



Considerations for IVA NDE Instrumentation for ISS On-Orbit NDE Applications

In-space Inspection Workshop

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July 15, 2014

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Sponsors: ISS Program,
JSC Engineering and
NASA Engineering Safety Center





Summary

- Need for ISS On-orbit NDE Equipment
- Inspection Cases
- Damage Detection Requirements
- Assessment of NDE Equipment for Use on ISS
 - Ultrasonic Testing and Eddy Current Testing Equipment
- NDE Test Protocols
- Ultrasonic and Eddy Current Scan Demonstration Examples
- Engineering Assessment Considerations
- Conclusions and Recommendations



Leroy Chiao Inside Destiny Space Lab



Zvezda Service Module

IVA – Intra-Vehicular Activity, activity inside a habitable space vehicle such as International Space Station





Need for On-Orbit NDE Equipment

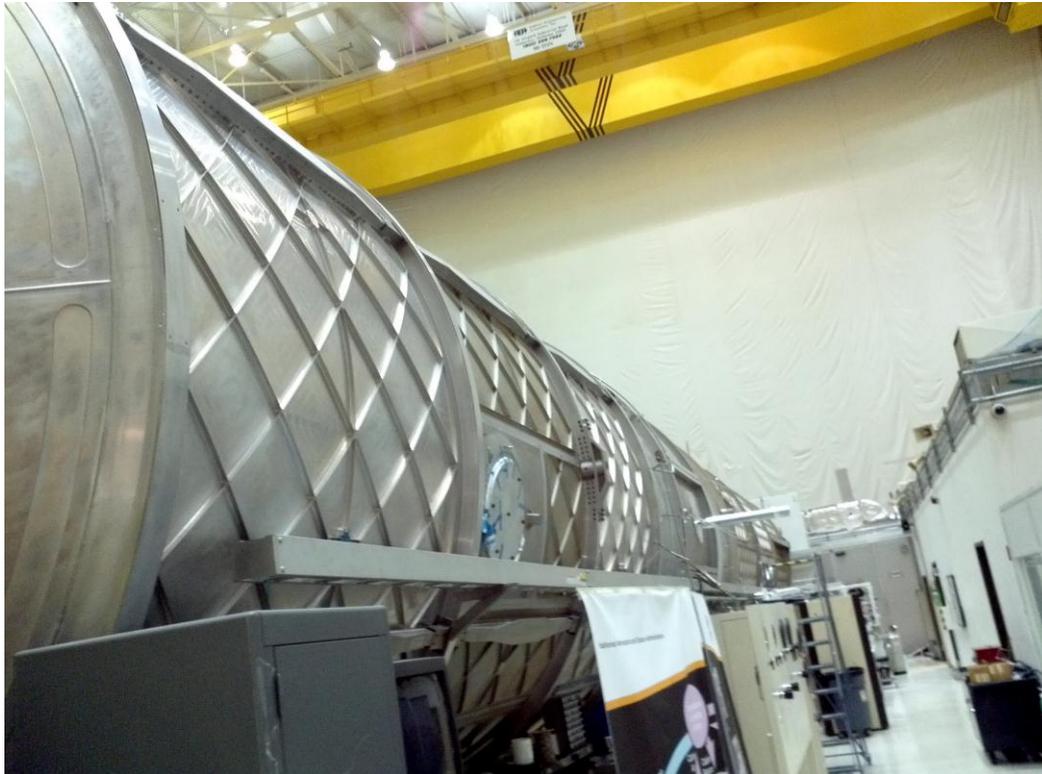
- There is a high risk of module damage/penetration from MMOD impact to the ISS over the life of the program.
 - At present, there is a greater than 33 percent probability of ISS penetration from MMOD over a ten year period.
 - MMOD threats have been changing as more debris is being created and additional modules are being manifested.
- Although on-orbit leak repair kits are available for pressure loss mitigation, these kits do not address structural repair needs.
- The needed NDE tools for damage and repair assessment are not currently available on ISS.

MMOD – Micro-Meteoroid and Orbital Debris





Pressure Wall on US Modules



Test Plate



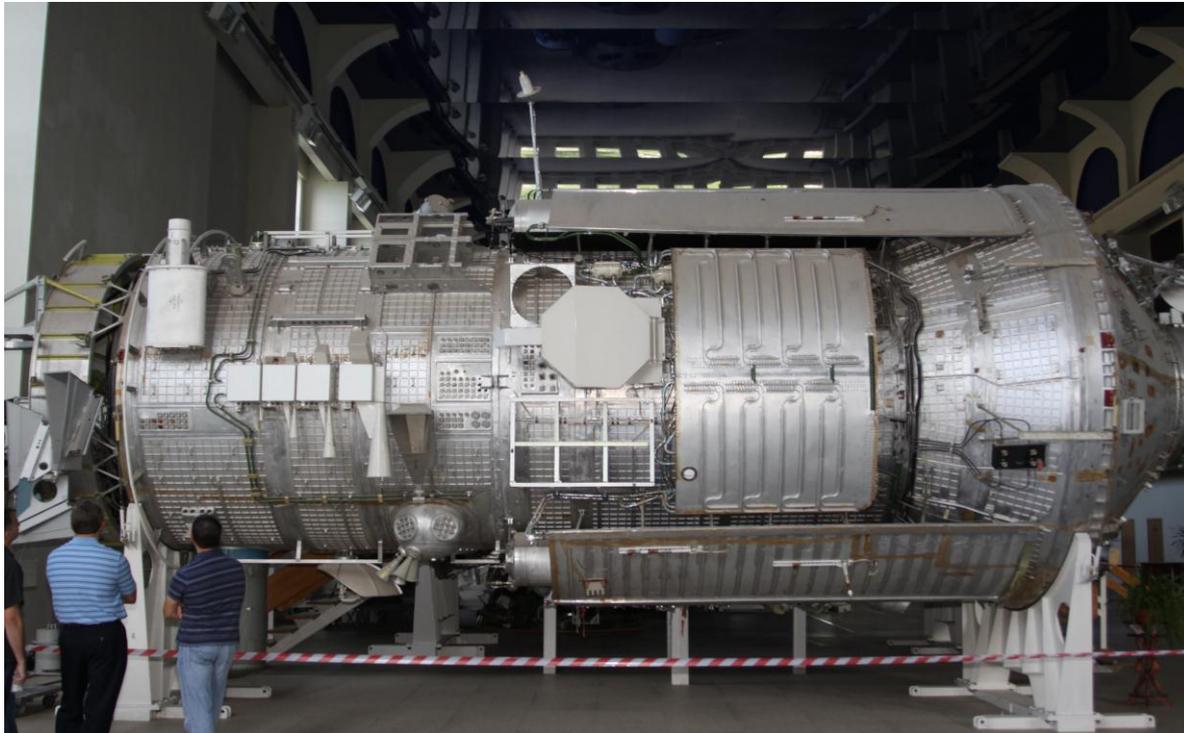
Grid Outside



Pressure Wall on Russian Modules



FGB



Orthogrid Outside or Inside



FGB – Functional Cargo Block (From Russian Funktsionalno-gruzovoy blok or ФГБ) or Zarya





Columbus Module

Columbus-Modul

Platz für Experimente, die außerhalb von „Columbus“ arbeiten sollen

Flüssigkeits-Labor

Fußrasten

Biologie-Labor

Physiologie-Labor

Experimentier-schränke

Platz für weitere Experimentier-schränke

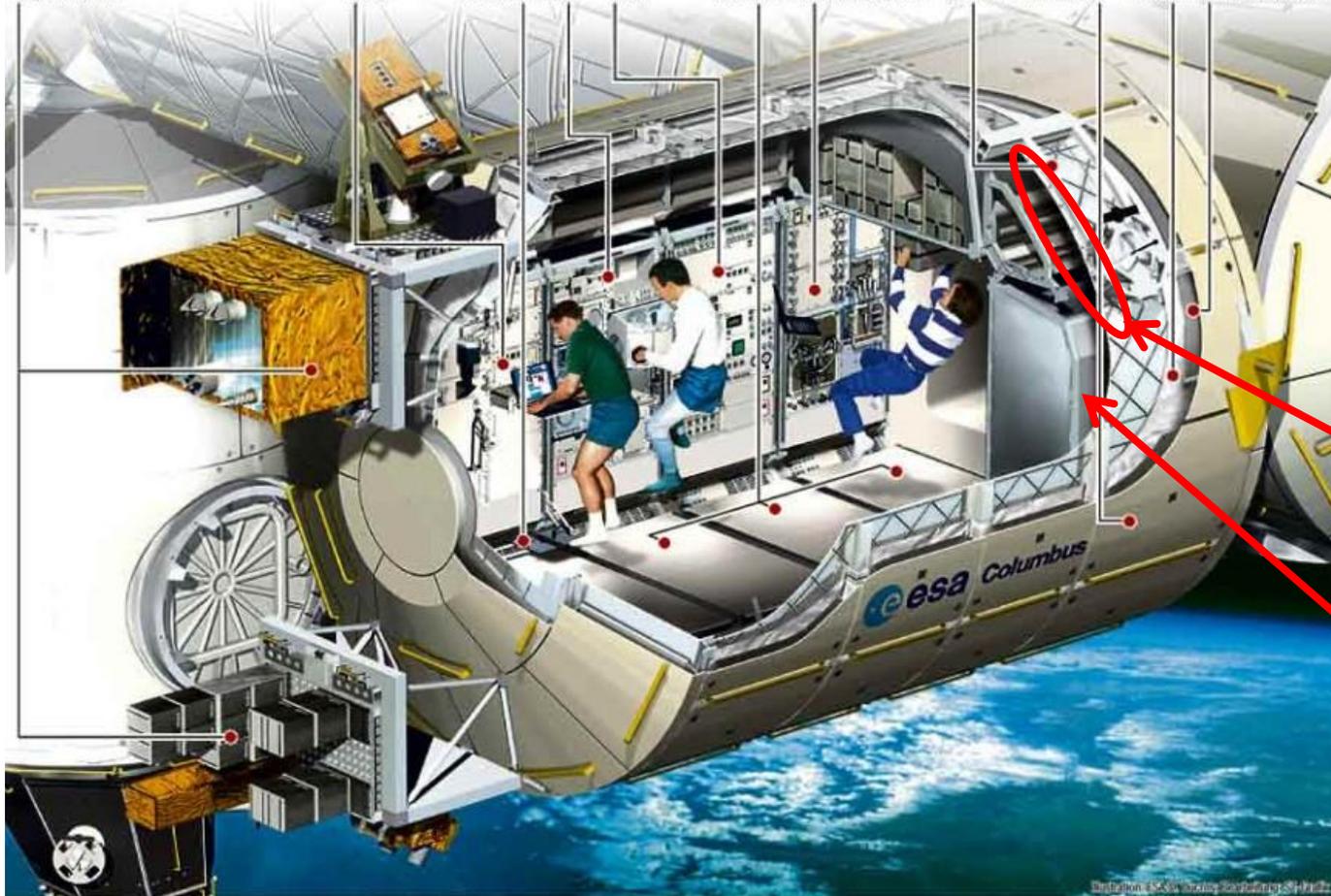
„Drawer Rack“: Regal für automatisierte Versuchsaufbauten

Tragende Struktur

Äußere Schicht der Schutzhülle

Viele Lagen Isolationsmaterial

Zweite Schicht der Schutzhülle gegen Weltraumschrott und Mikrometeoriten



Location of corner panel

Limited access behind rack if not removed

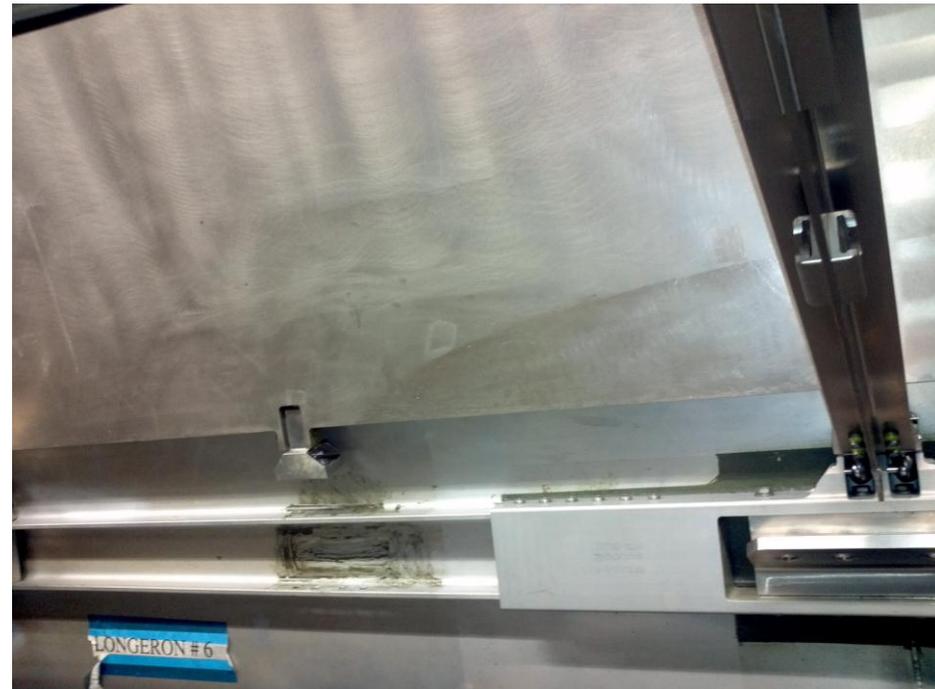




Limited Access Behind the Corner Panel



US Module



1 inch gap





Mitigation Steps for ISS Risk 4669 Requirements for NDE Inspection



Mitigation steps status for Risk 4669 “Pressurized Module Leak Detection and Repair“

Mitigation Step	Onboard ISS	Hardware status	Developer	New CR Req
1. IVA Leak Repair	Yes	USOS Cert completed RS Cert in work	US	No
2a. IVA Leak location ULD, “BAR” Set	Yes	Completed	US, RSC E	No
3. Autonomous leak detection system UBNT Hdwe option	No	On hold pending completion of step 8	US	Yes
4. NDE inspection IVA GFE option	No	Planning and Draft CR in work	US	Yes
6. EVA Leak repair hardware “Pressurizer”	Yes	RS Cert completed USOS Cert planning in work	RSC E	No
7. Permanent repair Structural repair with bonded or welded doublers	No	Planning and Draft CR in work	US	Yes
8a. Environment characterization tests, ground UBNT Phase I	No	Completed	US	No
8b. Environment characterization tests, ground UBNT Phase II	No	Planning in progress with RSCE and Khrunichev	US	Yes
8c. Environment characterization tests, ISS on-orbit UBNT Phase I UBNT Phase II	Yes No	Pending available crewtime Planning in progress with RSCE and Khrunichev	US	Yes





Inspection Cases

Provide Capability for the Following Inspection Cases

- Case 1: Damage to pressure wall with **leak**
 - NDE after pressure repair (flexible patch or rigid dome)
 - Ultrasonic sensor will contact pressure wall outside the repair due to inability to sense damage through repair patch (Tape or dome)
 - Shear wave scan
- Case 2: EVA Epoxy and Other Repair (future capability)
 - Ultrasonic inspection of bondline, zero degree scan
- Case 3: Suspect impact damage on ISS pressure wall with **no leak**
 - Ultrasonic zero degree scan and/or shear wave scan
- Case 4: Corrosion
 - Ultrasonic zero degree scan

EVA – Extravehicular Activity such as activity outside space station





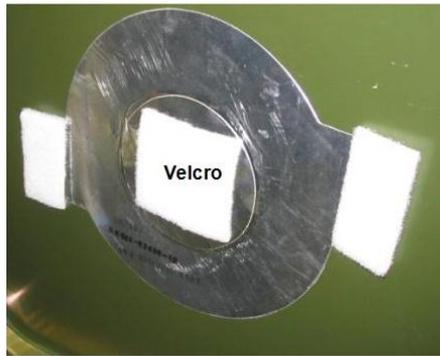
Inspection Case 1

Damaged area may be blocked by the leak repair patch

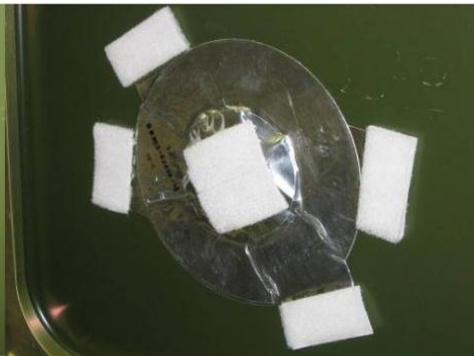
- Flexible Patch - Single and double thickness aluminum tape
- Rigid Patch - Dome-shaped aluminum plate with flexible seal

Flexible Patch

Single



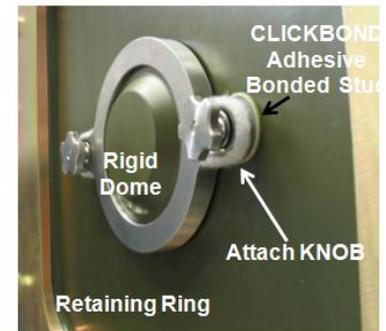
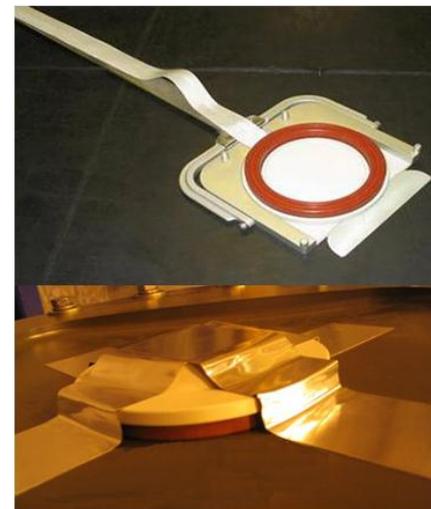
Double



Potential NDE Solution:

- Scan using ultrasonic shear wave from outside the patch
- Scan using low frequency eddy current array probe

Rigid Patch



Potential NDE Solution:

- Scan using ultrasonic shear wave from outside the patch before the second tape is applied





Damage Detection Requirements



1. Assess if a dome patch or tape is required, the initial hole size is needed (quick photo with damage and vehicle location/orientation ID)
 2. Assist in visibly locating the leak patch in difficult to access areas (e.g. between plate and pressure wall in utility areas) over the hole
 3. Assess the damage for information that can help fracture folks determine structural integrity, time to next inspection and repair needs/plans
- Inspection needs to provide:
 1. Bulge shape/orientation and position with respect to vehicle structure (3D map)
 2. Damage pattern with respect to the bulge(and vehicle structure) - thickness, shapes, etc. (3D map)
 3. Crack size, length, location (2D map)
 - **We mainly concentrate on the need #3 in this presentation**

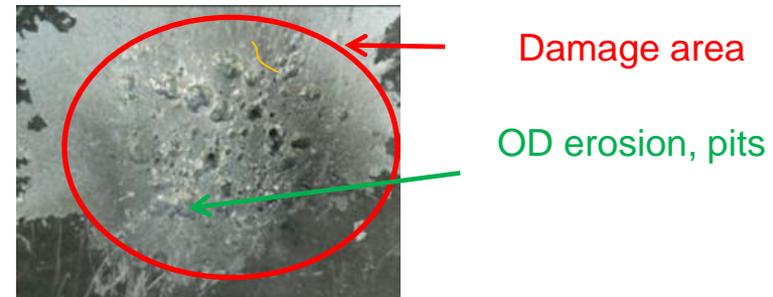
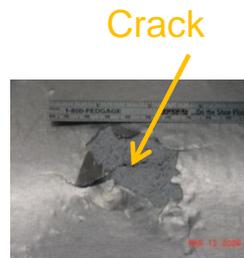
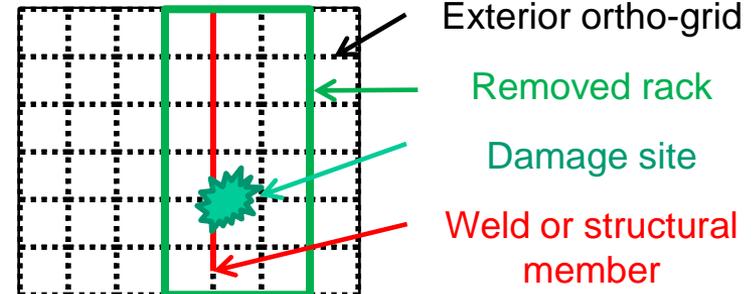




Damage Detection Requirements

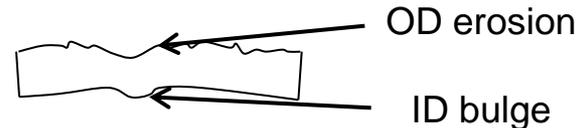


- Boundary Map: Location & orientation of damage with respect to the vehicle
- Bulge Map: Shape and orientation of any bulges due to impact
- Thickness Map: Erosion, corrosion, and pitting
- Crack Map: Crack location, orientation, length and depth



OD – Outer Diameter or Outer Mold Line
ID – Inner Diameter or Inner Mold Line

Cross section of damaged wall





Assessment of NDE Equipment for Use on ISS



The assessment focus is to recommend the optimal COTS NDE instrument for IVA applications.

- Manufactured a range of relevant test samples
- Demonstrated/evaluated how well different instruments can detect critical flaw types.
 - Evaluated six different portable instruments.
 - Three ultrasonic array systems, three eddy current systems.
- Evaluate on-orbit operational capabilities of each device.
- Evaluate potential certifiability of possible on-orbit instruments.

COTS – Commercial Off The Shelf



Photo of Astronaut Don Pettit scanning a curved machined plate with artificial flaws.





COTS Definition per SSP 50835, Revision D, Appendix M



- COTS is defined as commercially available hardware or software procured directly from a vendor or authorized distributor. COTS must meet the following criteria:
 1. Is portable (is not structurally mounted). Items mounted via a Bogen Arm are not considered structurally mounted.
 2. Has no design modifications to vendor configuration
 3. Has no reliability requirements
 4. Will be soft stowed for launch
 5. Is non-critical (2N, 2NR and 3)
 6. Contains only previously certified alkaline (maximum 12 volts / 60 watts) and/or coin cell batteries.
- Assessment
 - Ultrasonic Flaw Detector is considered to be “COTS”

COTS – Commercial Off The Shelf





NDE Test Articles and Standards

1. Ten Manufactured Standards Plates*:
 - a. Flaws: partial through the thickness holes (pits) and EDM notches (cracks)
 - b. Single flaws and multi-site flaws.
 - c. Flat with 1/16" and 3/16" thicknesses
 - d. Orthogrid waffle (FGB and SM)
 - e. Curved at 80" and 25" radii of curvature.
2. Five Hypervelocity Impacted Plates*:
 - a. Flat (1/8" to 1/4" in thickness)
 - b. Orthogrid waffle (FGB and SM)
3. Four bonded plates
 - a. Flat

*Scanned with and without repairs

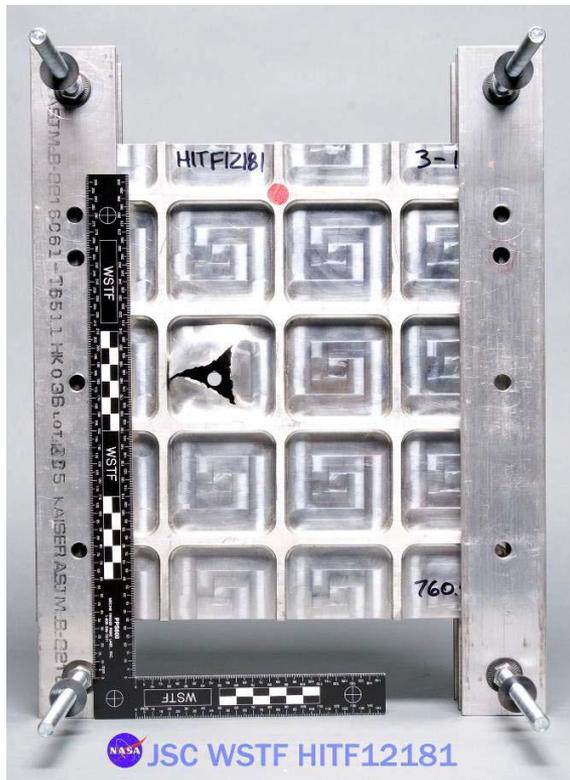




Impact Test Samples



Orthogrid Waffle on Russian Modules
Grid side
Flat Side



US Modules
Flat Plate



FGB and Service Module





Test Sample With and Without Repairs



Unrepaired surface

Tape repair

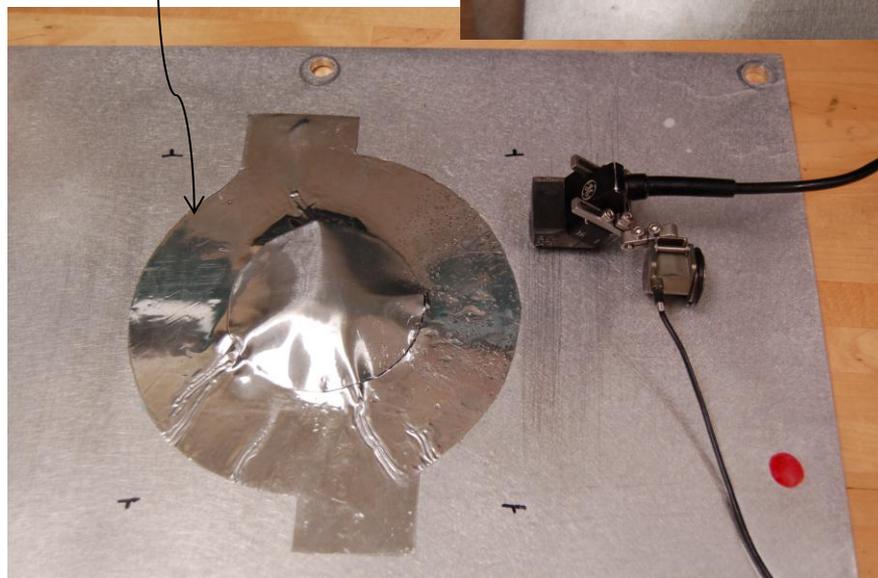


Plate repair



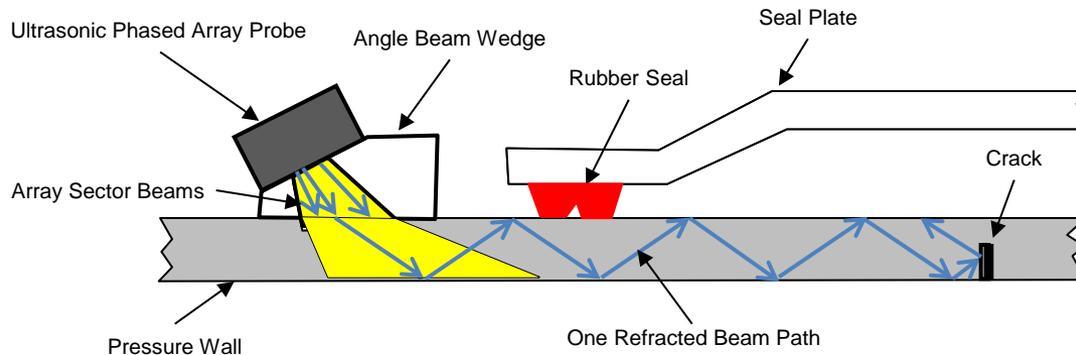


NDE Test Protocols

1. Ultrasonic Phased Array:

a. Angle Beam Wedge

- Bends the ultrasound at an angle into the plates.
- Can penetrate along the plate under the patches.
- Simple, quick, natural way to make a two dimensional image.
 - Mechanical scanner (encoder) in one direction.
 - Time in the second direction.
- Used on the manufactured standard plates and impacted plates.

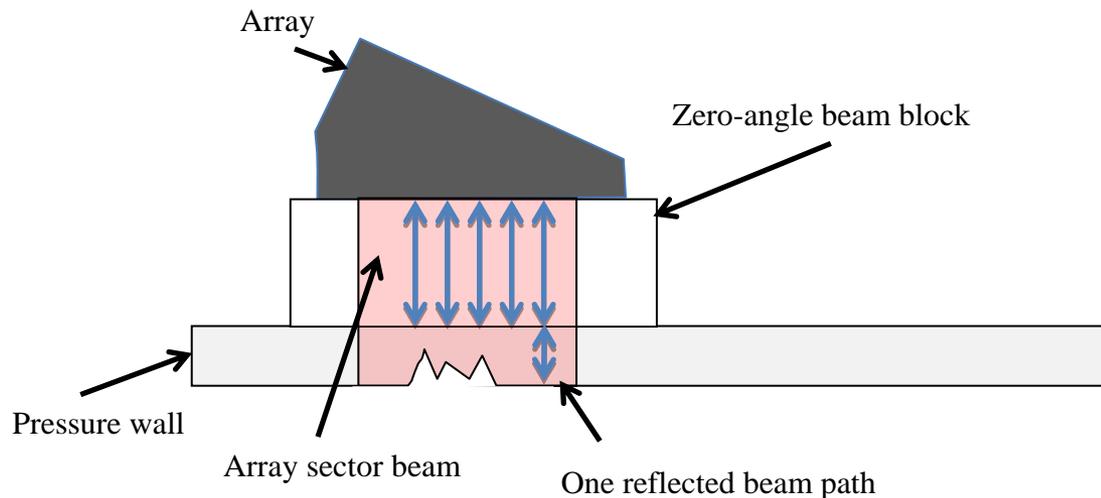




NDE Test Protocols

1. Ultrasonic Phased Array 0° Longitudinal Beam

- Used for bondline plates
- Useful when there is no patch to deal with
- Can measure thickness of a plate.

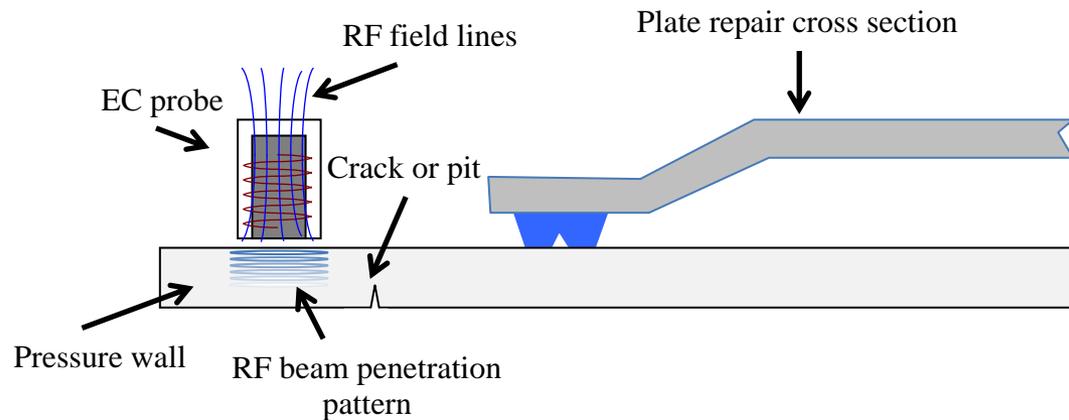




NDE Test Protocols

2. Eddy Current Scanners:

- Require that the probe penetrate through the aluminum to detect hidden damage
- Probe had to be very, very low frequency to work (skin depth limited)
- Couldn't work through the plate patch.

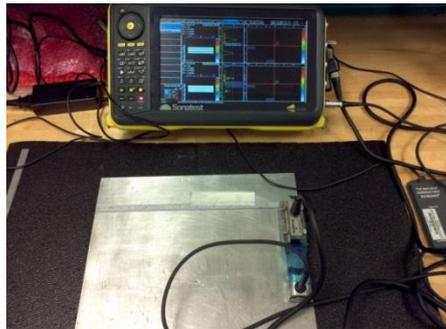




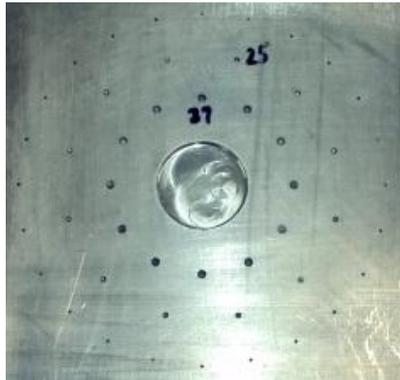
Examples of Ultrasonic Scans: Zero Degree and Shear Wave



Ultrasonic Zero Degree Scan

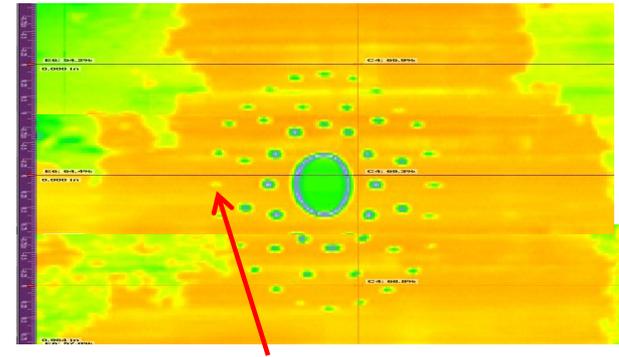


Sonatest Veo with
5L64 Transducer



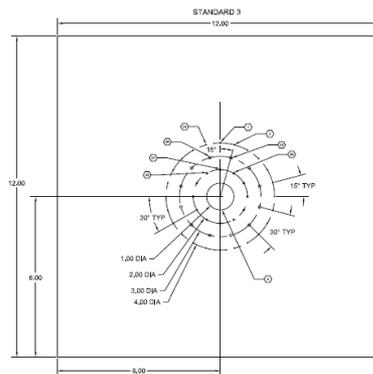
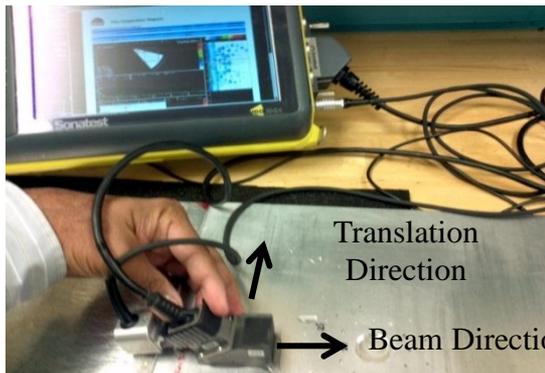
Standard 3

C-scan Display



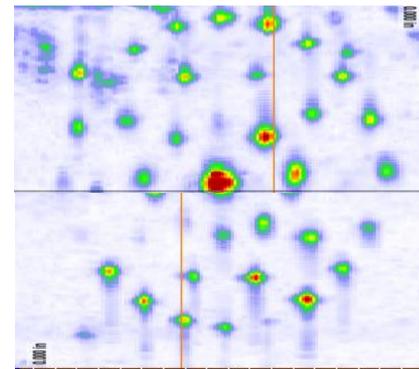
Smallest and shallowest hole
All holes were detected.

Ultrasonic Shear Wave Scan



Standard 3

Top Scan Display



Scan 1
Beam
Direction

Scan 2
Beam
Direction

Mosaic of
Two Scans



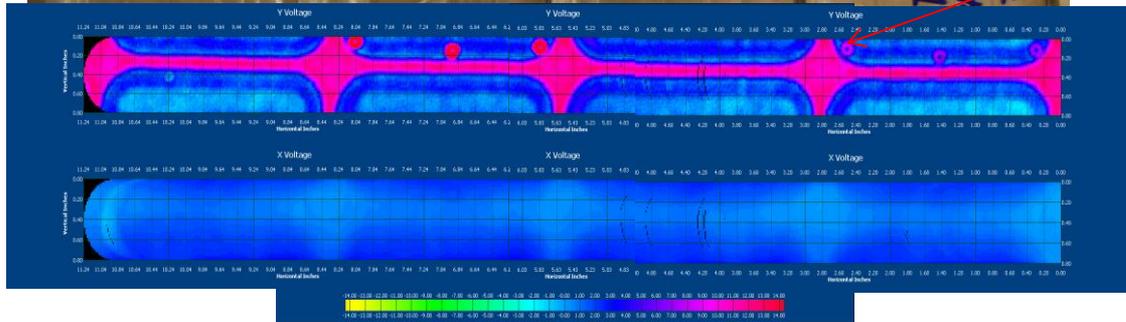


Eddy Current Scans on FGB NDE Test Standard with EDM Notches

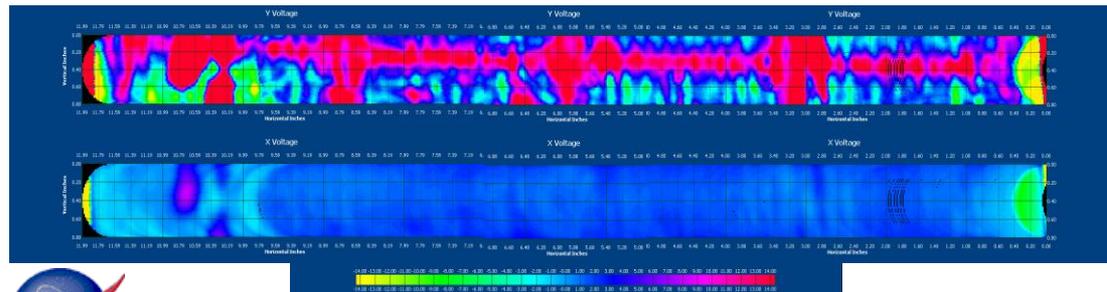


UniWest 454A ECS3 scans with and without repair tape attached.

Anomalies detected



EC scans made from IVA side without patches



Scans made from IVA side with tape patch (Some anomalies detected)





Engineering Assessment Considerations



Only the leading NDE instrument candidates were evaluated for:

1. Electromagnetic Interference
2. EMI Susceptibility
3. DC Magnetic Fields for Russian Launch Vehicles
4. Power Inverter Interface Requirements
5. Thermal Requirements
6. Materials and Processes Use and Selection, Off-gassing
7. Other
 - Sharp Edges and Corners Protection, Coin Battery Tracking, Cleanliness and Identification Labeling
8. Velcro Attachment Requirements





Conclusions from On-Orbit COTS NDE Equipment Assessment

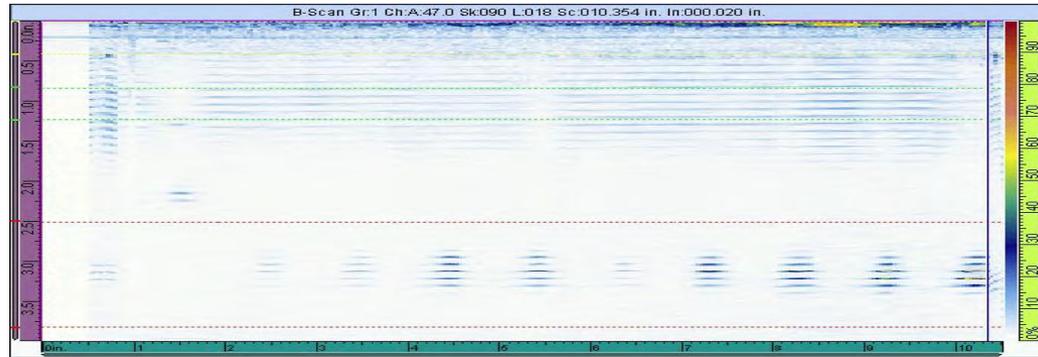
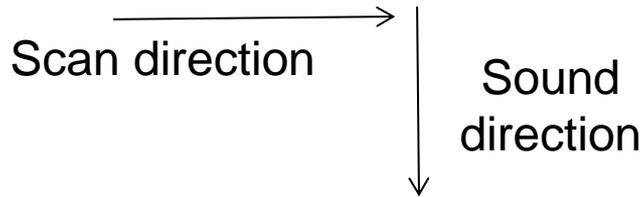


1. NDE systems evaluated were sensitive to detecting structural features such as orthogrid webs.
2. The systems evaluated were unable to detect damage directly adjacent to the orthogrid web under a patch.
3. Ultrasonic Phased Array systems were more capable than eddy current array/scanner systems in detecting and assessing damage from all the manufactured test plates and simulated MMOD impacts with the patches in place on ISS pressure wall specimens.
 - i. The Sonatest Veo and Olympus Omniscan MX-UT systems performed equally, while the GE Phasor had a software limitation.
4. The Sonatest Veo "Top-scan" saves the data from the different inspection angles, allowing additional analysis of the results on the ground.

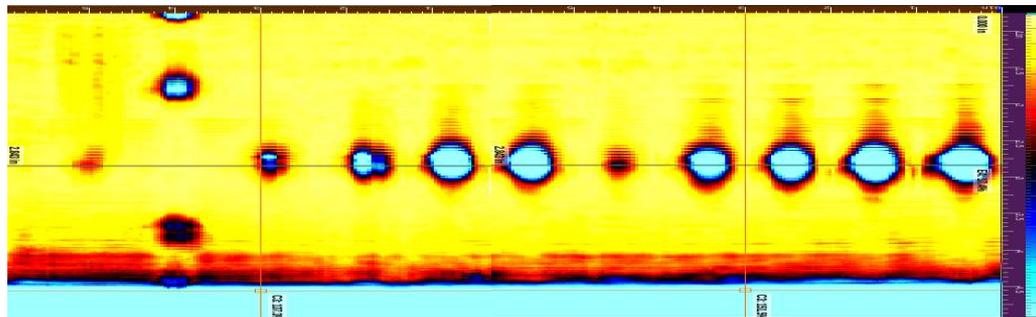




On-Orbit COTS NDE Equipment Assessment B-Scan versus Top-Scan



Omniscan MX
B-Scan Image
2 Mb per scan.
Only one ray direction.
Top Scan available
in post processing



Sonatest Veo
Real-time Top-Scan Image
26 Mb per scan.
Multiple ray directions

Real-time op-Scan Image is better for NDE evaluation





On-Orbit COTS NDE Equipment Assessment Astronaut/Operations Testing Findings



5. ISS crew, without any additional training, were able to quickly assemble and operate the NDE instruments evaluated using only simple one-page procedures.
6. The need for an additional computer for image display, as required by the UniWest 454A Eddy Current system with the ECS3 scanner was deemed more complicated than desirable for on-orbit operations.
7. Spring-loaded position encoders used in a zero-G environment will require a reaction force to keep the sensor in contact with the part undergoing inspection, which will complicate operations.
8. The probes/scanning components of NDE systems evaluated are too large (i.e. diameter and height) to permit inspections underneath racks and fixed structure and behind panels, which limit inspection regions (i.e. approximately 70 percent of U.S. module surface area and 30 percent of Russian module surface area)
9. All NDE systems evaluated were deemed usable, but a preference for the Sonatest Veo system was identified because of its simpler operating controls and computer-human interface, and the visual display.





Assessment of NDE Instrumentation for ISS-On-Orbit NDE Application

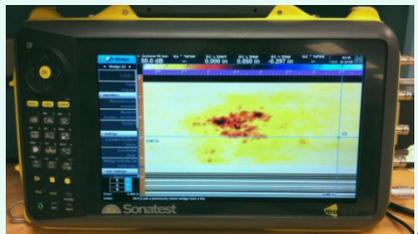


Ultrasonic Phased Array Flaw Detectors

1. Olympus Omniscan MX UT



2. Sonatest Veo

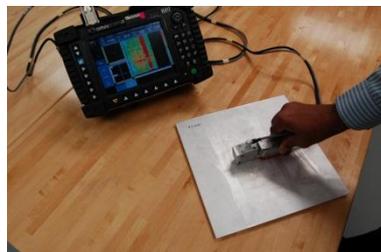


3. GE Phasor



Eddy Current Systems

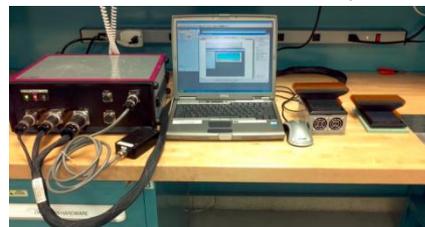
1. Olympus Omniscan MX EC Linear Array



2. UniWest 454A with ECS3 Eddy Current Rotating Probe Scanner



3. Jentek Sensors Grid Station, Linear Array



Six astronauts participated in the assessment and gave opinions on operations and suggestions for modifications

- Pettit, Walker, Metcalf-Linenburger, Fincke, Yui, Aunon
- Suggestions:
 - Try system out on zero-G flights.
 - Didn't like a spring loaded encoder (use an optical encoder?).
 - Want an edge guide to help with scanning.
 - Like water for a couplant (easy clean up).
 - Want simple procedures.
 - Emulate Human Research Facility (HRF) team's process.

Operations criteria:

1. NDE Crew Time for measurements
2. # Crew required
3. Setup/Tear Down Time
4. NDE Expertise/Training Required by Crew
5. Preventive/Calibration/Upkeep actions
6. Access Requirements
7. ISS Interfaces
8. Size (Storage and Access impacts)

Instrument Model	NDE Score 0 to 2	Ops/Astro. Score 0 to 5	Eng. Score 0 to 5	Net Score 0 to 20
Olympus Omniscan MX UT	1.62	3.15	3.95	11.5
Sonatest Veo	1.62	3.5	3.95	12.07
GE Phasor XS	0.98	2.7	N/A	2.65
Olympus Omniscan MX EC	0.2	2.45	N/A	0.49
UniWest 454A ECS3	0.07	2.2	2	0.29
Jentek GridStation	0.04	N/A	N/A	0

 Sonatest Veo was selected by NESCC Team based on the comparative evaluation of these instruments



On-Orbit COTS NDE Equipment Assessment Recommendations



The following NESC recommendations are directed to the ISS Program if a decision is made to utilize commercial field portable NDE instrumentation aboard the ISS to mitigate IRMA risk 4669.

1. Select the Sonatest Veo Ultrasonic Phased Array system for further testing, modification, and eventual certification for flight





Objectives in Phase 1 and Later Phases



- Provide capability to inspect ISS pressure wall for MMOD impact damage before and after leak repair
 - Phase 1: Ultrasonic Flaw Detector for ISS
 - Provide NDE capability in pressurized IVA environment to inspect areas where direct hand access is available in U.S. and Russian modules (70% of U.S. modules)
 - Provide 2-D scanning capability on U.S. modules (not a requirement for Russian modules due to interior ortho-grid but some coverage is possible)
 - Later Phases
 - Provide IVA coverage for areas within a reach of a ~3 ft. long custom reach tool
 - ♦ Custom scanner at the end of reach tool with attachment/hold-down mechanism
 - ♦ Scanner should work within the 1” gap underneath U.S. module stand-off areas and over the Russian module ortho-grid structure
 - ♦ Wireless encoder to improve ease of scanning operation





Ultrasonic Flaw Detector System Application Requirements and Performance Characteristics



- Ultrasonic Flaw Detector Application Requirements
 - **Capable of performing ultrasonic zero degree and shear wave scans on flat or slightly contoured (radius > 25') ISS aluminum pressure shell wall to provide evaluation of suspect MMOD damage and repair of the same. Ultrasonic Flaw Detector is not meant for detecting leak due to MMOD damage.**
 - Provide NDE capability in pressurized IVA environment to inspect areas where direct hand access is available in U.S. (estimated 70% area) and Russian modules
 - Capable of producing 2D scans on approximately 8" x 8" areas in presence or absence of a dome or tape patch repair.
 - See "inspection cases" and "damage detection requirements" for more details
 - Verify written procedures by scanning NDE Standard 3 and 5 on ground and on ISS (DTO)
- Veo Performance Characteristics
 - USB port on Veo and USB memory stick for data storage and file transfer
 - Verify on qualification unit
 - Other instrument performance characteristics per Veo (16:128) specifications
 - See "Veo specification" by Sonatest Inc.
 - Ethernet and VGA ports are available on Veo but are not planned to be used.
 - Verify on qualification unit





Physical Interface Requirements

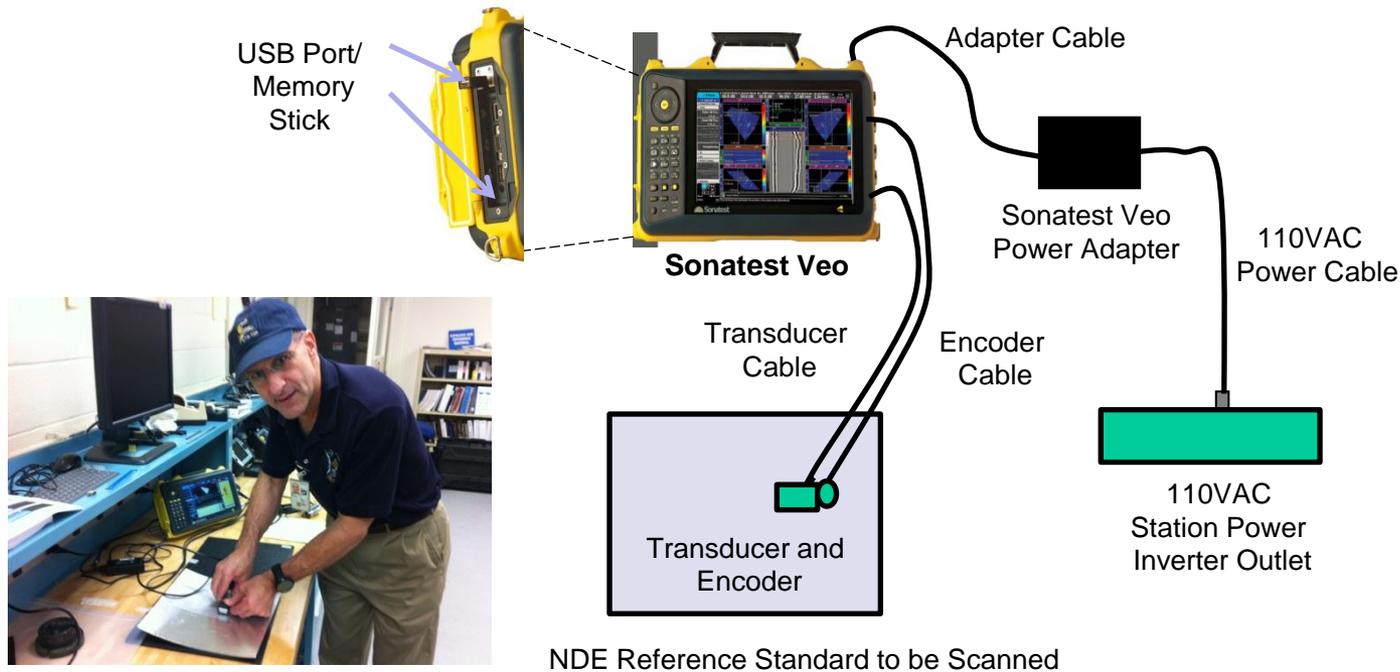


- Restrained on-orbit by a Nylon hook-and-loop fastening system, “Velcro”™
 - Use Velcro on Veo, NDE standards, transducer cables, encoder cables, soft cases etc.
- USB memory stick is used for data storage and file transfer
- Interface to the power inverter in USOS providing 110 VAC output for Ultrasonic Flaw Detector. Battery is not used to power the instrument.
- An ultrasonic transducer would contact the inspection surface. Potable water (approx. 1 teaspoon) is used as a couplant. Use water from crew drinking water bag. Water is preferred by crew over gel type medical ultrasound couplant Aquasonic 100 which is available on the ISS.
- An encoder (wheel) would contact the inspected surface during scanning.
- A 300mm steel ruler would be taped to the surface to act as a guide for scanning and to provide scale in photographs of the inspected area.
- A crew member would hold the transducer/encoder assembly in one or two hands and scan the part surface. A second crew member may be needed to operate the Veo instrument and assist the first crew member as needed. One crew member may be sufficient for the ISS demonstration of ultrasonic scanning on test pieces but if used in actual inspection of the pressure wall, two crew members would likely be needed.





Ultrasonic Flaw Detector System Configuration



Astronaut Don Pettit
Scanning an NDE Standard

Hardware Criticality: 3

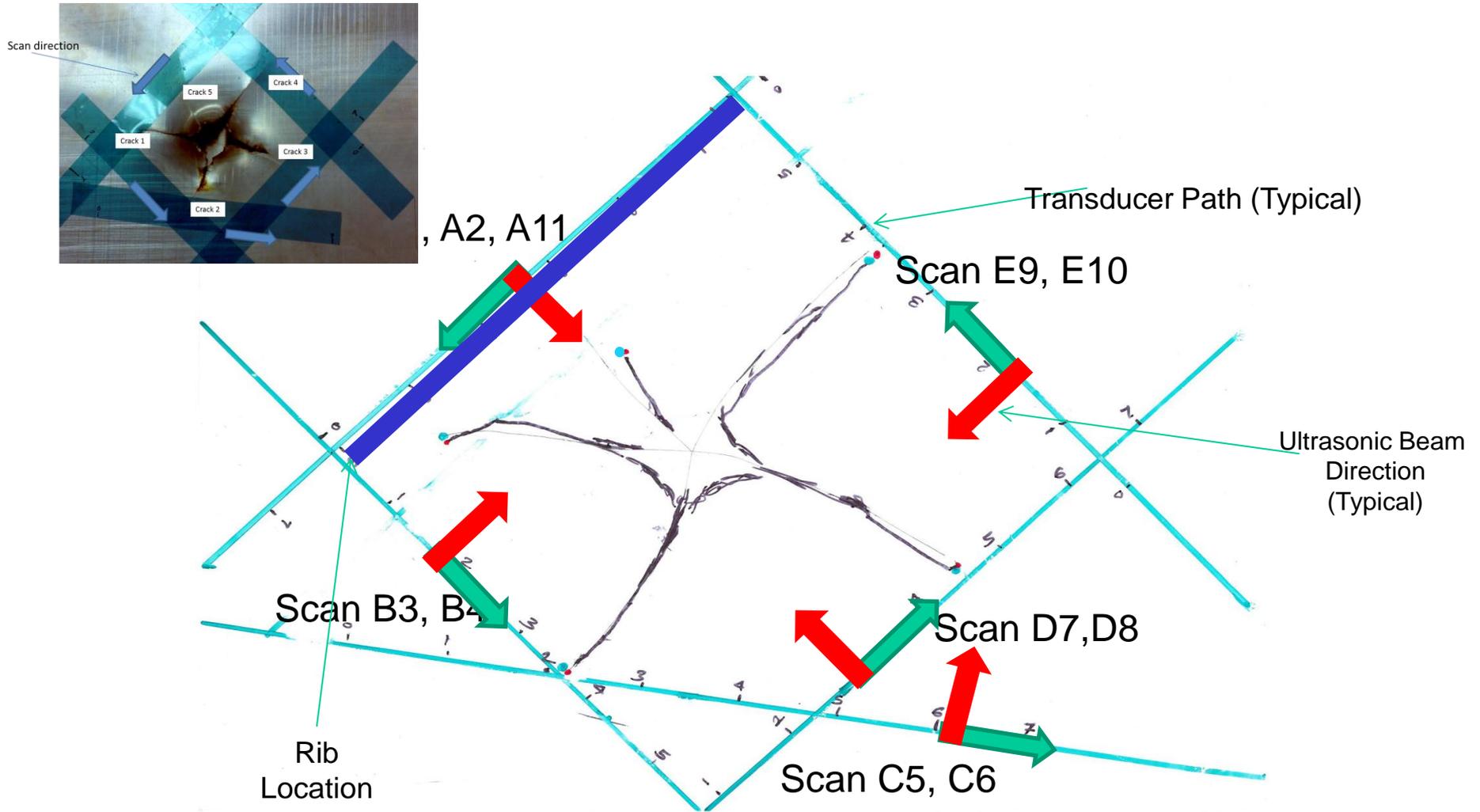
Software Classification: C

Software is contained within the Sonatest Veo instrument. There is no requirement to communicate with a laptop.





Damaged Plate, Shear Wave Scan Paths and Template

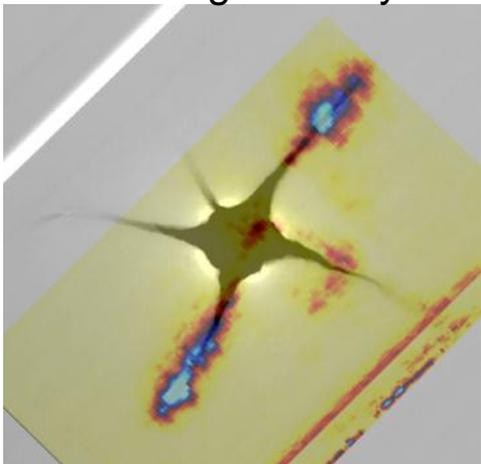




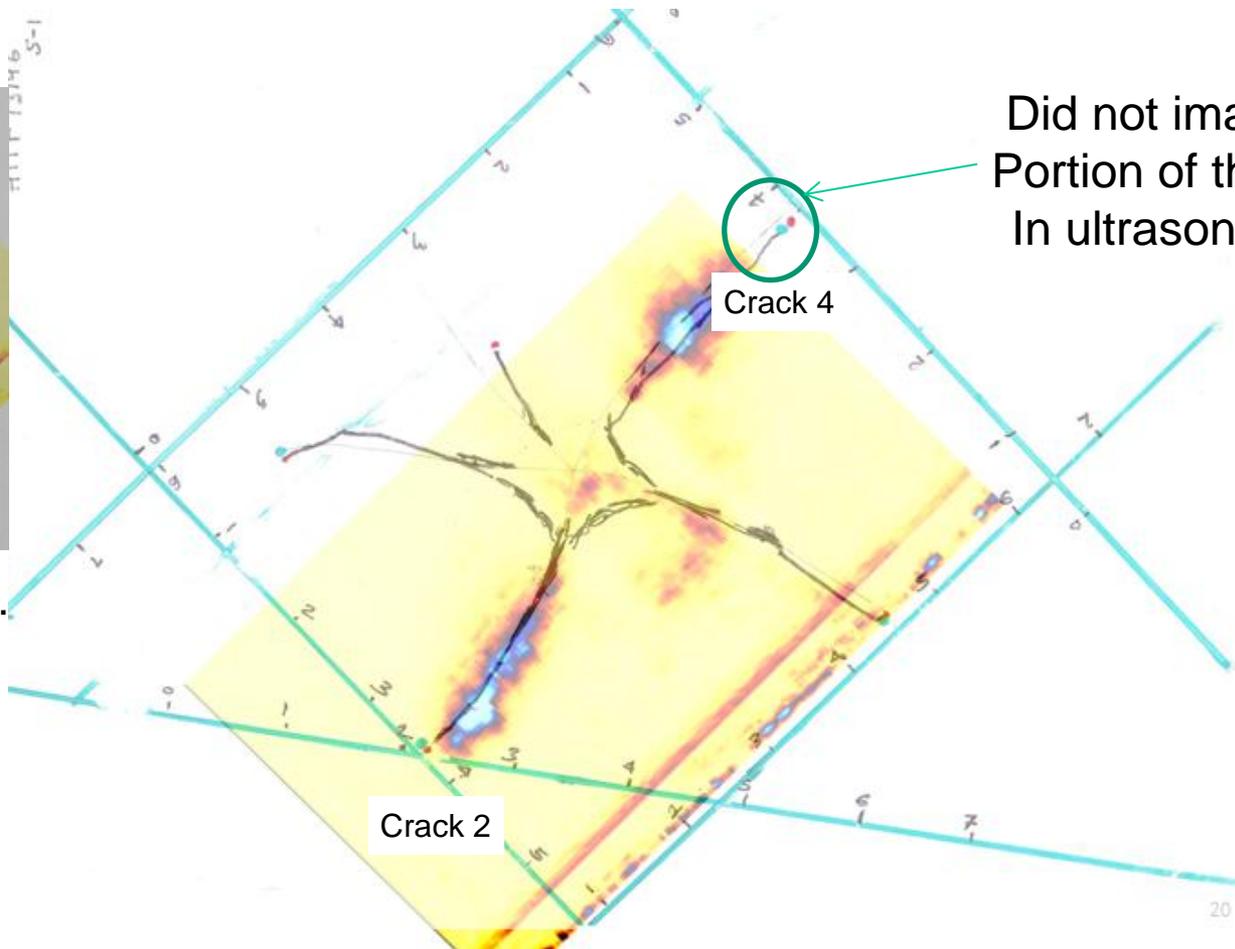
Scan Superimposed on the Scan Template



Scan D7 Superimposed on Digital X-ray



Cracks 2 and 4 Detected.



Did not image this Portion of the crack In ultrasonic scan

Crack 4

Crack 2

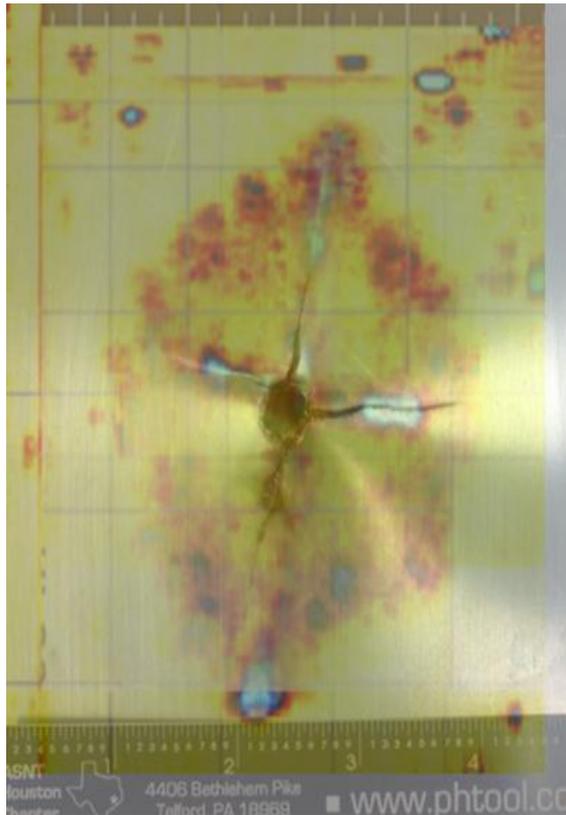




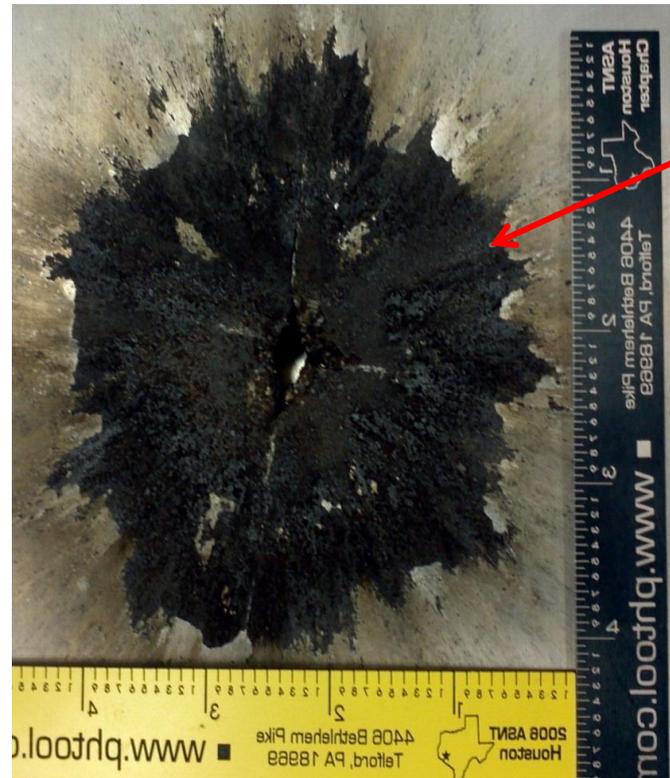
Example of C-scan Image Comparison With Damage Photo



Superimposed Scans



Mirror Image of Impact Side Photo



The photo image matches with the superimposed scan image approximately. Ultrasonic scan shows considerable variation in the signal response from the cracks. Crack orientation, depth and other damage in the path of ultrasonic beam influences the ultrasonic signal amplitude from cracks. Overall damage area given by the ultrasonic scan matches (+0.0, -0.4") with the visually observed dark soot region.

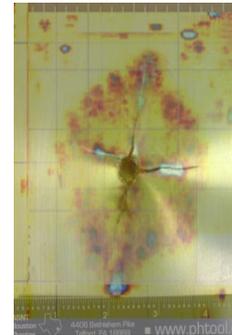




Conclusions and Recommendations



- Ultrasonic and eddy current Scanning are viable for IVA NDE applications however many improvements are necessary
- Array eddy current systems need to become compact
- Wireless or non-contact encoder would be desirable so that the astronaut does not have to move the encoder with transducer.
- Access under the ISS racks or corner panels is very limited. Need NDE device on a stick.
- Software to mosaic, merge and superimpose NDE scans and images is needed.



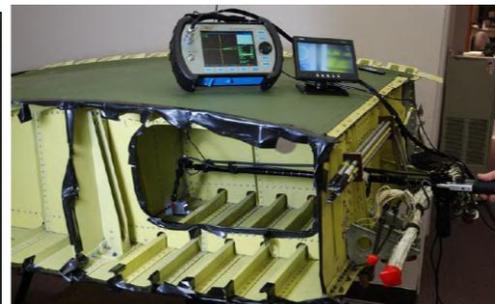
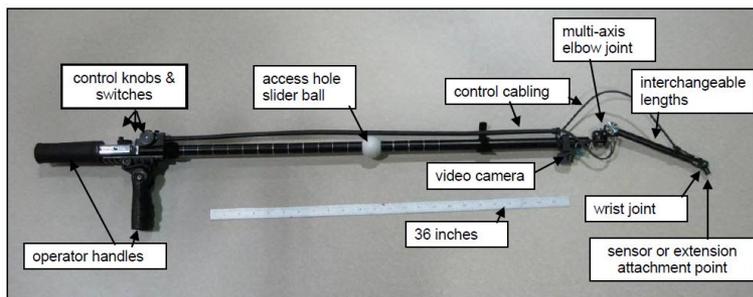
Mosaic, Merge, and Superimpose Scans and Images (Shown: Manually Superimposed Composite Image)



Wireless Tracking or Encoder Sensor (Shown IR Sensor)



Wireless Tracking or Encoder (Shown Visible Light Camera Tracking)



NDE Reach Tool (Shown: Uniwest/Boeing/US Air force Surgical NDE Tool)



List of Enhancements Needed for IVA and EVA Inspections



1. Eliminate wheeled encoder. Implement "wireless" or optical/infrared encoders
2. Lower profile transducers and scanners that can be attached to reach devices
3. Scan superimpose, mosaic and merge software.
4. Software/new camera sensors that can create a 3D map from simple camera/borescope "pictures" of the damage.
5. Visible inspection in difficult to access areas - reach tools, more control for existing videoscopes, tiny rovers, 3D - see where to position patch with the tool.
6. Monitoring inspection devices and procedures after initial damage inspection.
 - Post inspection monitoring for damage change detection - e.g. Metis sensors installed to trigger inspections
7. Penetrating imagers - see damage through a metal barrier - Aluminum tape patch, aluminum dome patch or through the thicker plate that is near the pressure wall along the utility runs
8. Making it possible for the astronaut to operate equipment with both hands and not float away - temporary adhesion for feet/knees.
9. Glue-less temporary adhesion for sensors

