# Recent Progress on 3D Backscatter X-Ray NDE

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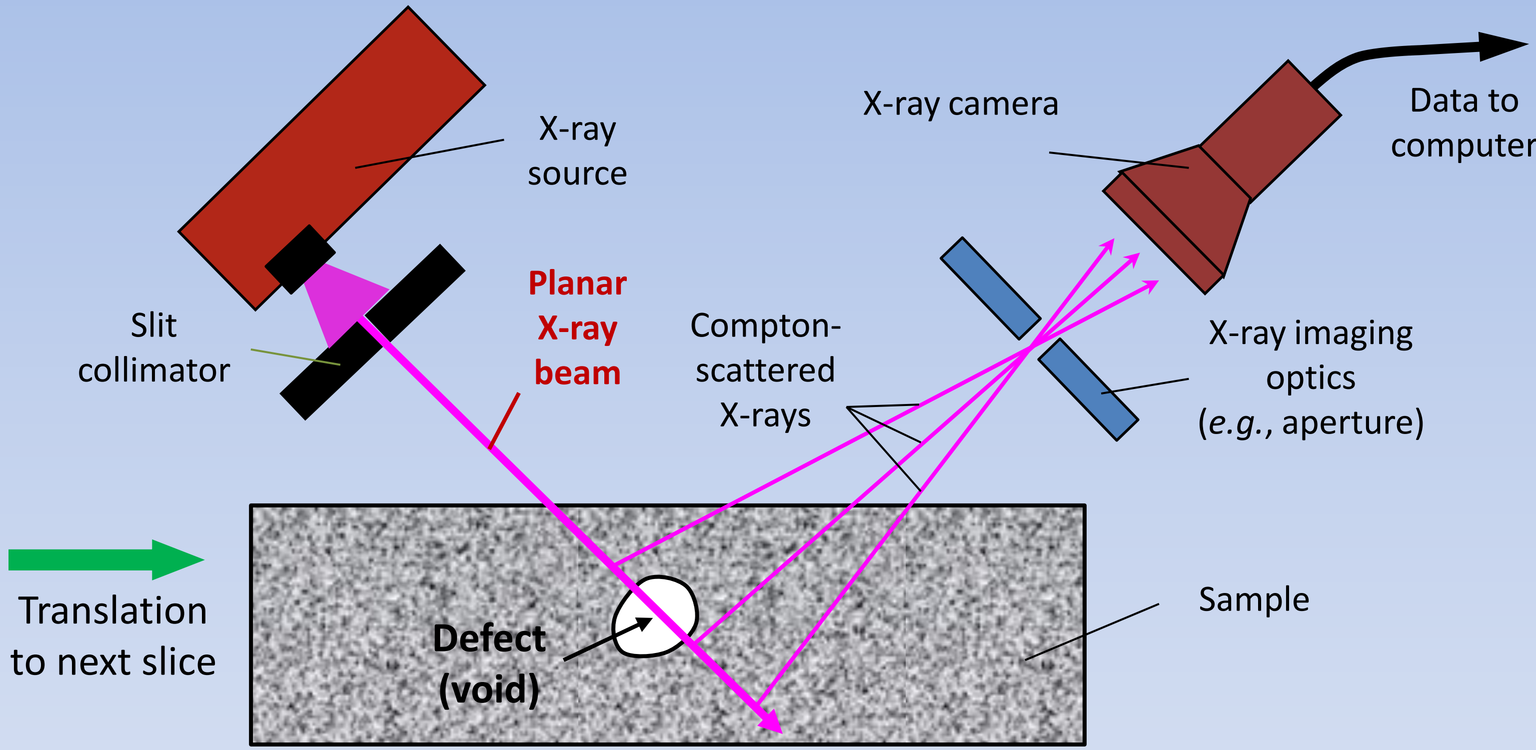
# Typical Aerospace Industry NDI Requirements:

- NDI of large structures (need one-sided approach)
- NDI of nonuniform, multilayer, or composite structures
- Applicability to conductive and nonconductive materials
- 3D defect detection and visualization capability
- High resolution and contrast
- Noncontact operation

# One-Sided 3D NDI Using Compton Imaging Tomography (CIT)




- Unlike other Compton backscatter methods, **permits 3D imaging**
- Structure is acquired slice by slice, with subsequent stitching into 3D density map
- 3D data can be visualized **plane-by-plane** or via **volume rendering**

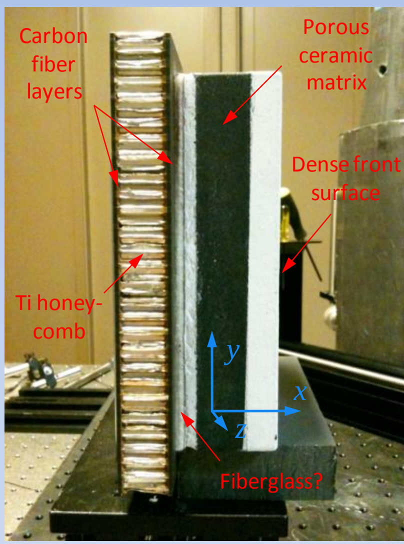
# Main Features and Advantages of CIT

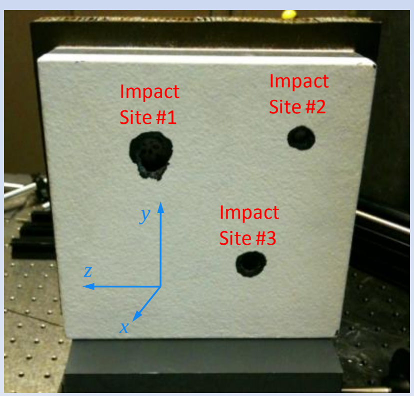
- Based on **X-ray Compton scattering**, rather than transmission (as in conventional radiography)
- **Single-sided operation:** suitable for large aerospace components
- Works well with **multilayer and composite structures**, conducting and insulating materials, no problems with air gaps
- **3D defect detection** and localization with sub-mm accuracy
- High penetration in typical lightweight aerospace materials
- Easy-to-interpret output, with possibility for **3D data visualization**

# CIT Applications and Results

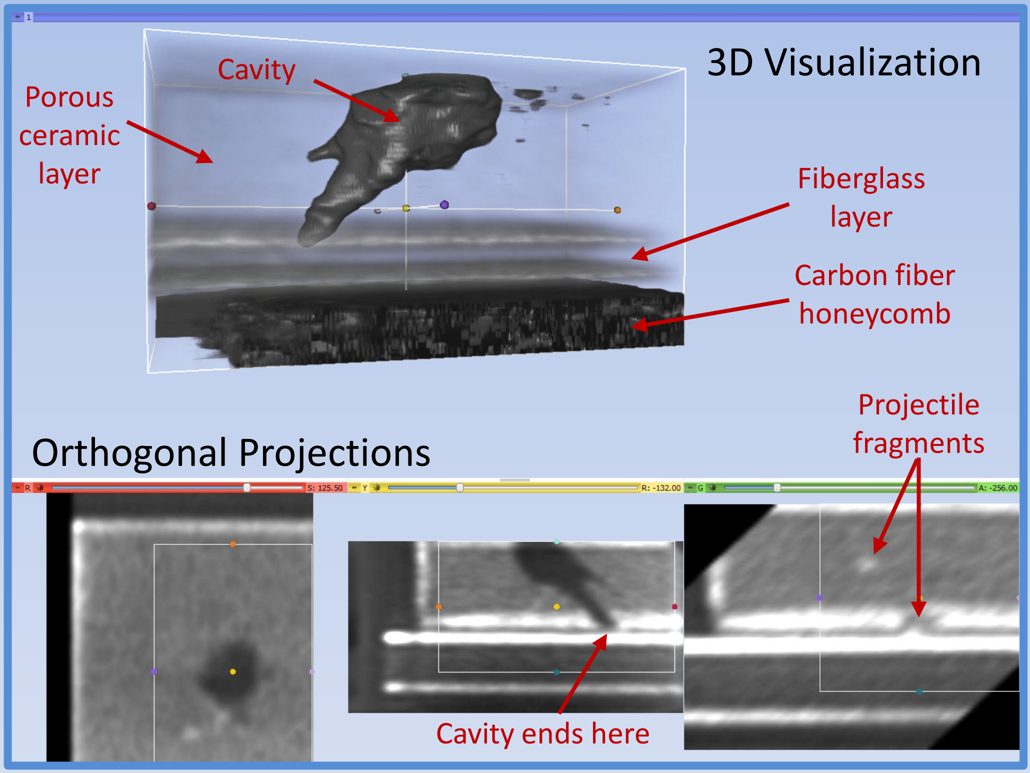
# 3D Inspection of Spacecraft Thermal Protection System (TPS)

## NASA AETB-8 Tile



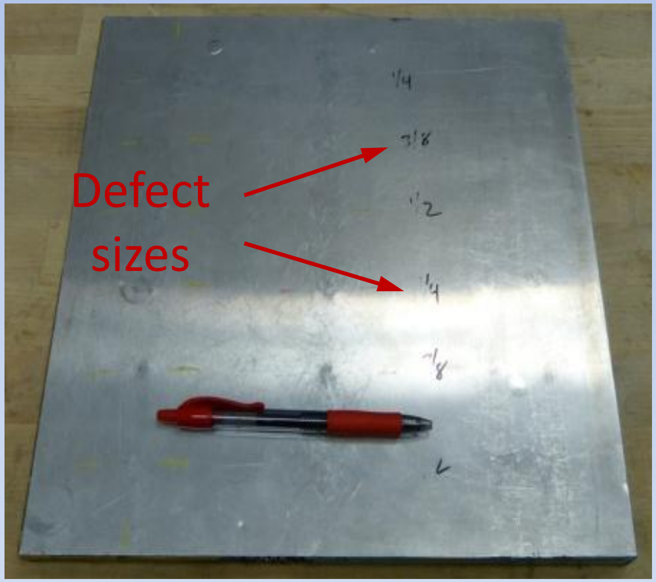



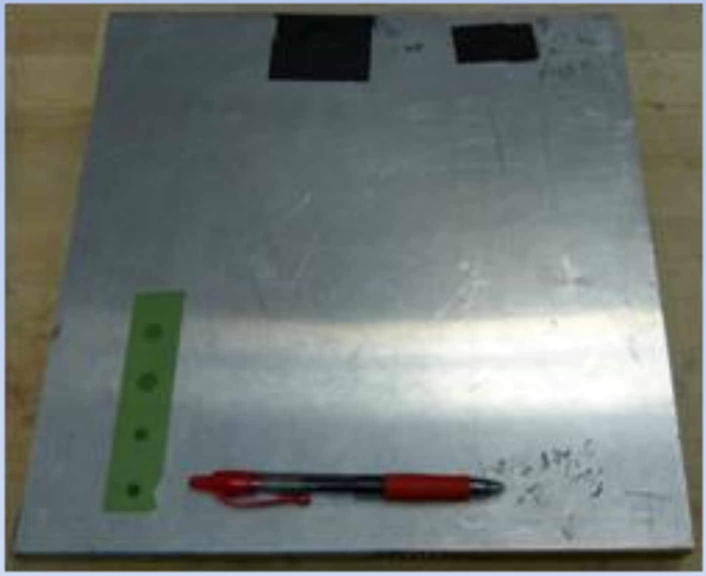

## Impact Site #1




- ❑ Preflight and postflight TPS inspection
- ❑ *In-space* detection of critical micrometeoroid damage in TPS before re-entry

# NDI of Aluminum Honeycomb Structure: Sample



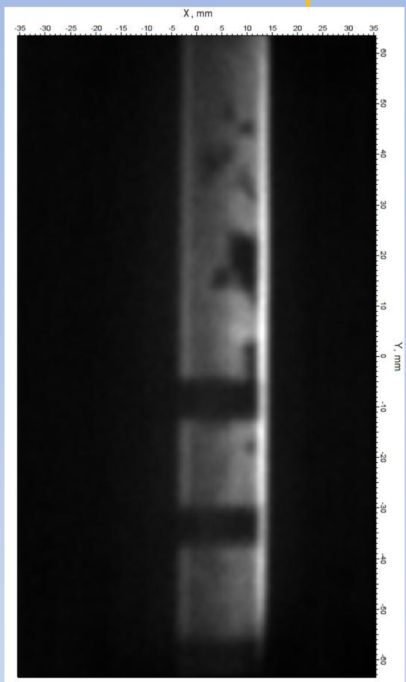
**Dimensions:** 300 x 300 x 16 mm

**Cell size:** ~4.4 mm

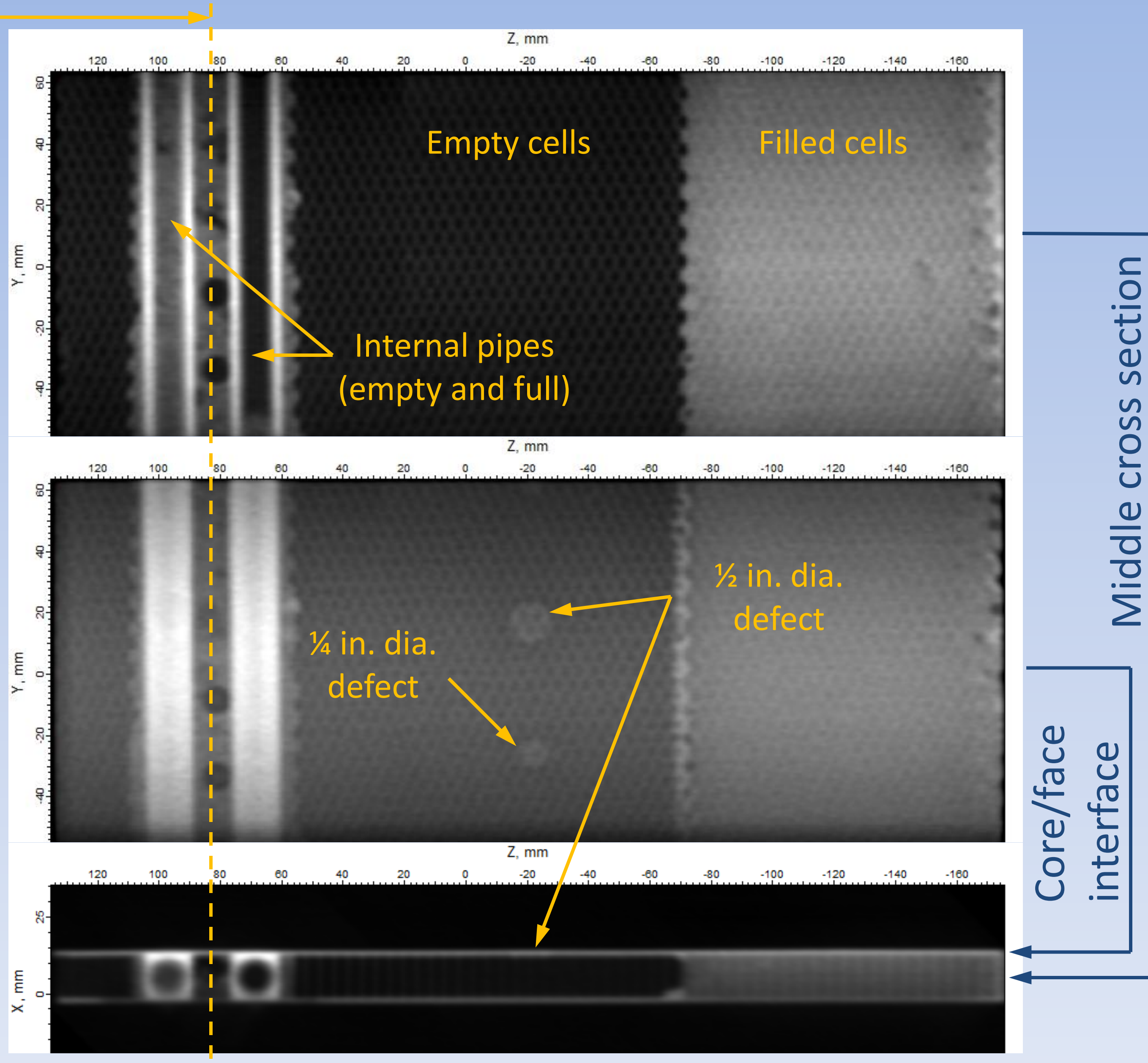
**Built-in defects:** simulated delamination (Teflon inserts), *~200 μm thick*

# NDI of Al Honeycomb: Results



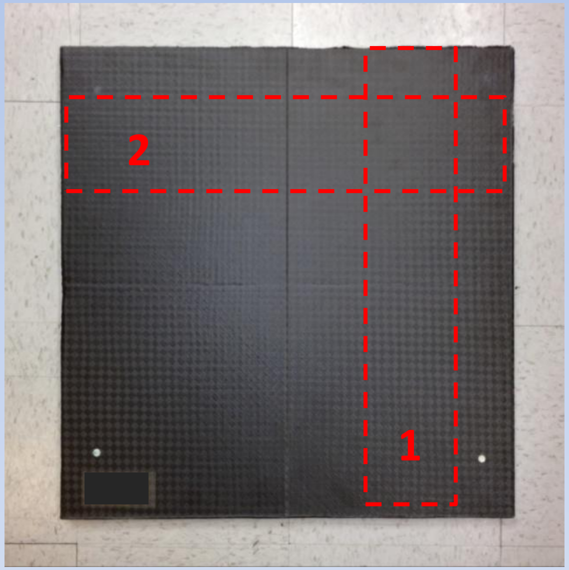



Side cross section (x-y)

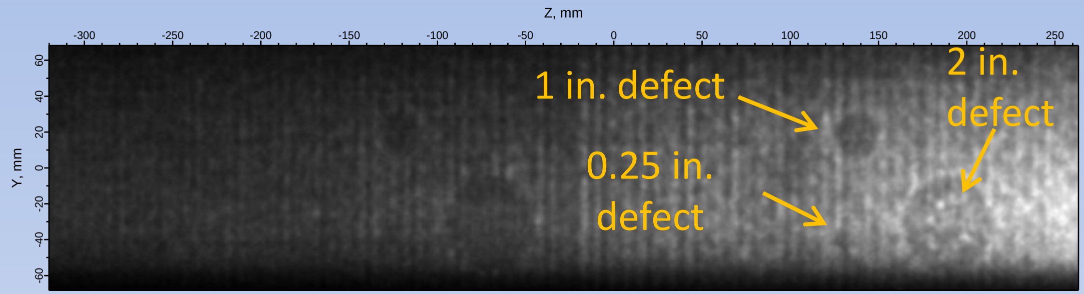


# Detection of Defects and Disbonds in Composite Honeycomb Structures

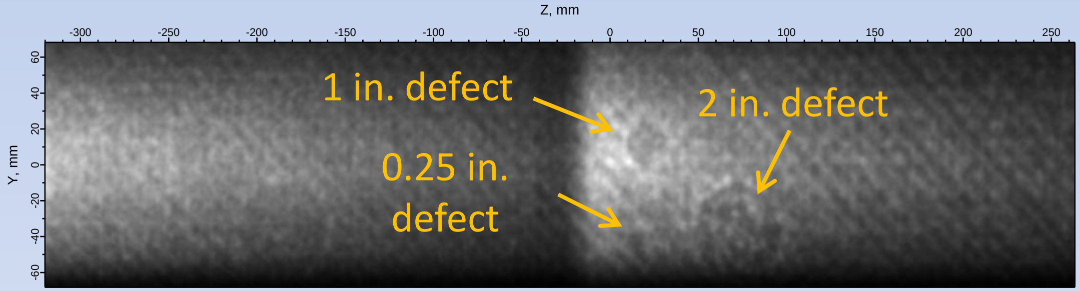
**Spacecraft payload fairing sample**




Area 2, Front Side




Area 2, Back Side

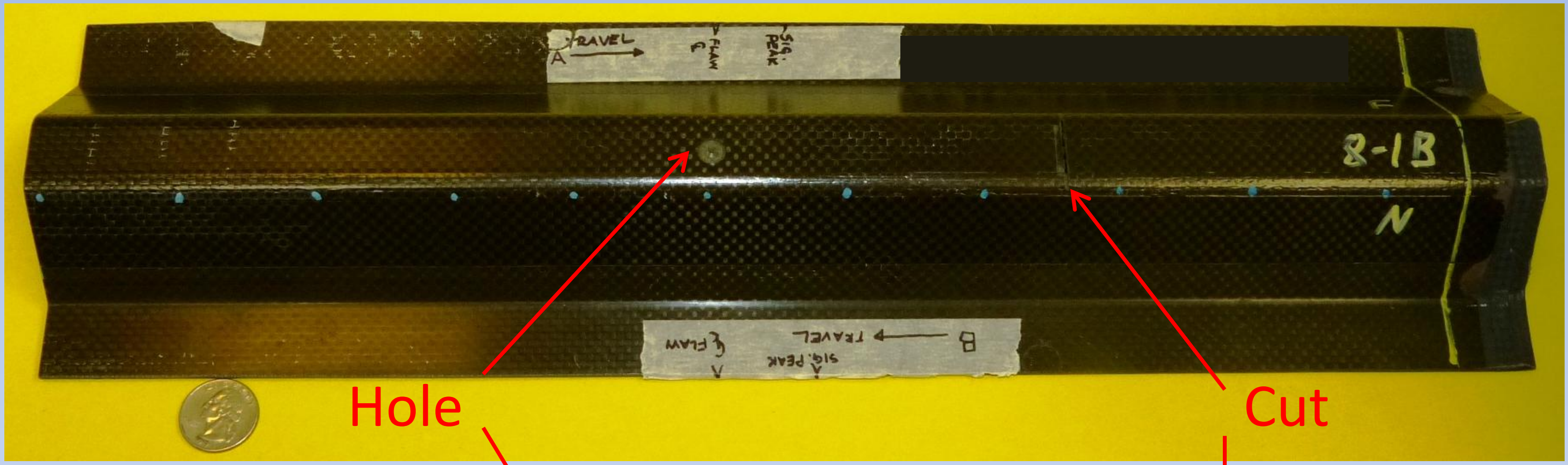



- ❑ Applicable to any honeycomb materials
- ❑ **Scans both sides at the same time**
- ❑ Detects disbonds as thin as **3 mil (75 µm)**
- ❑ Current scan speed ~1 hr/ft$^2$, potential speed **~1-4 min/ft$^2$**

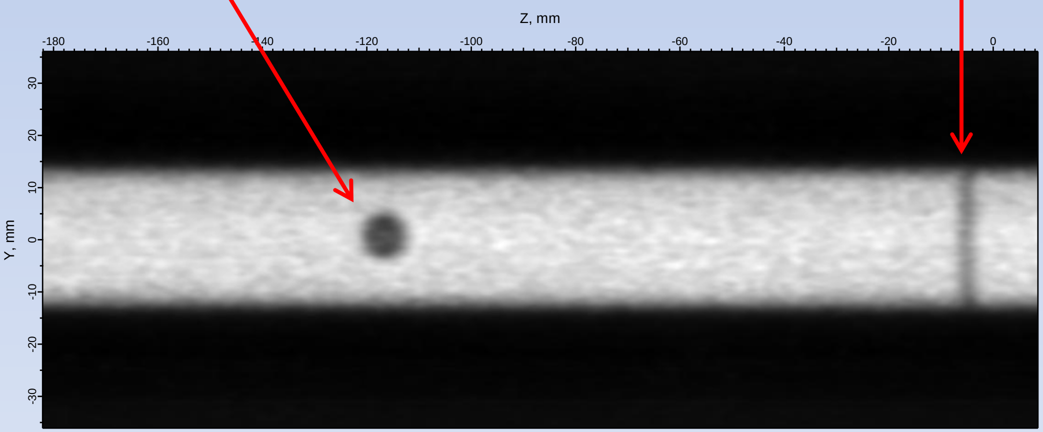
# NDI of Carbon Fiber Aircraft Components Through Air Gaps



***Back side** of the sample*

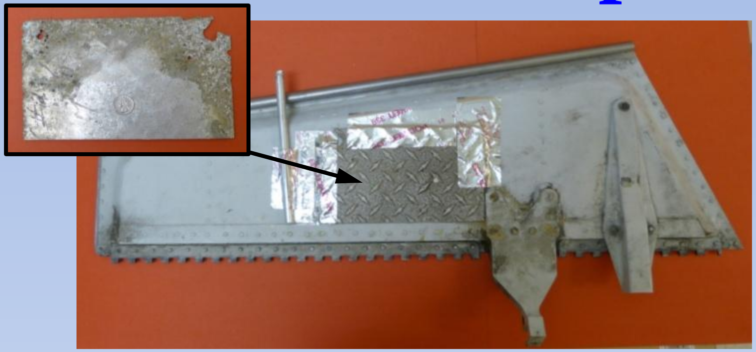



CIT image of the back side, taken ***from the front side***

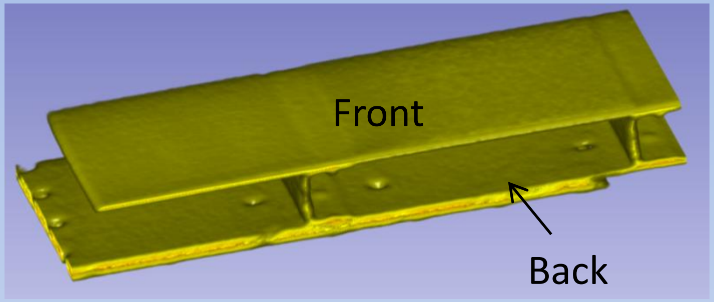



**CIT is currently the only technology capable of detecting defects in inner layers through air gaps**

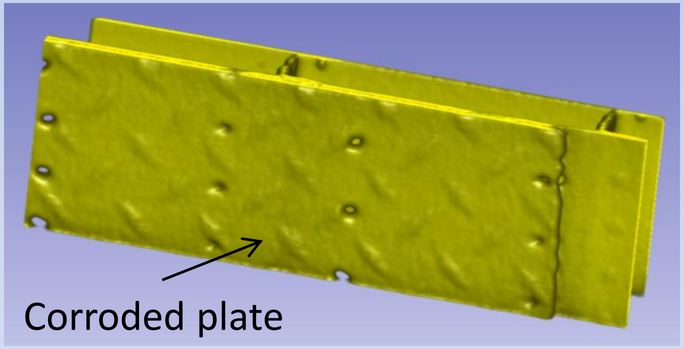
# Corrosion and Defect Detection in Multilayer Aerospace Components



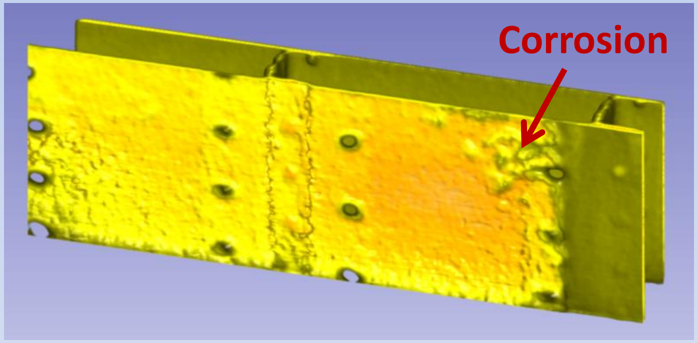
**Aircraft part with corroded plate attached to its back**




**Reconstructed view with front side (*scan side*) on top**




**View from back**



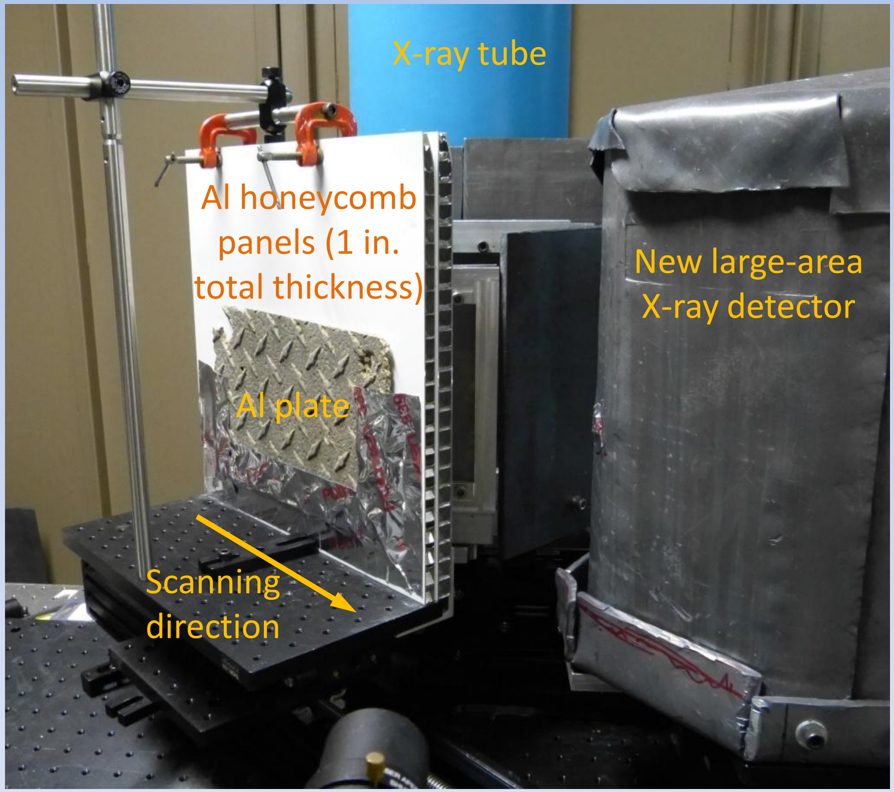

**Corrosion exposed by slicing through the attached plate**

Corrosion can be nondestructively detected in hard-to-access locations of aerospace components by inspecting 3D images for abnormal density variations

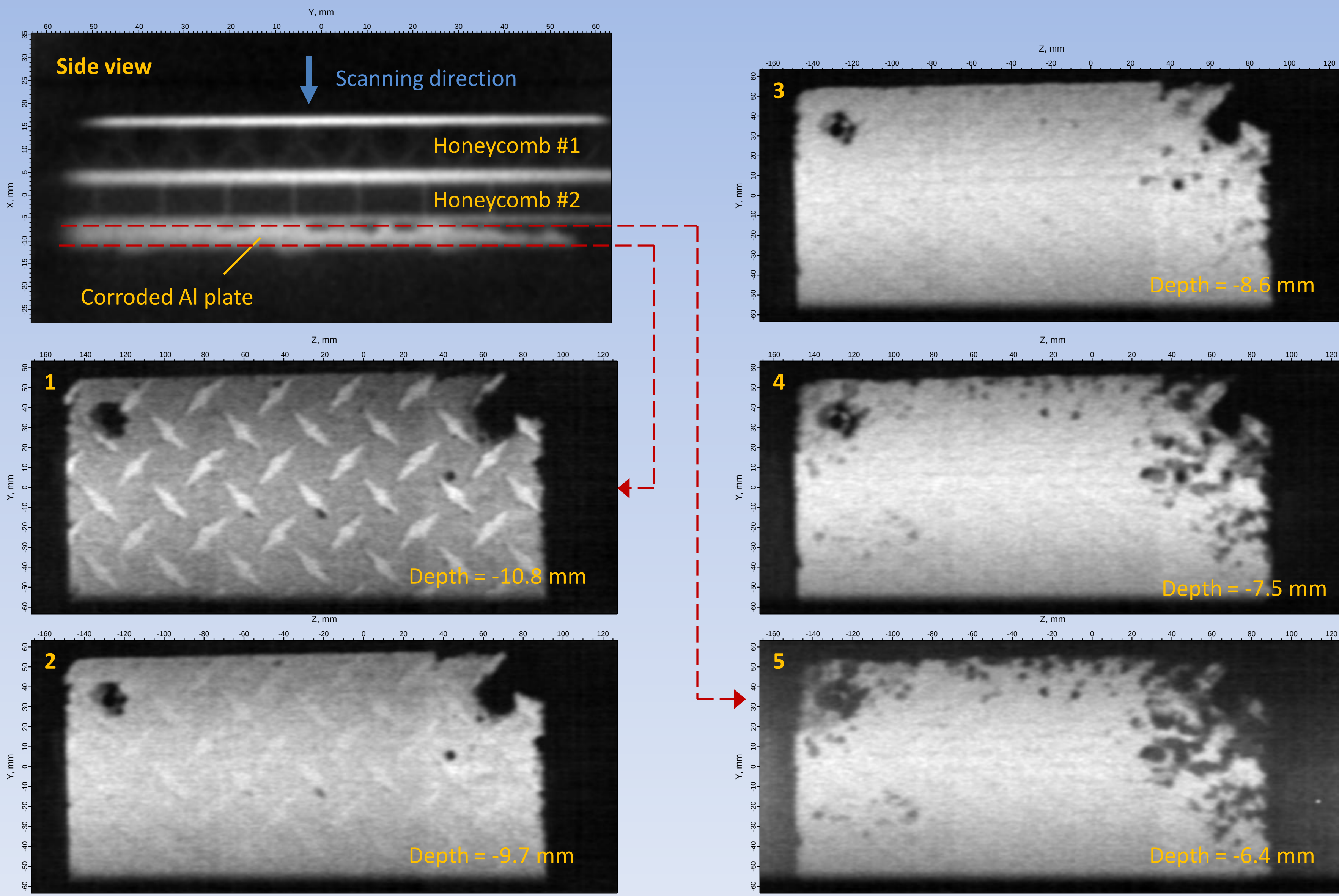
# Corroded Diamond Plate Behind Honeycomb Panels: Experimental Setup

Corroded Al Plate (Front)

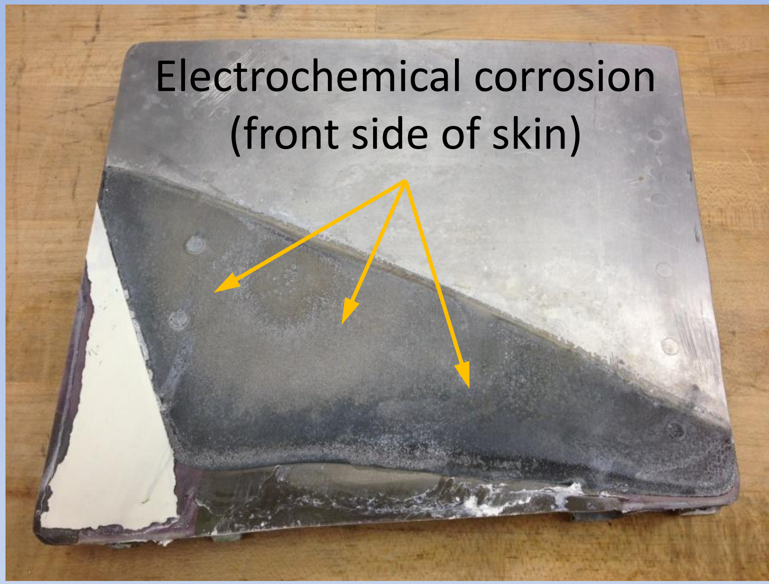
Corroded Al Plate (Back)

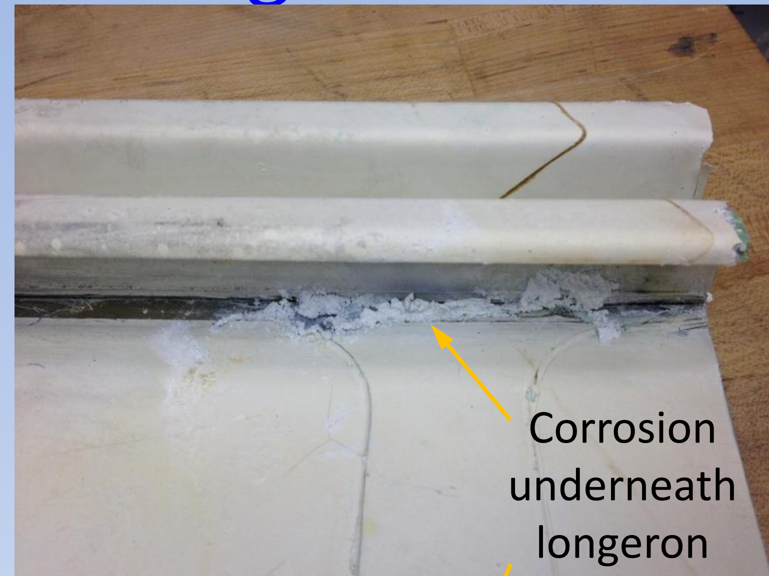


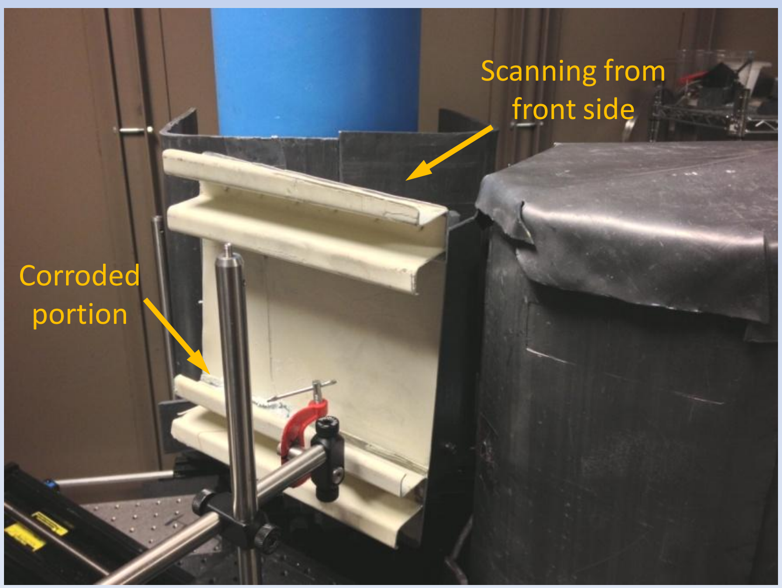
# Reconstructed CIT Cross Sections of the Corroded Diamond Plate

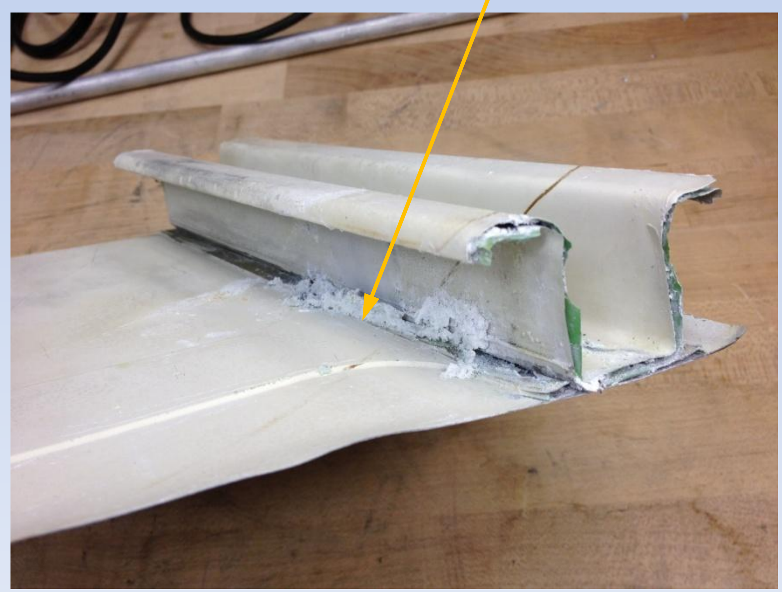


# Corroded Aircraft Fuselage Section

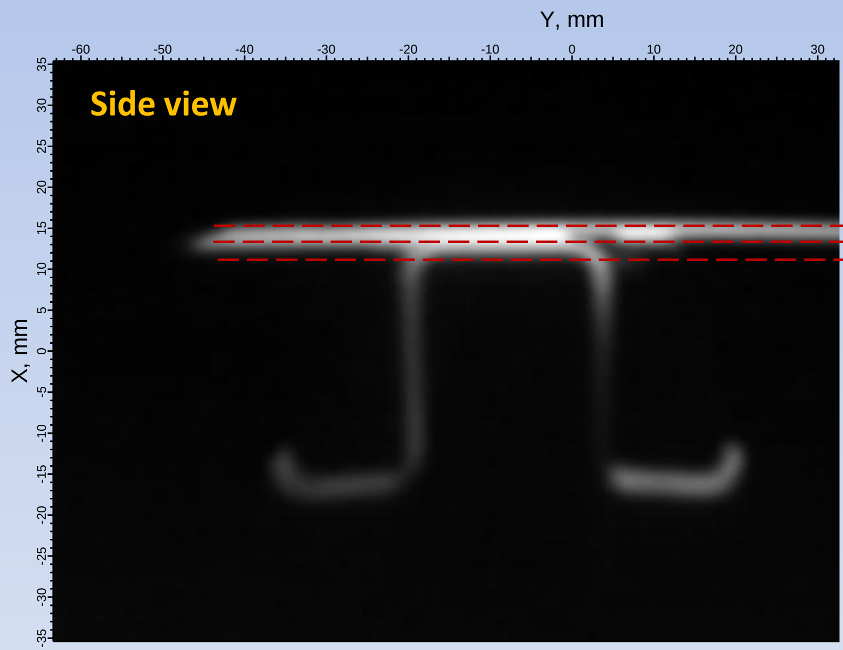


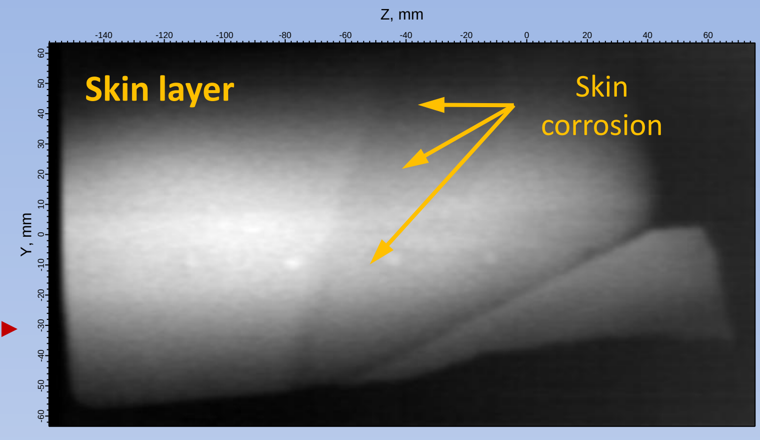



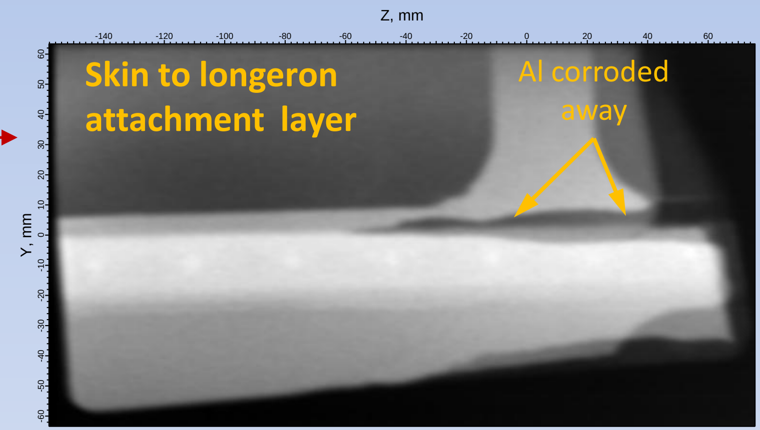



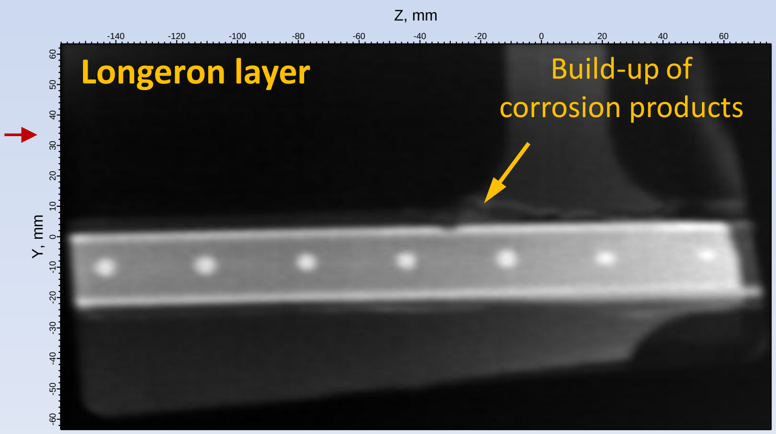



# Reconstructed CIT Cross Sections of Corroded Fuselage



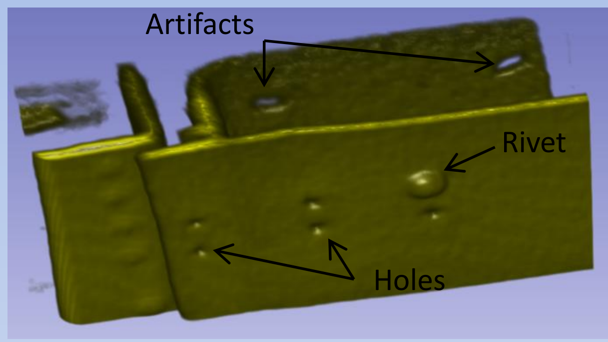



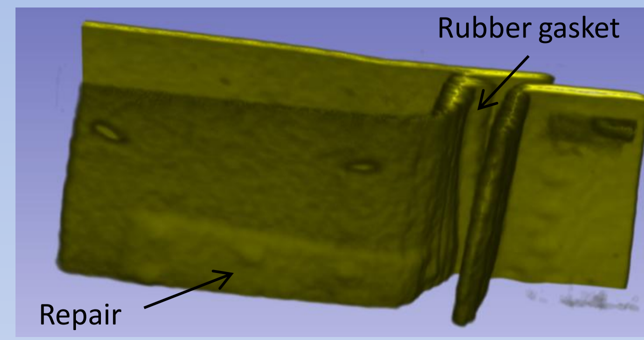



# 3D Imaging for FOD Detection and Reverse Engineering

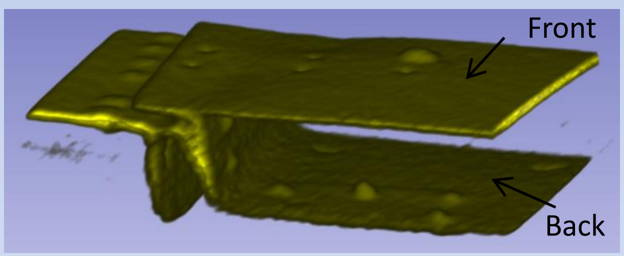
## 3D Visualization of an Aircraft Door Section



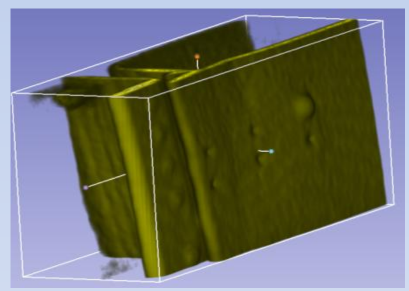

**Front view**

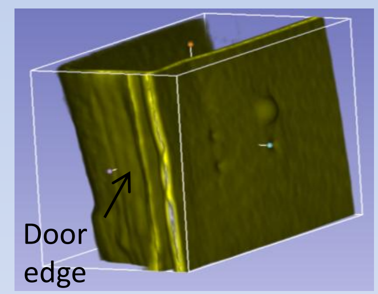



**Back view**




**Bottom view**





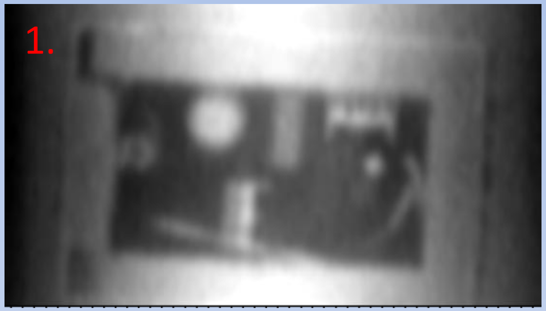

**Side views:** whole structure (*left*) and exposed door edge (*right*)

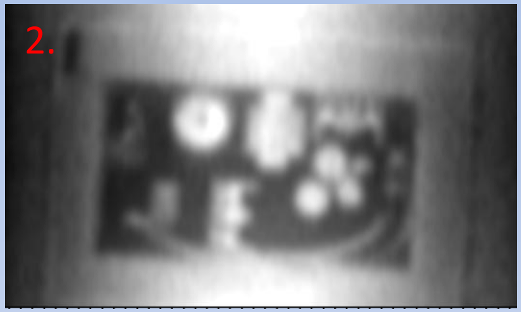
- One-sided scanning achieves tomographic **3D imaging of large components *in situ***, without their disassembly or removal
- Convenient GUI provides easy 3D manipulation and virtual dissection

# Underwater NDI

Sealed electronic circuit attached to a surface underwater


## 3D Reconstruction at Various Depths



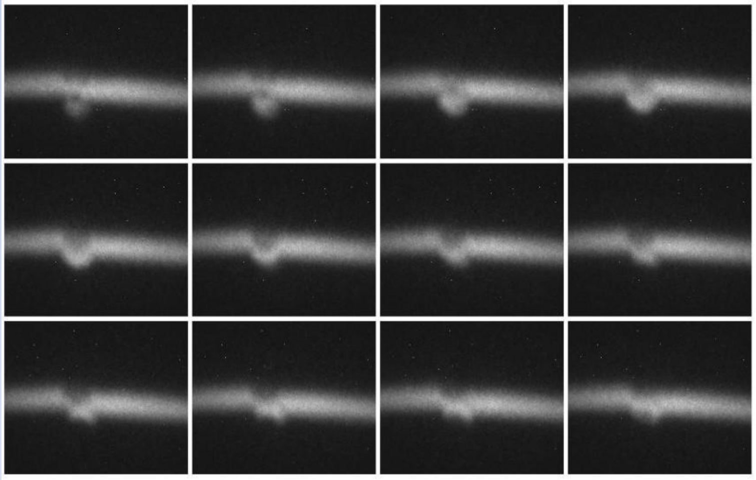



- ❑ Facilitates underwater structural analysis through **non-contact, one-sided 3D imaging of internal structure**
- ❑ 3D rendering of internal electronics structure is possible

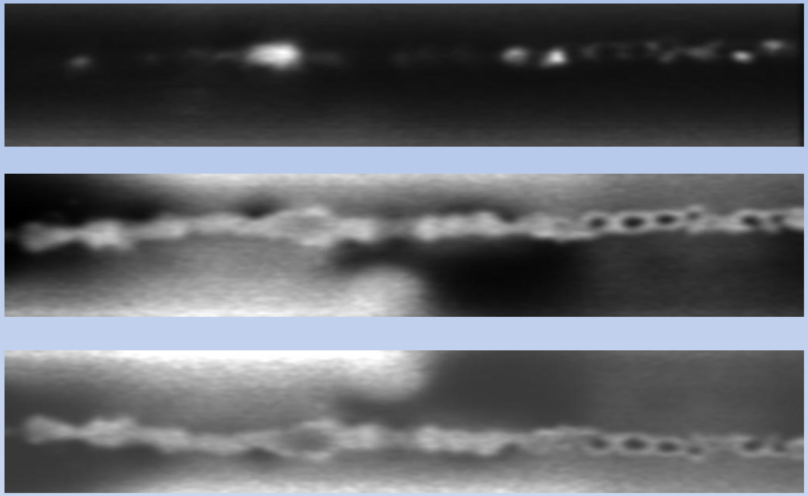
# In-Process, Real-Time Weld Quality Control

Welded steel sheet

Measured weld cross sections (can be used for *real-time* quality monitoring)



Reconstructed (from 3D data) weld cross sections at various depths



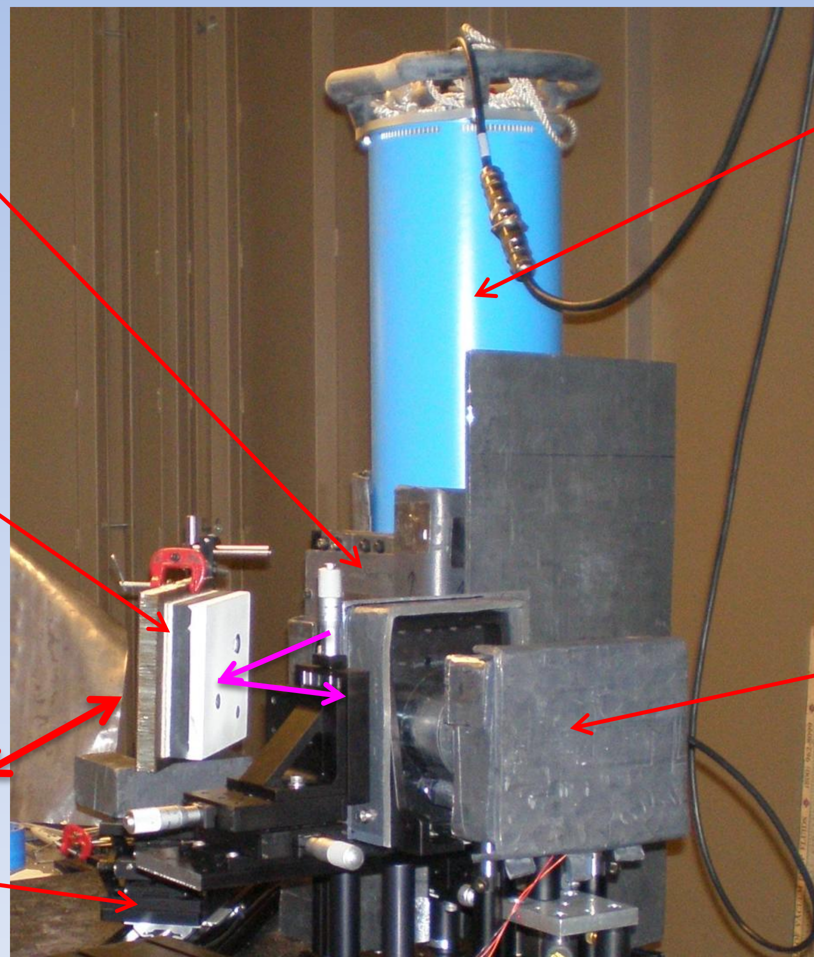
- ❑ CIT imaging through the whole weld thickness is possible **in real time** (while the weld is still hot) and can be used for adjusting welding parameters on the fly
- ❑ After weld completion, 3D images can be used for final inspection and QC

# CIT Hardware Development

# Benchtop CIT Prototype (Early 2012)

Vertical lead slit

225-kV X-ray source



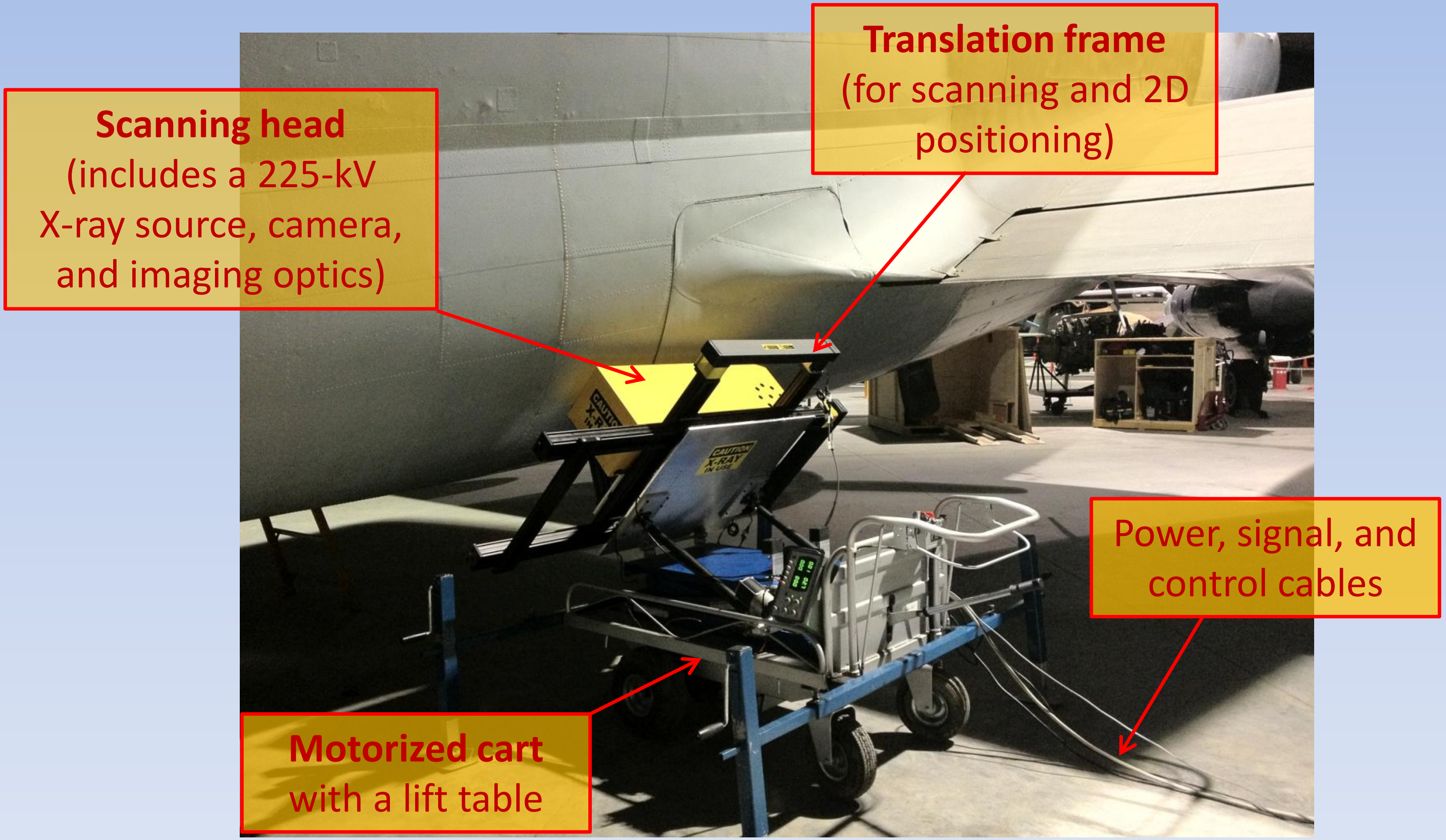
Mounted test sample

*Sample translation*

X-ray camera

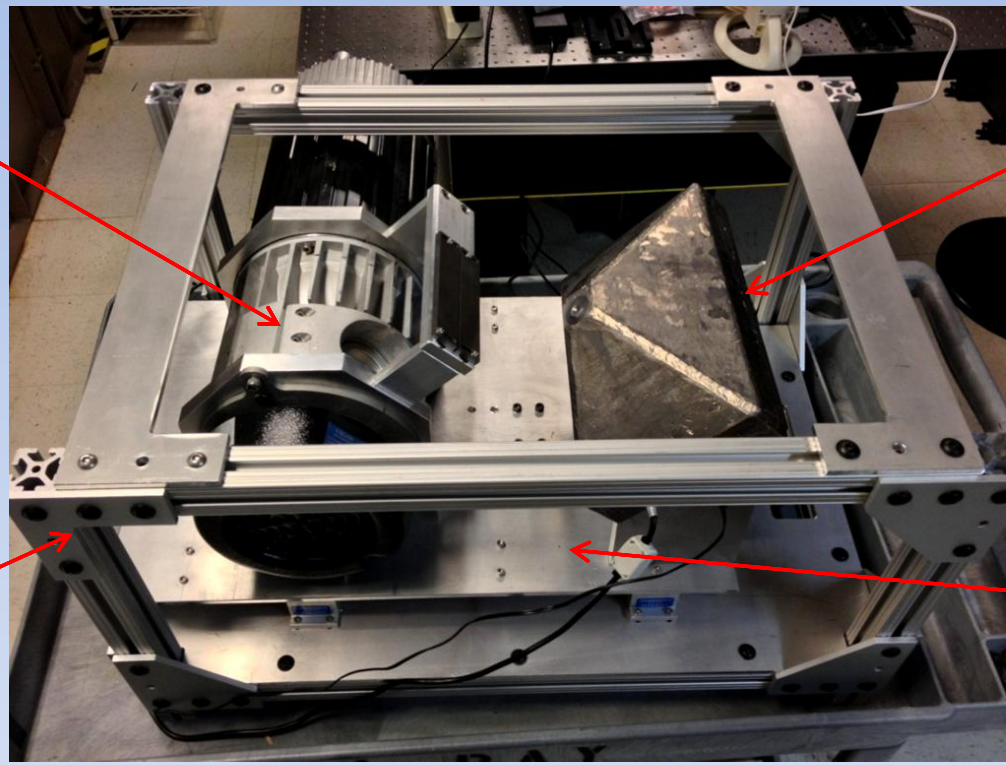
Translation stage

# Gen-I Mobile CIT Scanner for Aircraft NDI (9/2012)




Demonstrated at Warner-Robins AFB in 2012

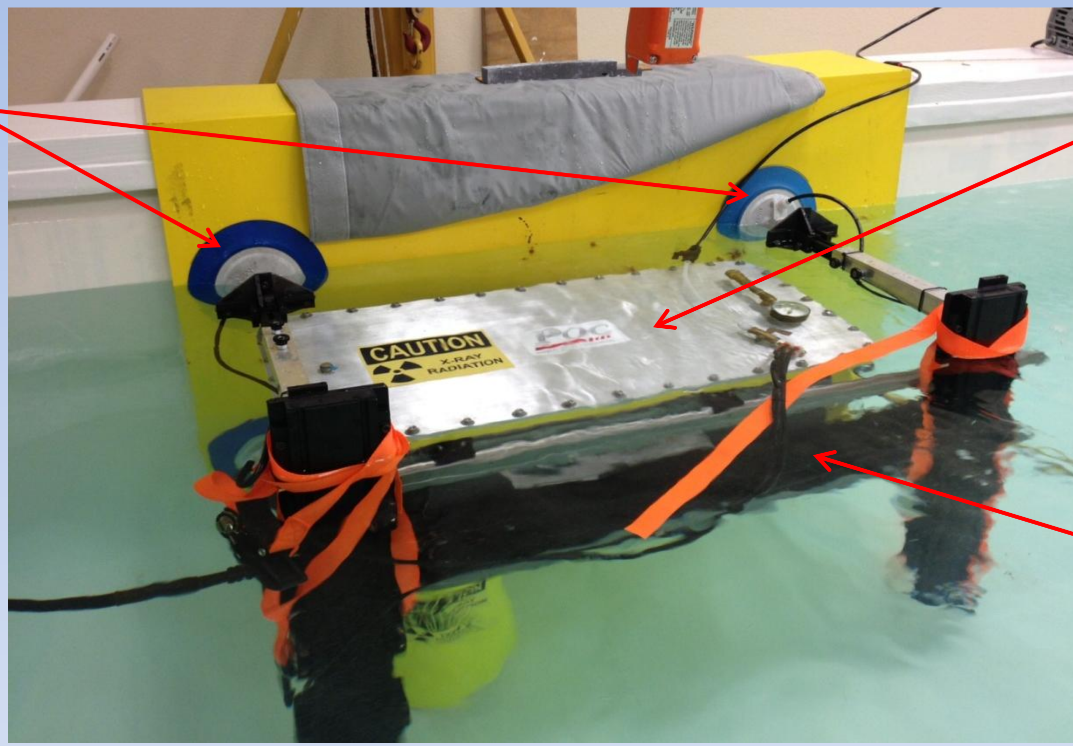
# Gen-II Portable CIT Scanner for General NDI (9/2013)




- ❑ Developed in NASA Phase II SBIR as an intermediate prototype
- ❑ Includes integrated translation stage for scanning
- ❑ Robust, can be mounted on a robotic arm to handle a variety of surfaces
- ❑ Dimensions: ~70x45x35 cm; weight ~75 kg

# Gen-II Portable CIT Scanner for Underwater NDI (3/2014)

**Suction cups**

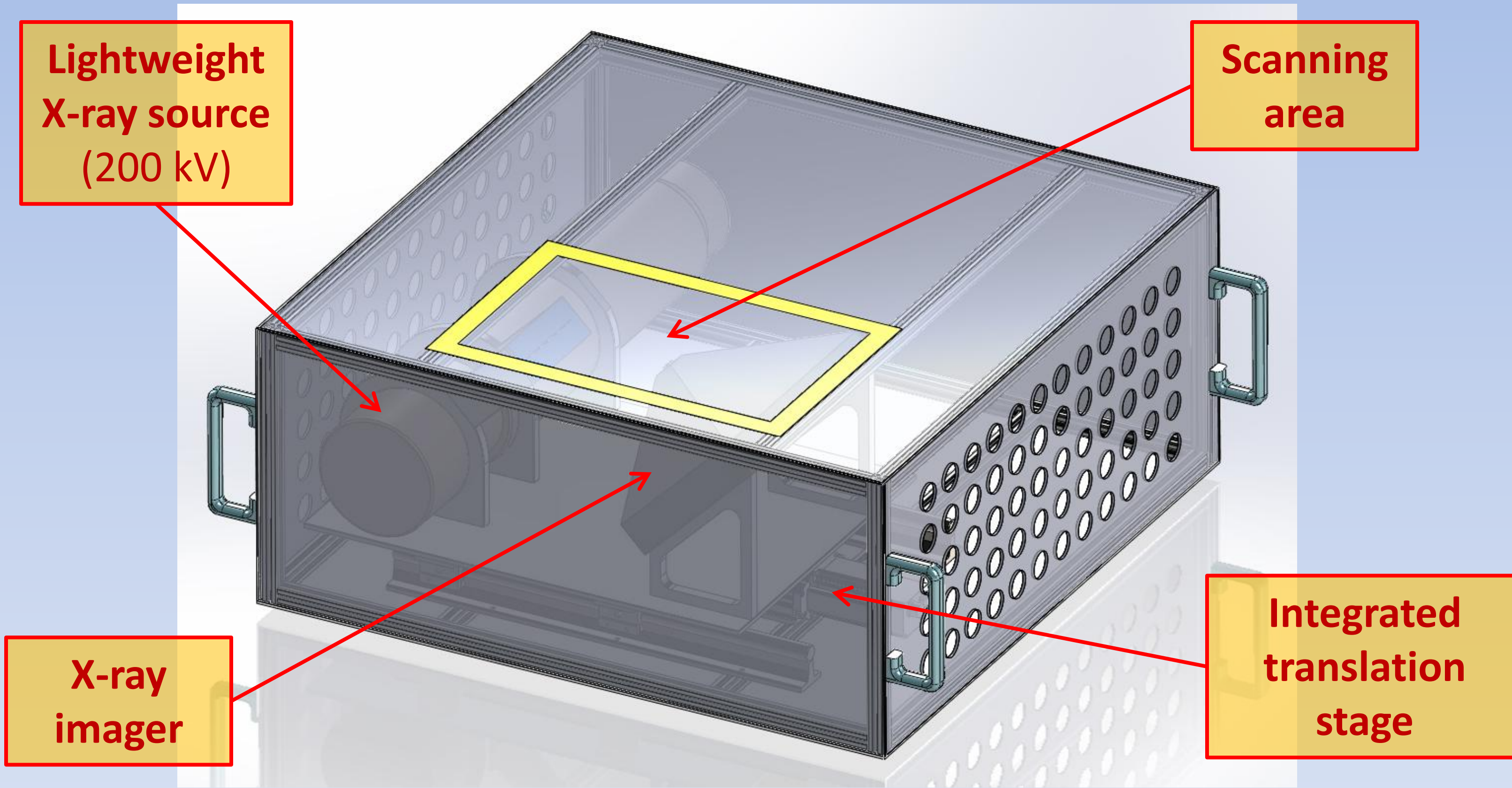



**Underwater housing with X-ray source** (200 kV) and detector

**Translation stage** (for scanning)

- ❑ Prototype developed for ONR (Navy Phase II SBIR)
- ❑ Capable of operating at depths up to ~10-30 m
- ❑ Includes translation stage for scanning
- ❑ Attached to a surface with suction cups
- ❑ Dimensions: ~70x60x50 cm; weight ~100 kg

# Gen-III Lightweight Portable CIT Scanner (~9/2014)



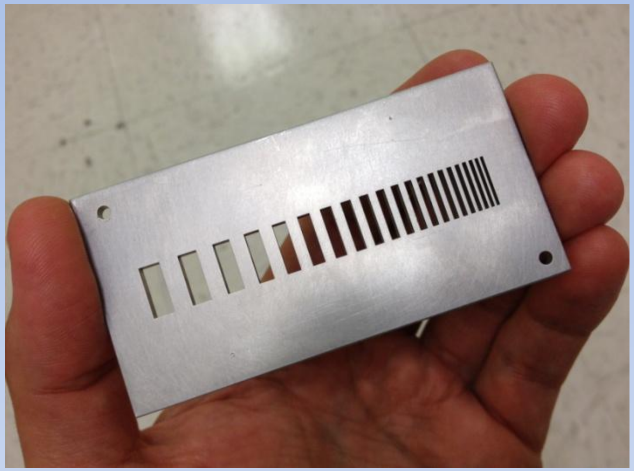

- Currently under development for NASA R&D (Phase II SBIR)
- Field of view: 20 cm (w) x 12 cm (h) x 10 cm (d)
- Dimensions: 76x72x33 cm; weight ~48 kg
- Fully enclosed system: no external moving parts

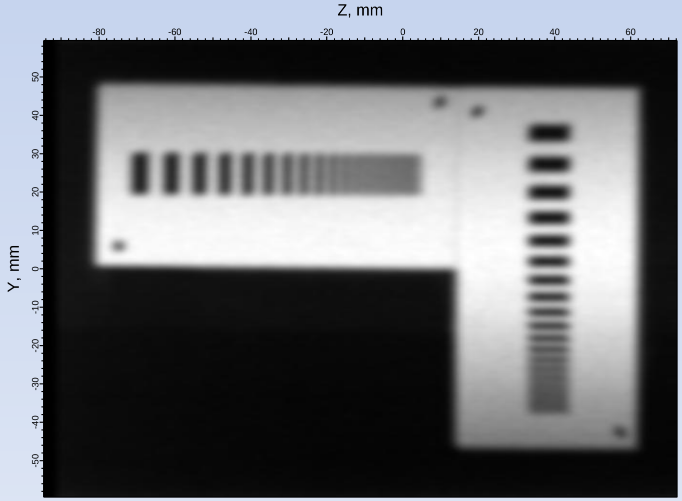
# Key Specifications

| Parameter | Value |
|---|---|
| Resolution (*x*/*y*/*z*) | 1.5-2.5 mm |
| Field of view (width) | ~10-15 cm |
| Field of view (length) | ~15-30 cm (depends on translation range) |
| Field of view (depth) | ~5-10 cm |
| Density resolution | ~2-3% |

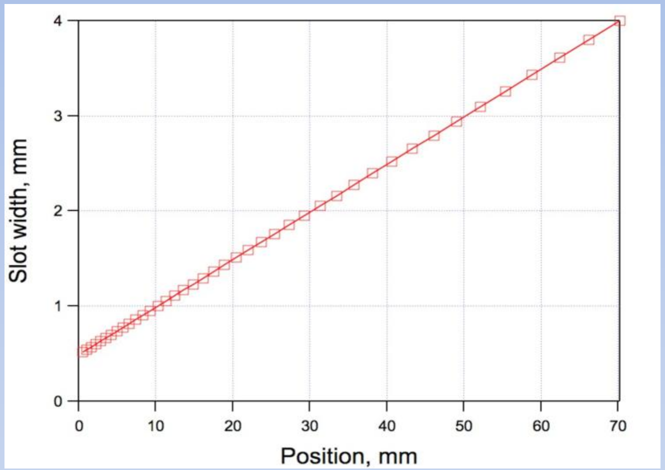
# Resolution Characterization

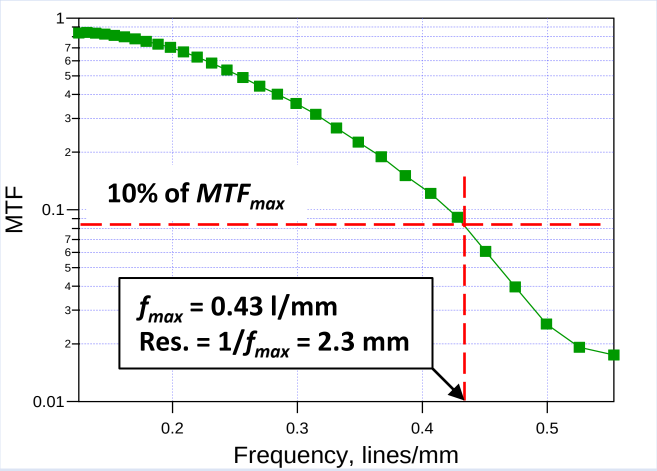
## Al test sample and its CIT image






## MTF and resolution analysis



# Typical CIT Penetration Depth with a 200 – 250 kV Source

| Material | Chemical Composition | Density, $g/cm^3$ | X-ray Att. Coef. @100 keV, $cm^2/g$ | Penetration Depth, cm |
|---|---|---|---|---|
| Aluminum | 100% Al | 2.7 | 0.17 | 4.2 |
| Avcoat | ~50% $SiO_2$, 50% C | 0.5 | 0.16 | 24 |
| C/C composite | 100% C | 1 | 0.15 | 14 |
| Silica ceramics | 100% $SiO_2$ | 1.5 | 0.17 | 8 |
| Titanium | 100% Ti | 4.5 | 0.272 | 1.6 |
| SS304 stainless steel | 70% Fe, 20% Cr, 9% Ni, 1% Si | 8.06 | 0.365 | 0.7 |

Experimental penetration depth estimate:

$$L_{CIT}(E) \sim 2L_{att}(E) = \frac{2}{\sigma(E)\rho}$$

$\sigma(E)$ = scattering cross section for photon energy E ~80-100 keV
$\rho$ = material density

# Scanning Speed

Current scanning speed: **80 min/ft²** (8-s exposure per 1-mm slice, 15 cm (5 in.) wide)

Potential straightforward enhancements in speed:

| System Modification | Speed Improvement |
|---|---|
| Higher-power X-ray source (3 kW vs. current 1.2 kW) | 2.5x |
| Multiple cameras (four vs. one) or large flat-panel detector | 2x – 4x |
| Optimization of the scanning geometry, imaging optics, and sample irradiation uniformity | 2x – 3x |
| **Total:** | **10x – 30x** |

Therefore, potential scanning speed is: **3-8 min/ft²**

# Safety

Any NDE system utilizing X-rays is a potential safety hazard. However, a **CIT-based NDE system is inherently much safer than comparable X-ray radiography systems**, because:

- Most of the generated X-ray flux is blocked immediately in front of the source with the slit aperture; only 1-2% of the flux is used for sample irradiation.
- Backscattered X-rays not used for imaging can be effectively blocked by appropriate shielding.
- Any unabsorbed portion of the X-ray beam transmitted through the sample can be minimized by choosing appropriate X-ray source voltage (lower voltage → higher absorption → fewer residual X-rays).

The **exclusion zone** for the current CIT prototype:

- **~4-5 m:** in open air (can be reduced to 2-3 ft with further optimization)
- **<1 m:** in underwater environment.

# Future CIT Development

Two new NASA SBIR Phase I's recently started:

- ❑ **Multifunctional Compton Inspection Tool (MCIT)**
  *Improved system design, with fewer moving parts, smaller weight and size, and increased functionality*

- ❑ **Thermal Protection Systems Nondestructive Evaluation Tool (THRON)**
  *System optimization primarily targeted at more effective 3D NDE of the TPS - collaboration with SpaceX*

***POC thanks NASA for its continued support!***