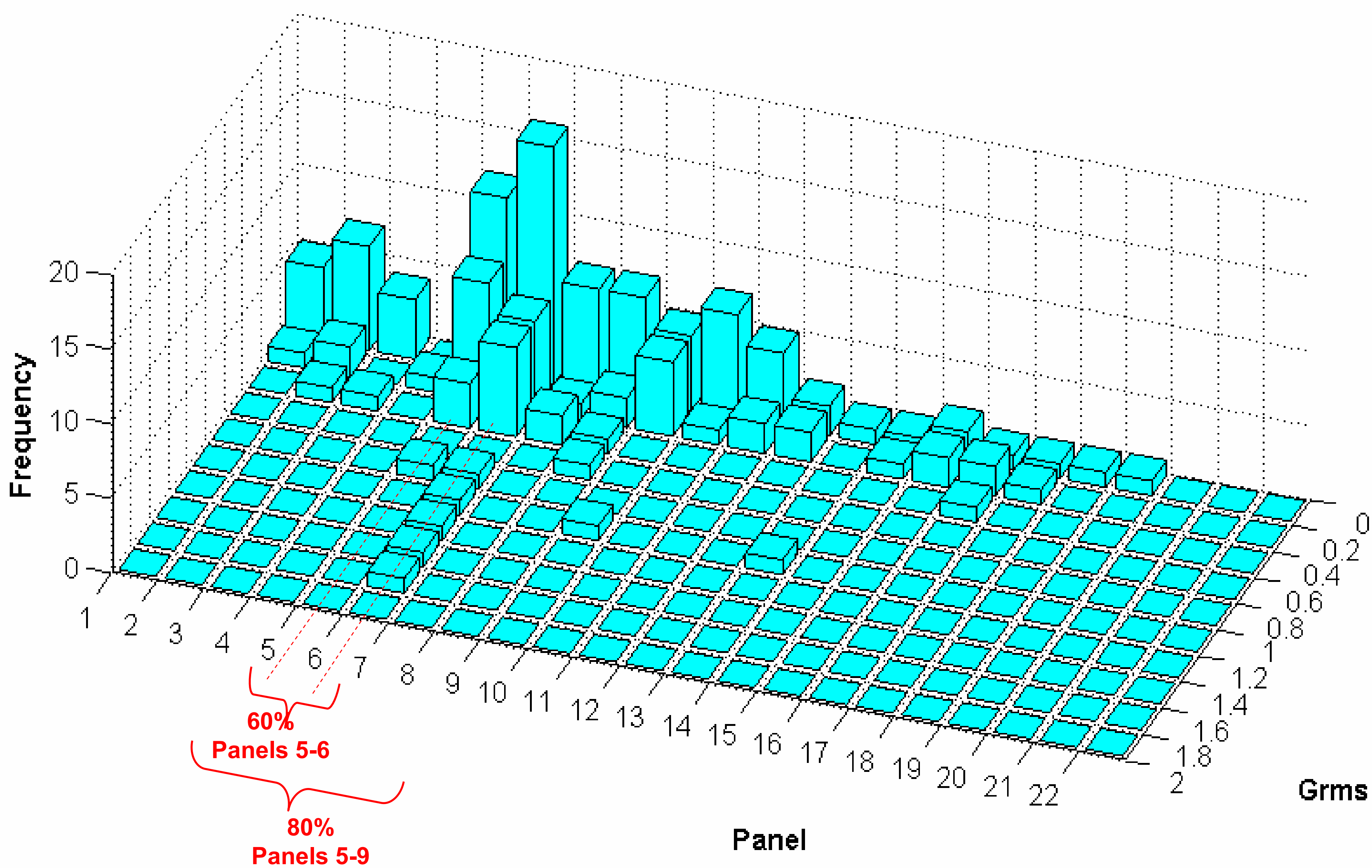
146 total impacts Auto-detected after MET 80 seconds

- 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



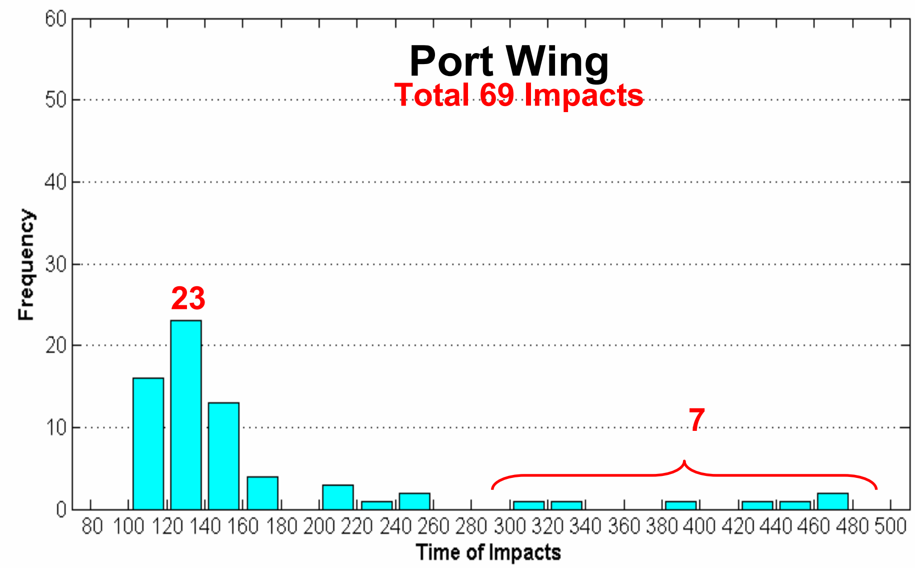
STS-114 Frequency & Magnitude of Impacts by Panel

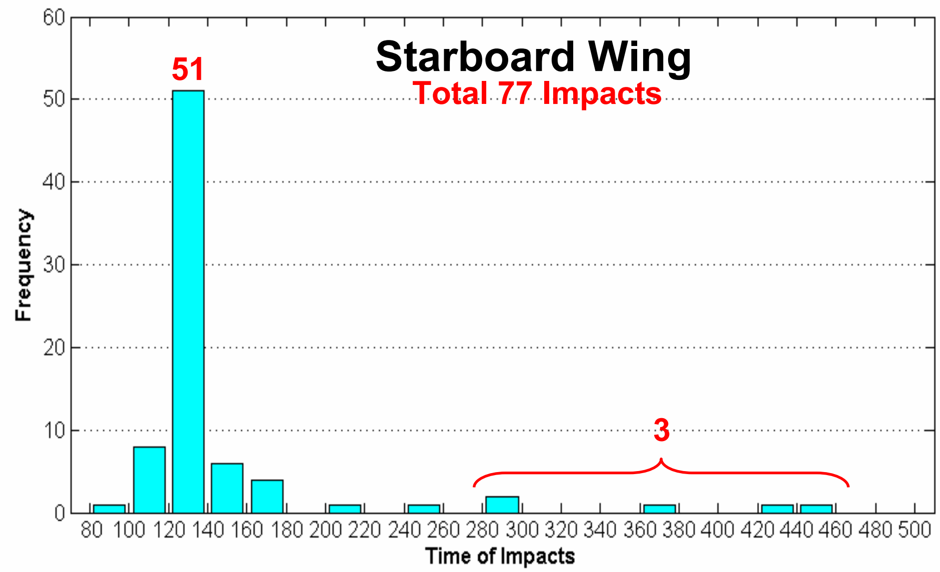
after 80 seconds MET

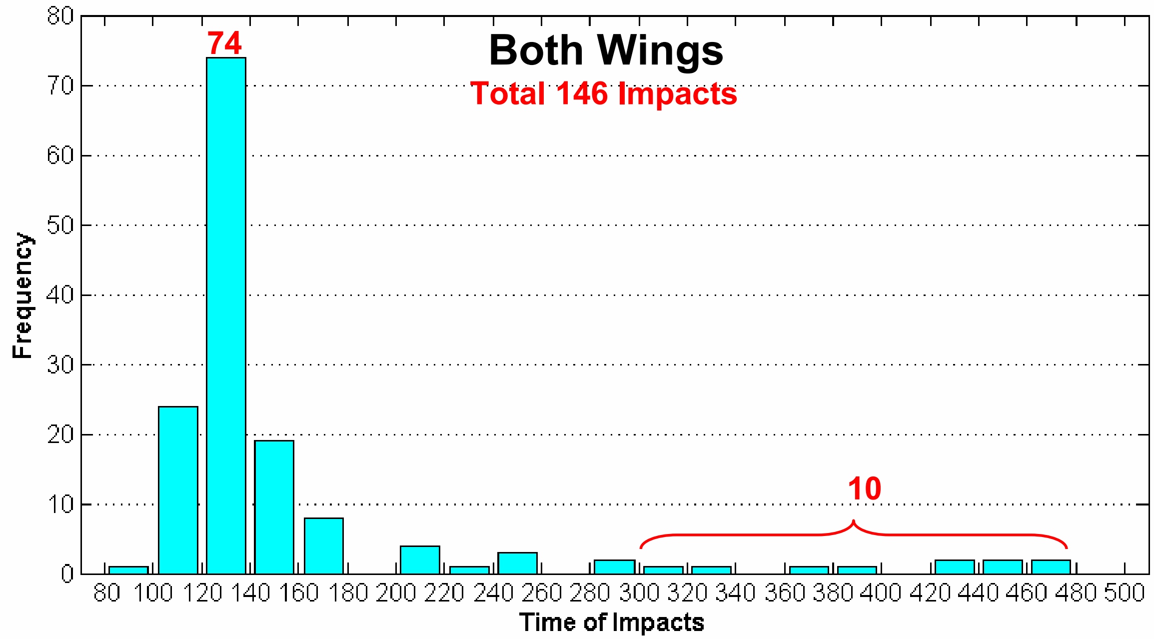


STS-114 Frequency of Impacts over Time

after 80 seconds MET

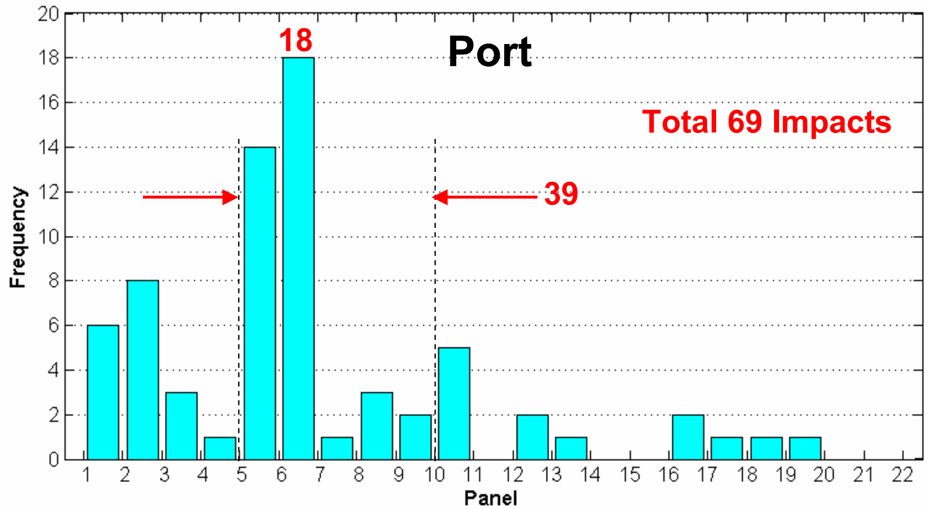


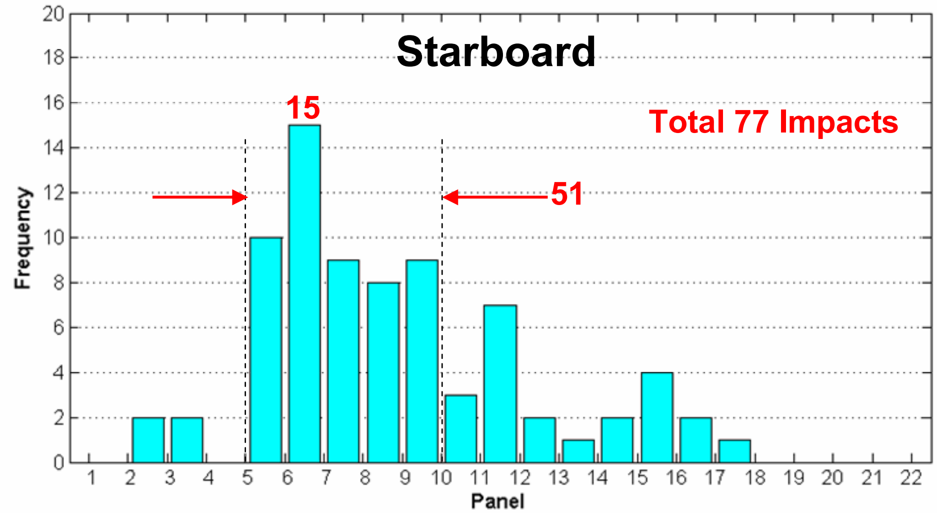


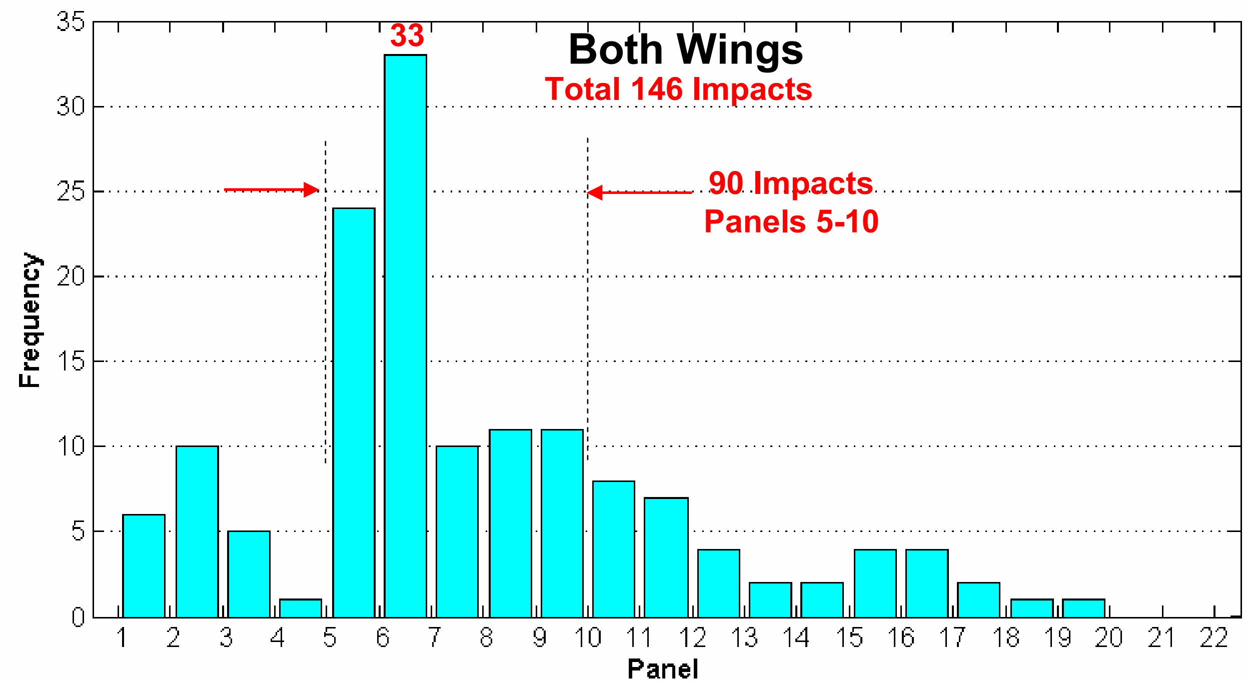


STS-114 Frequency of Impacts by Panel

after 80 seconds MET



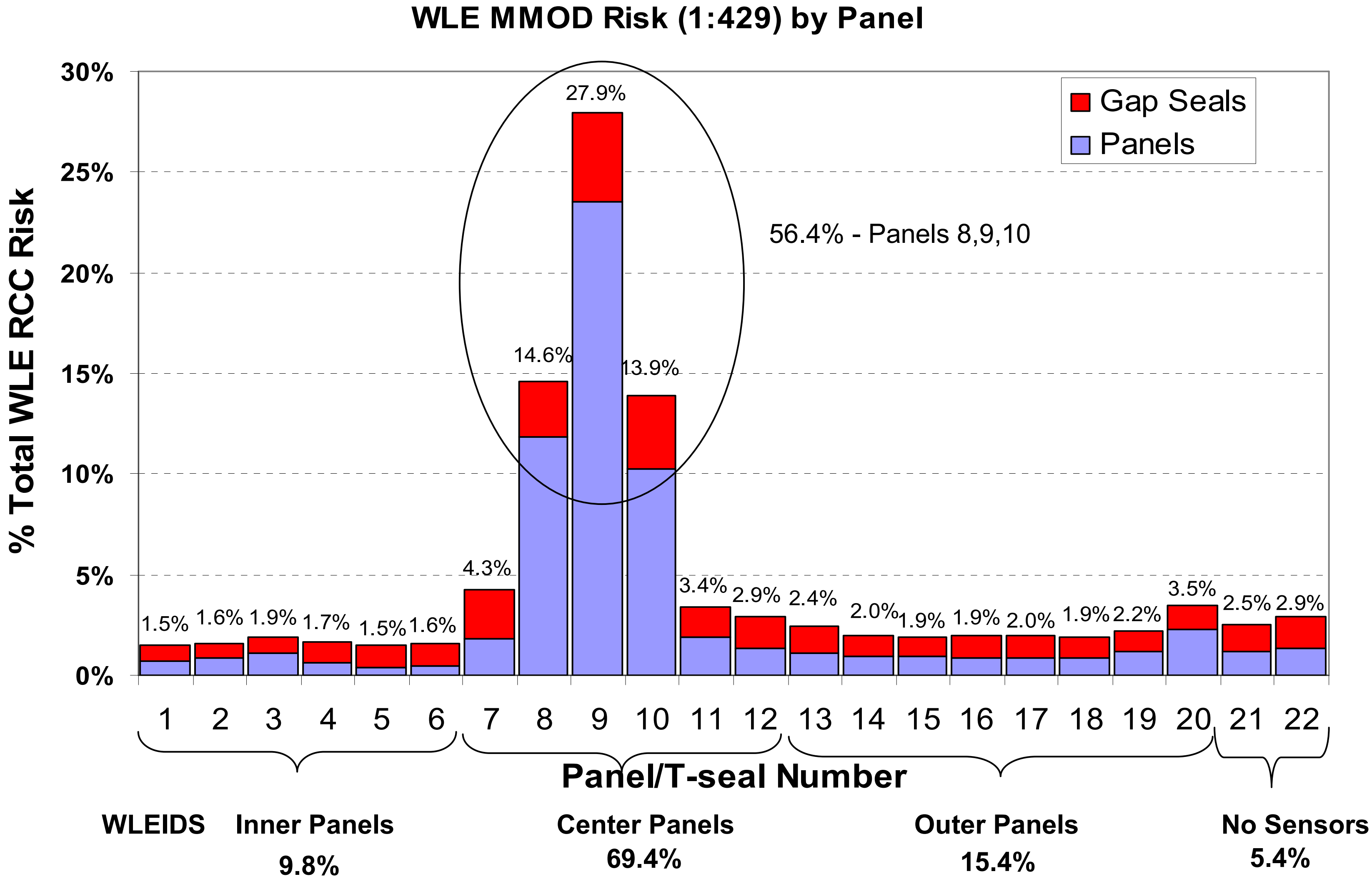




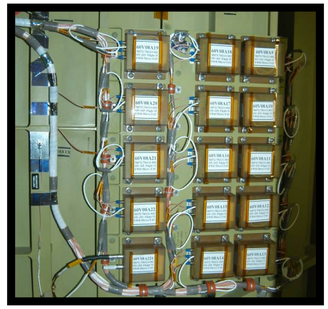
WLEIDS 2nd Purpose: MMOD Impact Indicator

Used to influence TPS Late Inspection priorities & planning

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

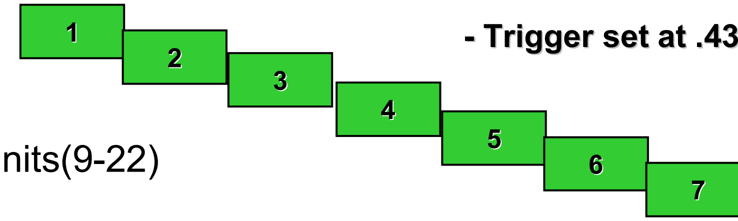


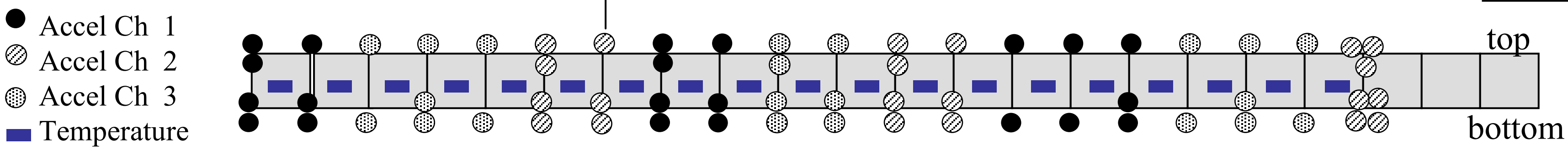
WLEIDS On-Orbit Impact Monitoring



Forward/Inbd Sensor Units(1-8) Aft/Outboard Sensor Units(9-22)

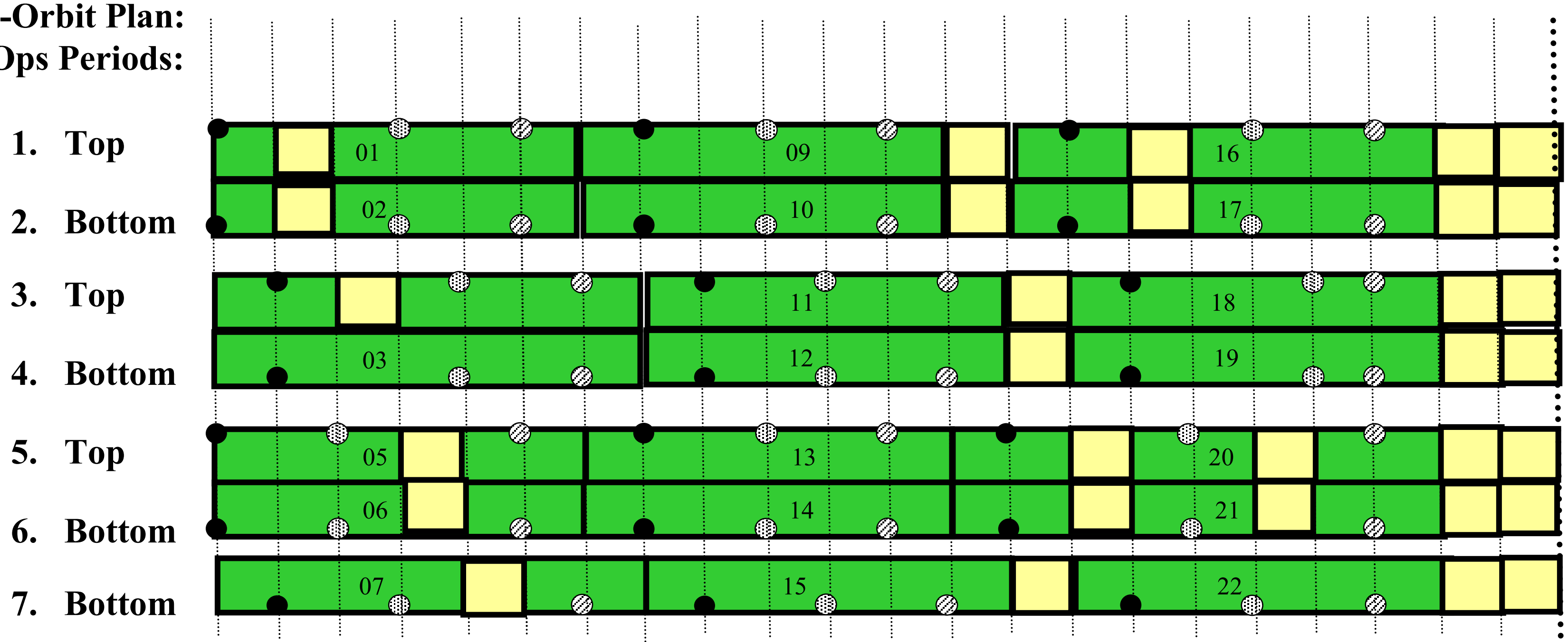
- Start after Ascent Assessment Complete
- 7 groups of 3 sensor units each
- Record ½ sec of raw data if triggered
  - Trigger set at .43g's

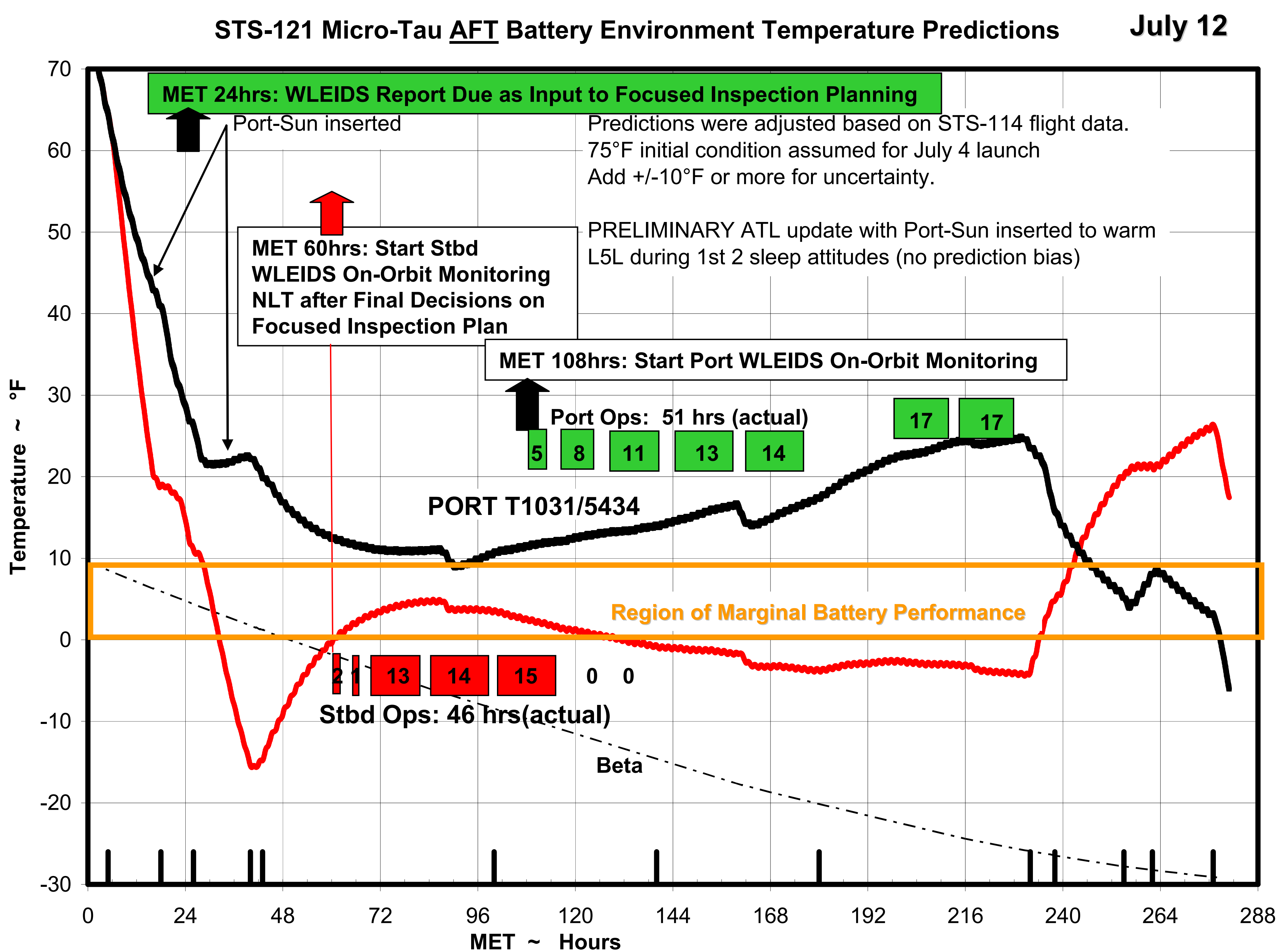


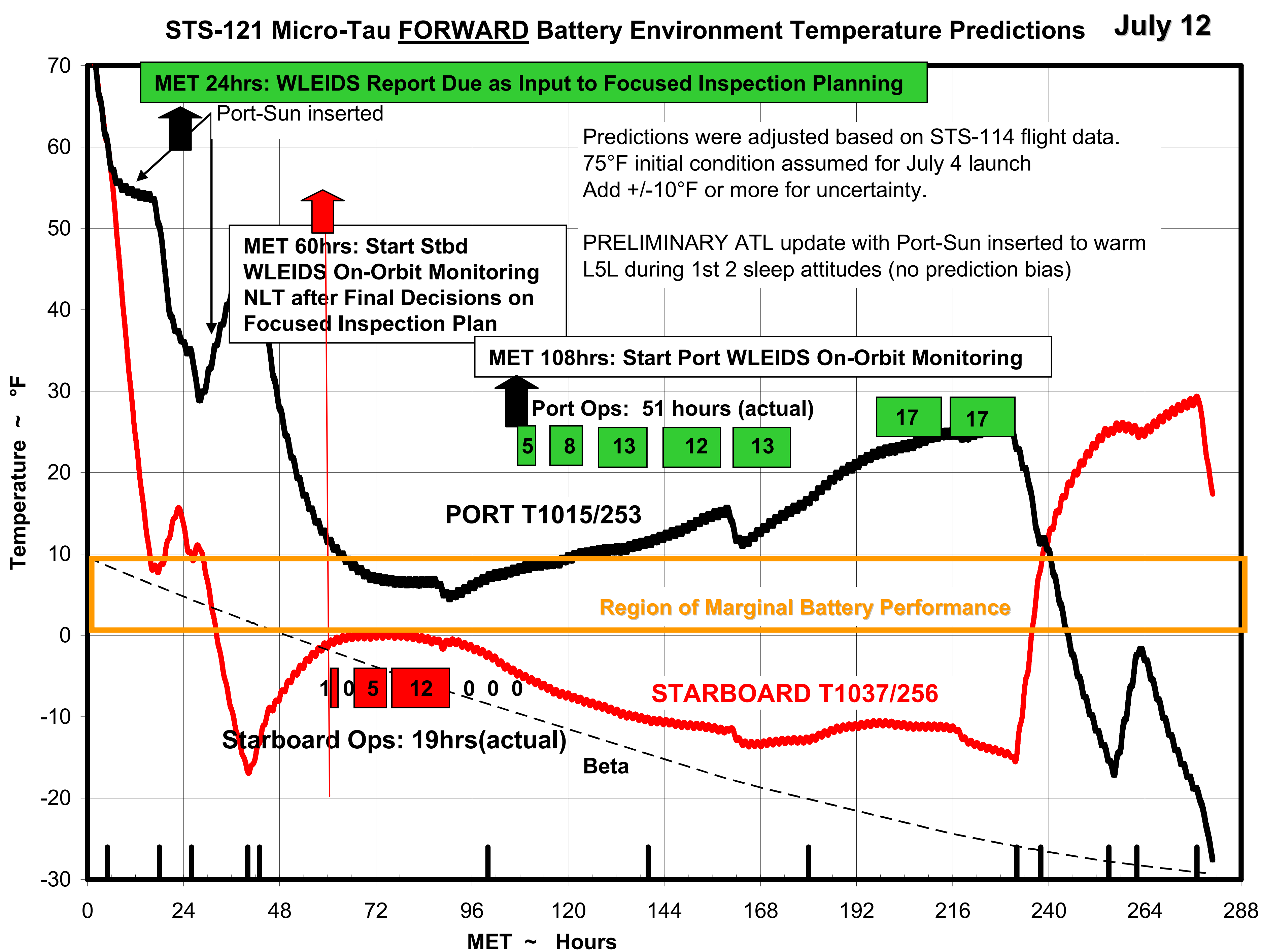


RCC Panels: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

On-Orbit Plan:
7 Ops Periods:




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
70
60
50
40
30
20
10
0
-10
-20
-30
0
24
48
72
96
120
144
168
192
216
240
264
288
MET ~ Hours



STS-121 Micro-Tau FORWARD 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 hours (actual)
5
8
13
12
13
17
17
PORT T1015/253
Region of Marginal Battery Performance
1
0
5
12
0
0
0
STARBOARD T1037/256
Starboard Ops: 19hrs(actual)
Beta
Temperature ~ °F
70
60
50
40
30
20
10
0
-10
-20
-30
0
24
48
72
96
120
144
168
192
216
240
264
288
MET ~ Hours

WLEIDS Ground Impact Tests

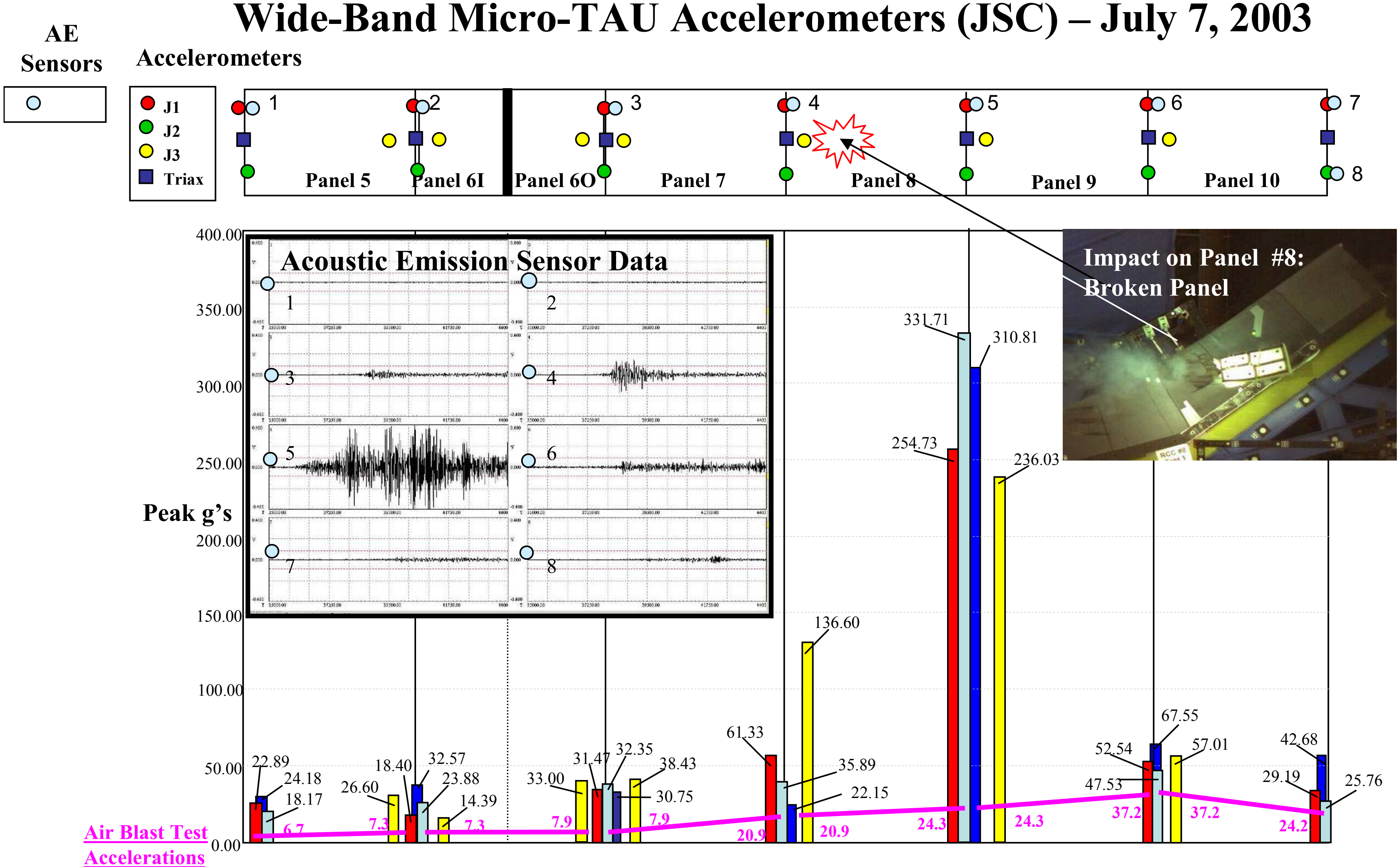
- **STS-107 CAIB investigation thru Sep 2003** – Leading Edge Test Article Impact Tests
  - LESS Test Article design like Columbia, some differences with current Orbiters
  - High accelerometer readings behind the spar and ability to localize what panel the impact occurred on
  - Micro-WIS flight experience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

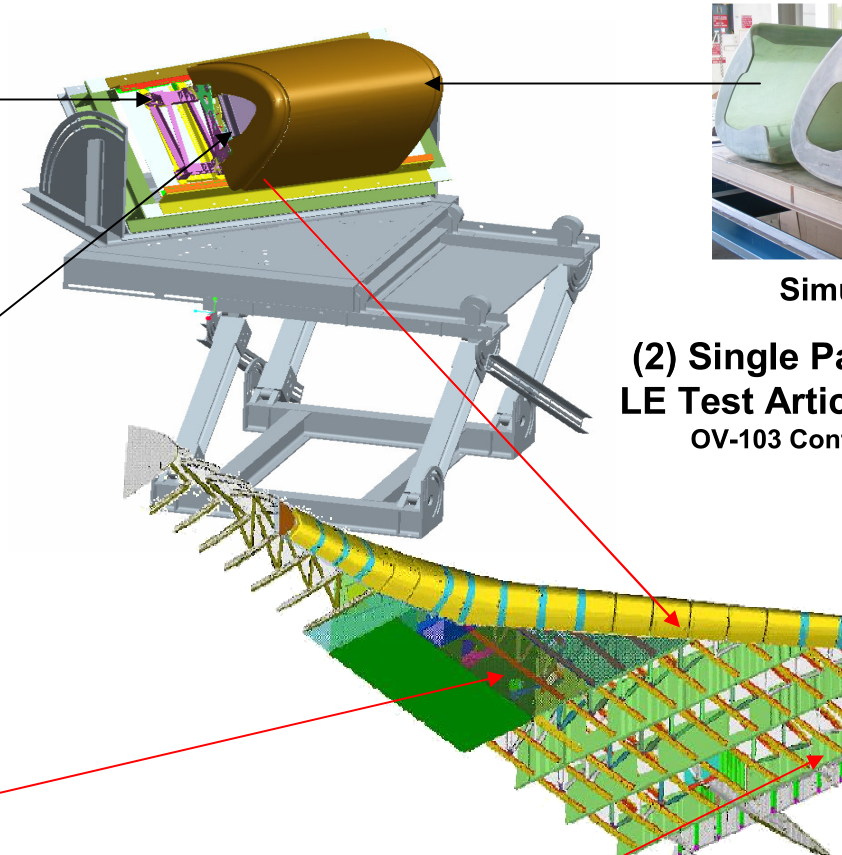
Wide-Band Micro-TAU Accelerometers (JSC) – July 7, 2003



New Test Articles for Impact Sensor Testing

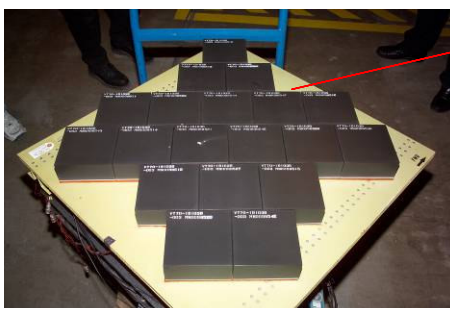
Corrugated Spar

Spar Fittings

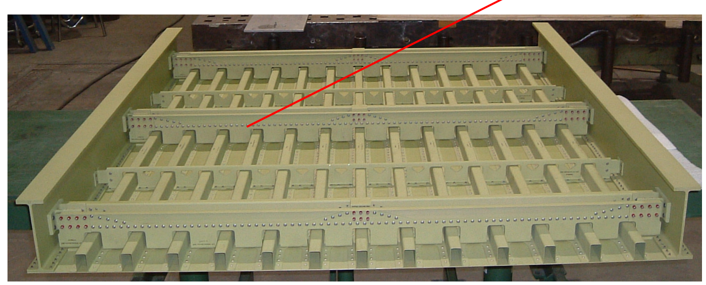


Simulated RCC Panels(10)

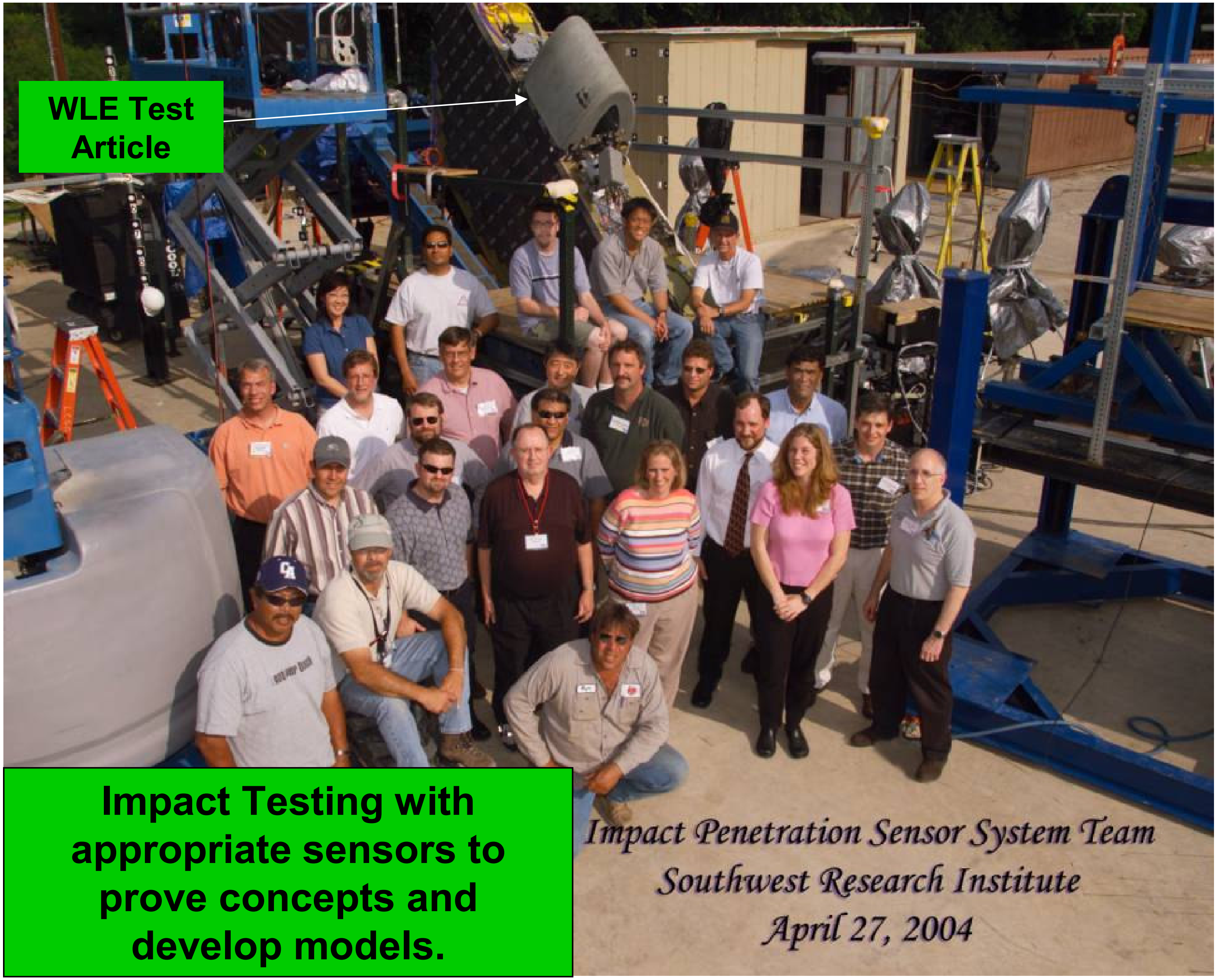
(2) Single Panel (16R)
LE Test Articles/Stands
OV-103 Configuration



(8) Honeycomb Panels
34"x34"

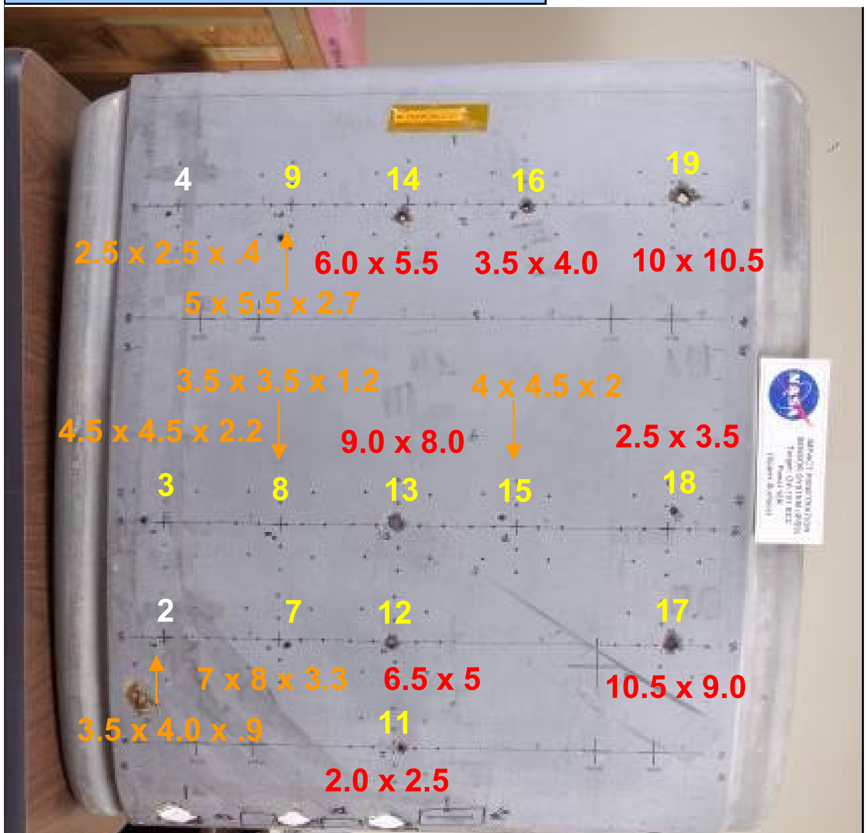


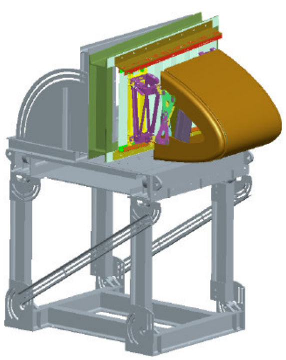
(2) Large Skin Stringers
and Strongbacks
66"x60"


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

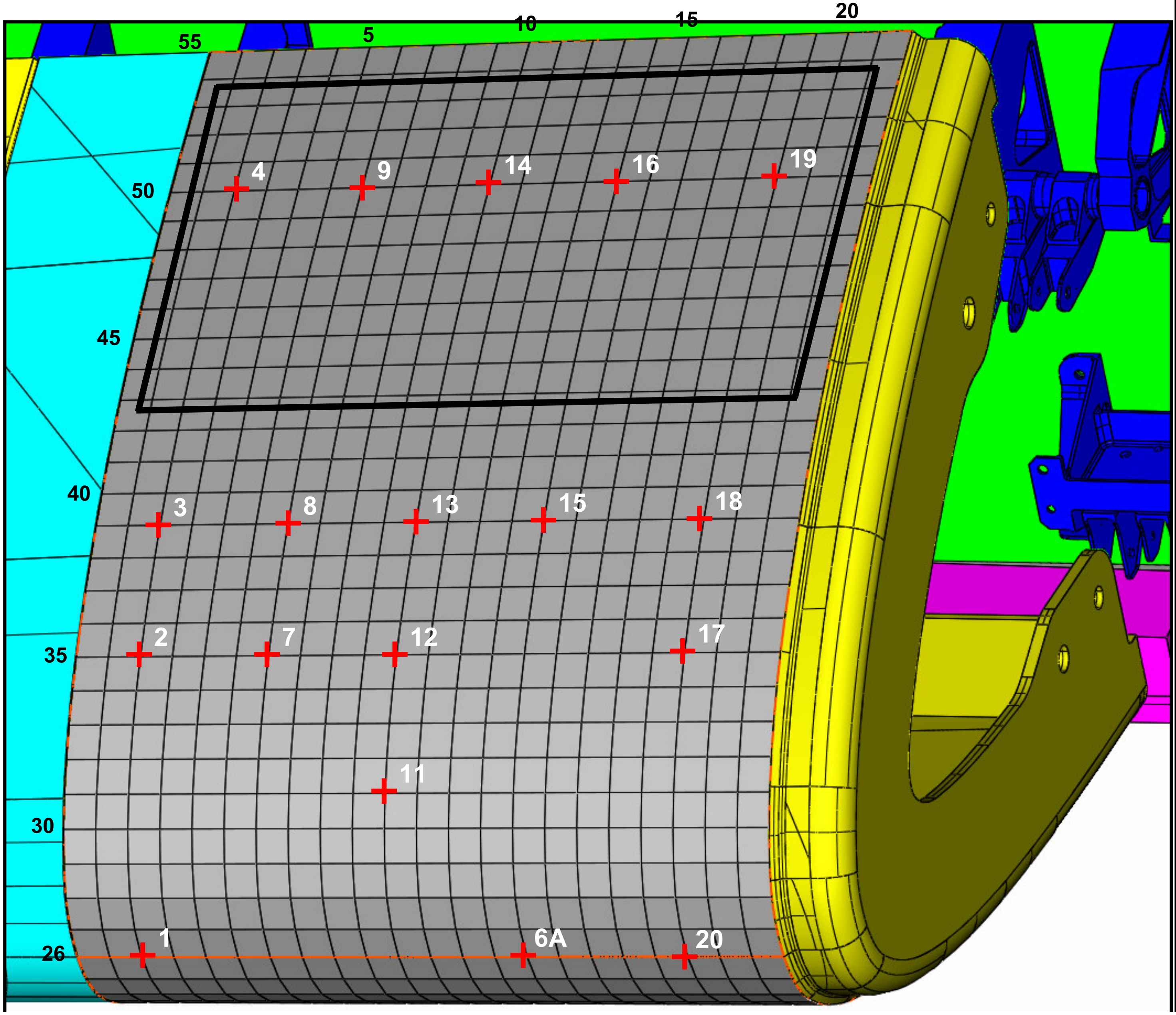
Damage: Coating, Crater, Hole
Length x Width x Depth (in mm)





Note: AE data in separate report

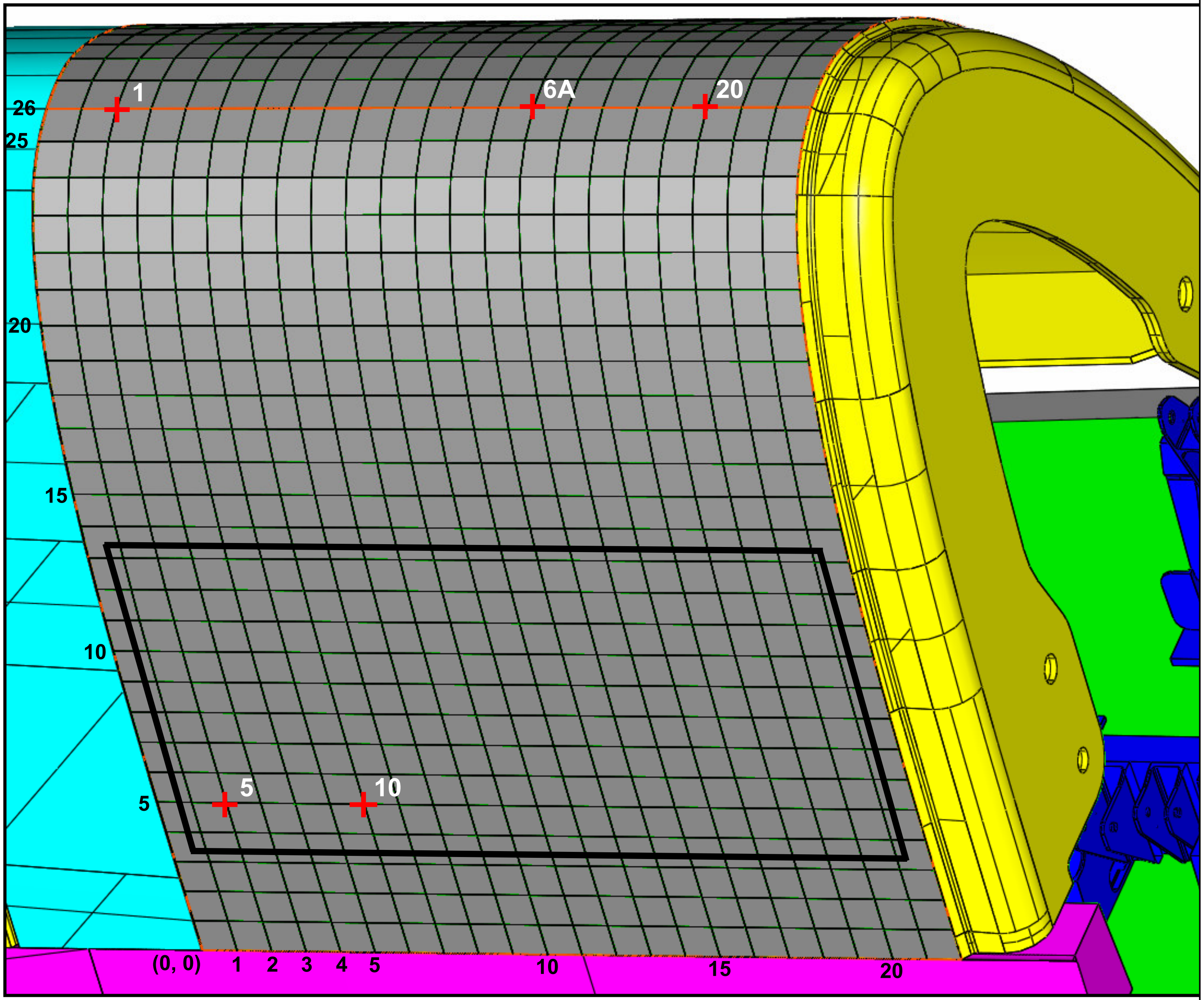
RCC Panel 16R – Upper Surface (Hypervelocity Impact Locations)



Shot #	Size mm	Angle Deg	Peak-G (x) UO	Peak-G (x) UI	Peak-G (x) LO	Peak-G (x) 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

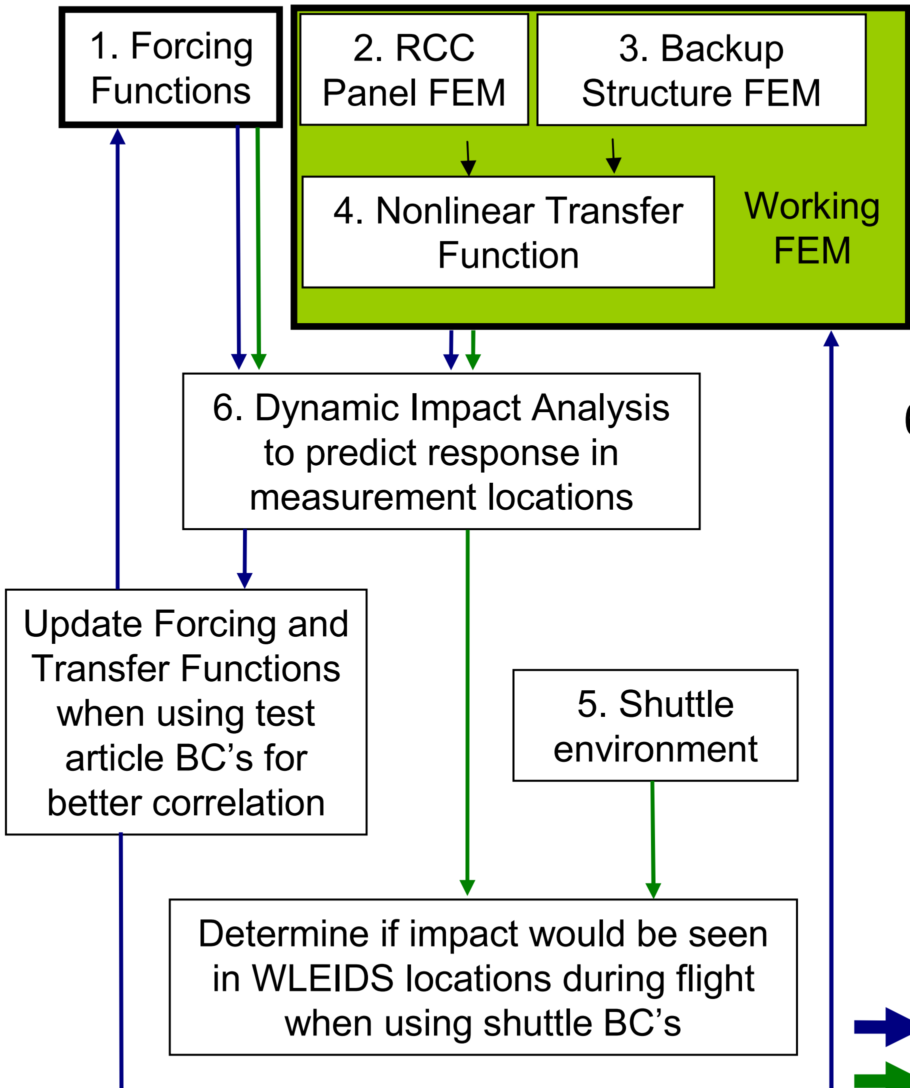
RCC Panel 16R – Lower Surface (Hypervelocity Impact Locations)



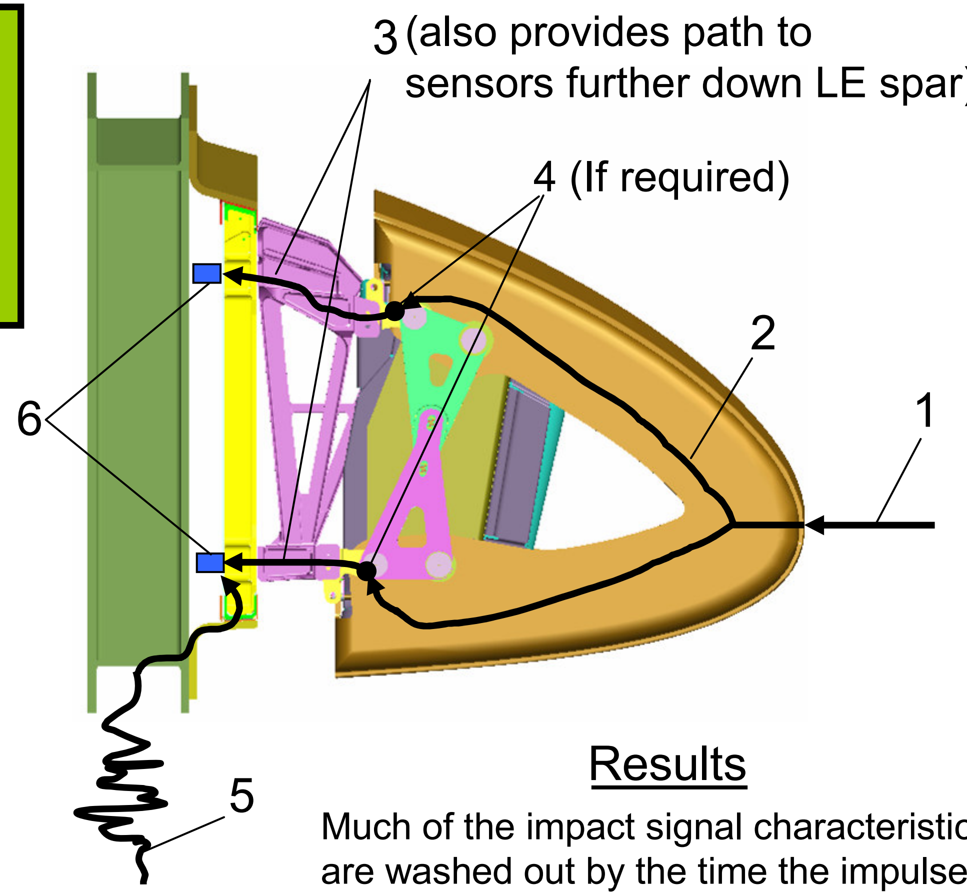
Shot #	Size mm	Angle Deg	Peak-G (x) UO / LO	Peak-G (x) UI / LI
1	0.4	90	.55 / .55	.53 / .61
2	0.4	60	.70 / .76	.52 / .58
3	1.0	45	4.9 / 3.7	2.9 / 3.8
4	0.4	30	.56 / .33	.28 / .39
5	0.6	45	1.2 / 1.8	1.1 / 1.2
6A	0.8	90	3.3 / 3.0	2.6 / 3.1
7	1.0	30	4.8 / 5.6	4.5 / 5.5
8	0.6	60	2.0 / 1.5	1.2 / 1.8
9	1.2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