Advanced Microwave Systems and Techniques for Non-Metallic Piping

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CEO-Advanced Microwave Imaging

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(AMWI)

Founded 2020

Bob Stakenborghs, CEO

16 years experience in field MW inspection and material interaction

ASME, ASTM, ISO, ASNT committee member

Authored ASME, ASTM MW inspection standards

- To advance the art and science of microwave inspection through:
  - State of the art electronics
    - Multi-frequency and advanced single frequency systems
  - Calibrate-able and repeatable systems
    - Simple calibration for repeatable results
  - Bespoke Antenna System
    - Only system with inspection specific antenna
  - Proprietary and specialized data acquisition and analysis software

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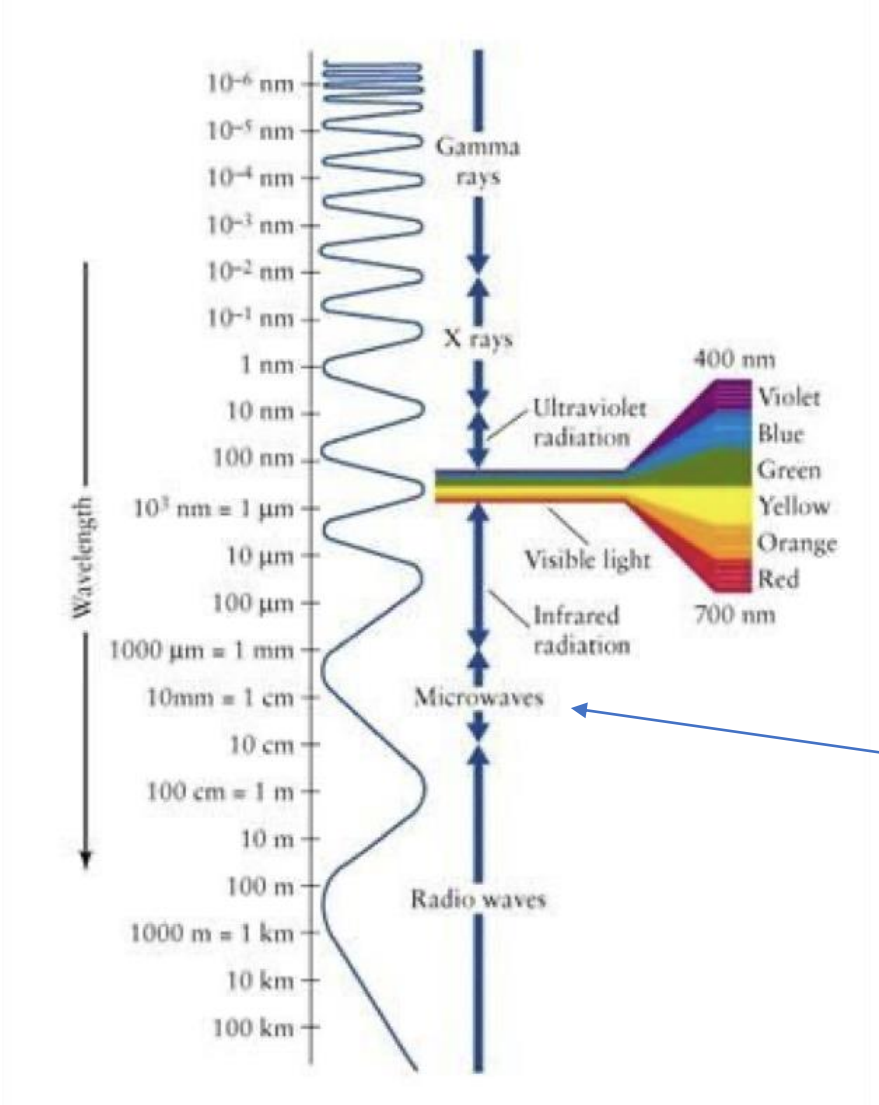
Microwave Inspection

Inspection of non-metallic materials using Electro-Magnetic Radiation (EMR) in the microwave frequency range.

Approximately

300Mhz to 300 GHz



MW Frequency Range

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Brief History MW Inspection

- MW Inspection has been described in texts since 1950's
- Field inspection since early 2000's
- Current standards:
  - ASNT - SNT-TC-1A 2016 Microwave Included as a Method
  - ASME BPV Section III Appendix XXVI - MW included as an inspection technique for HDPE piping
  - ASTM E3101 and E3102 - MW Inspection of HDPE butt and Electro Fusion Joints
  - ISO, ASME Section V and other standards under development

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Advanced System

System Characteristics make advanced inspection possible.

Multi frequency applications using Vector Network Analyzer (VNA) provides additional data for analysis.

- Multi-frequency system
  - Metrology grade equipment used to generate signal
    - VNA – 85MHz to 18GHz range
    - 201,401,801 data points selectable
    - Fully calibrate-able
      - Open
      - Short
      - Load
      - Calibration screen built into data acquisition software
    - Highly repeatable results

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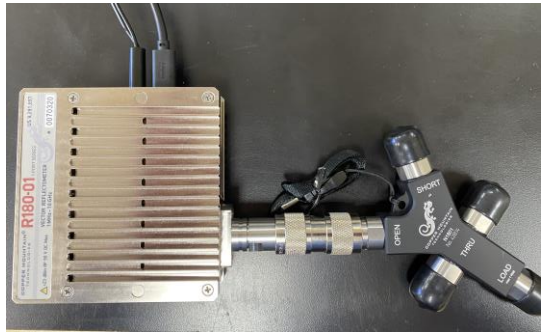
Simple Three Step Calibration

OPEN



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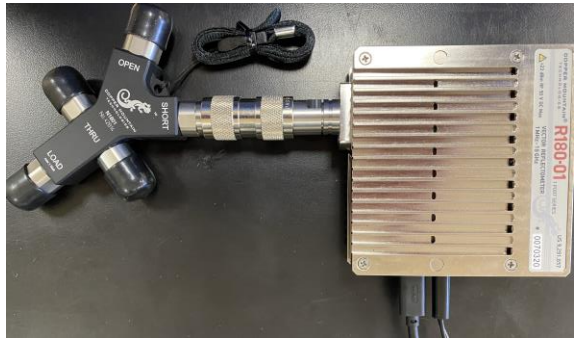

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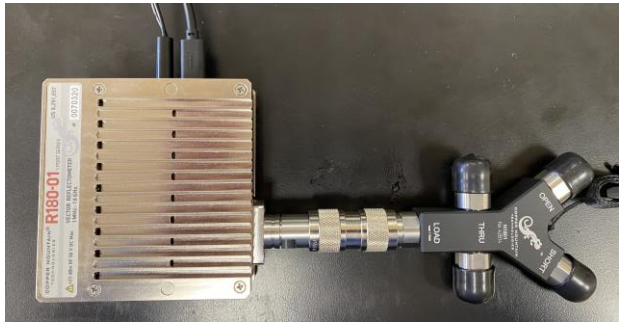

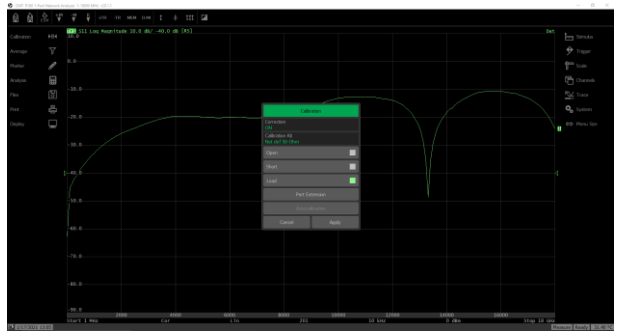

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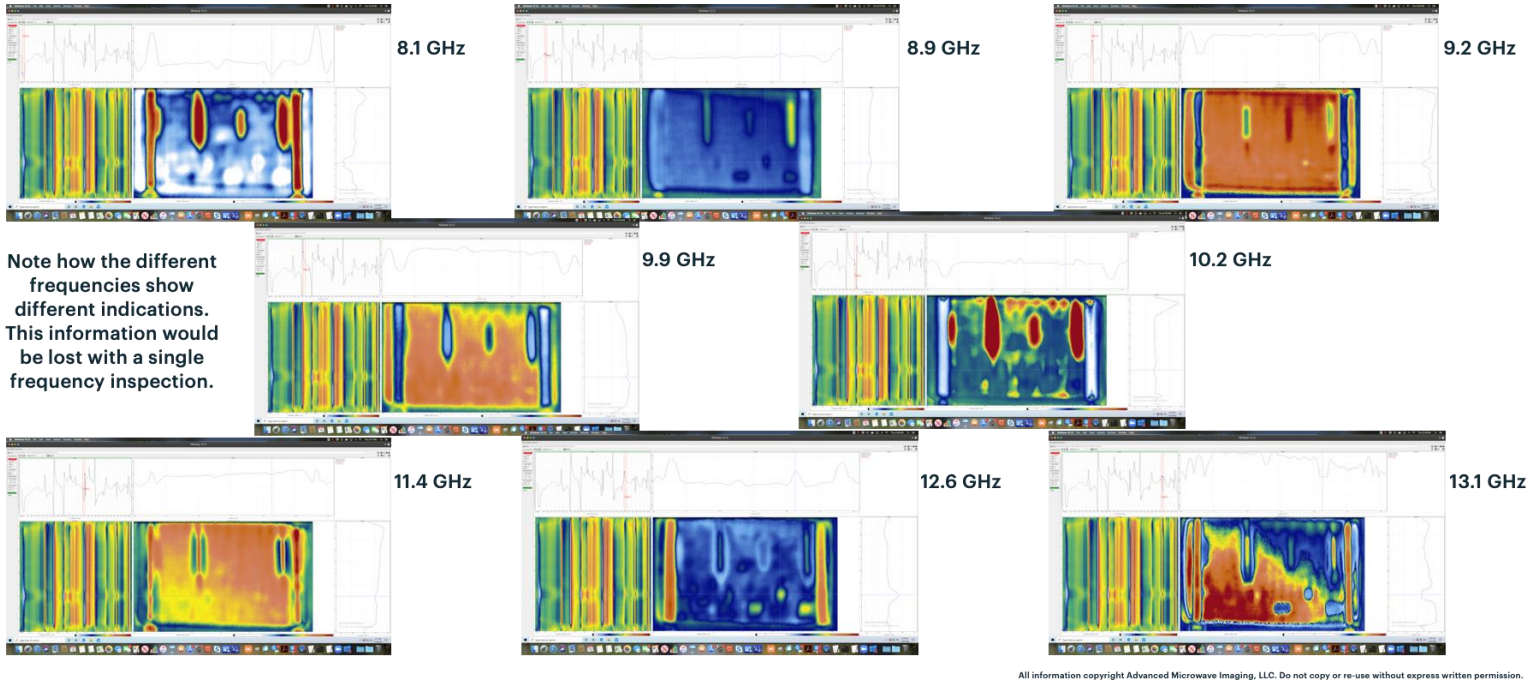
Advantages of Multi Frequency Interrogation

Data acquisition across a frequency range provides for a large amount of data that can be analyzed

Software allows for display of:

- Real
- Imaginary
- Magnitude
- Phase

Image Sequence of 25MM Thick Fiberglass Part



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Bespoke Antenna System

- Only field inspection system using antenna designed specifically for inspection
  - Others use open waveguide which have no controlled spot size and are highly inefficient
  - Can be specifically designed for inspection application
- Characteristics
  - Reasonable match across the band, $|S_{11}|$ ~ -10dB or better
  - Field **confined to a controlled and well defined spot size**
  - To achieve this smaller spot size the mode has been changed by the probe from an air filled waveguide at TE10 to a rod probe with hybrid HE11 mode

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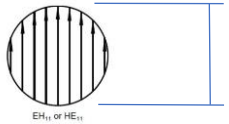
Antenna Patterns

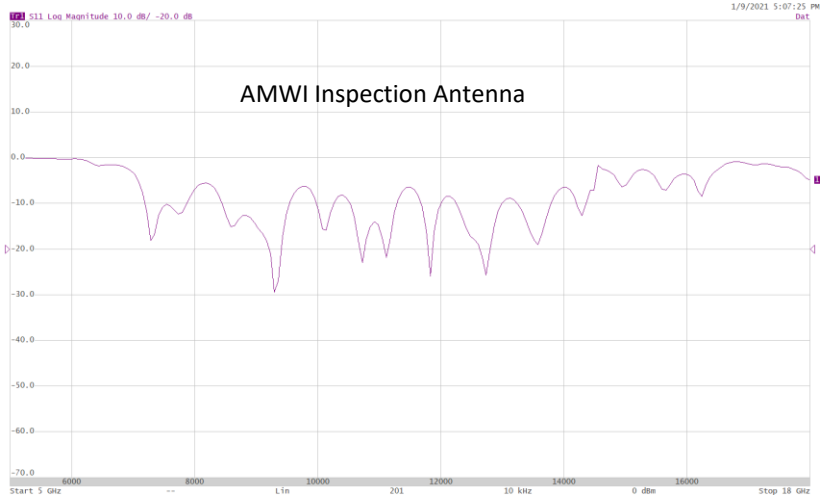
AMWI inspection antenna has multiple return peaks at 20dB or higher plus well defined spot size.

Open waveguide has limited return peaks and not suitable for multi frequency use.

AMWI Inspection Antenna

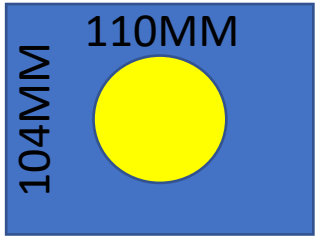


Beam pattern well defined to a spot size of 50MM diameter at 50MM below antenna. (Beam approximately 20MM Diameter at surface)

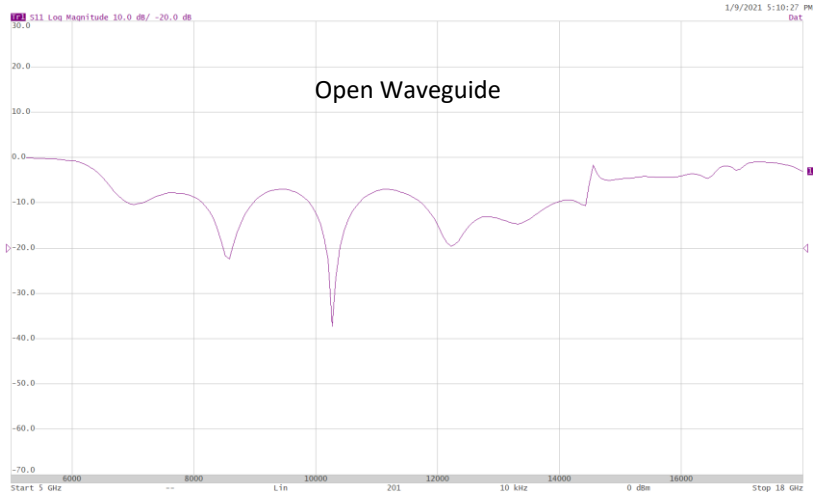


Open Waveguide

Energy spreads at 45 degrees from aperture in two dimensions plus uncontrolled surface wave and large standing wave ratio at surface



WR42 (24.5 GHz) Open Waveguide
"Spot" Size at 50MM (Blue)
versus
AMWI Antenna at 50MM
(Yellow)
(To Scale - Approx.)



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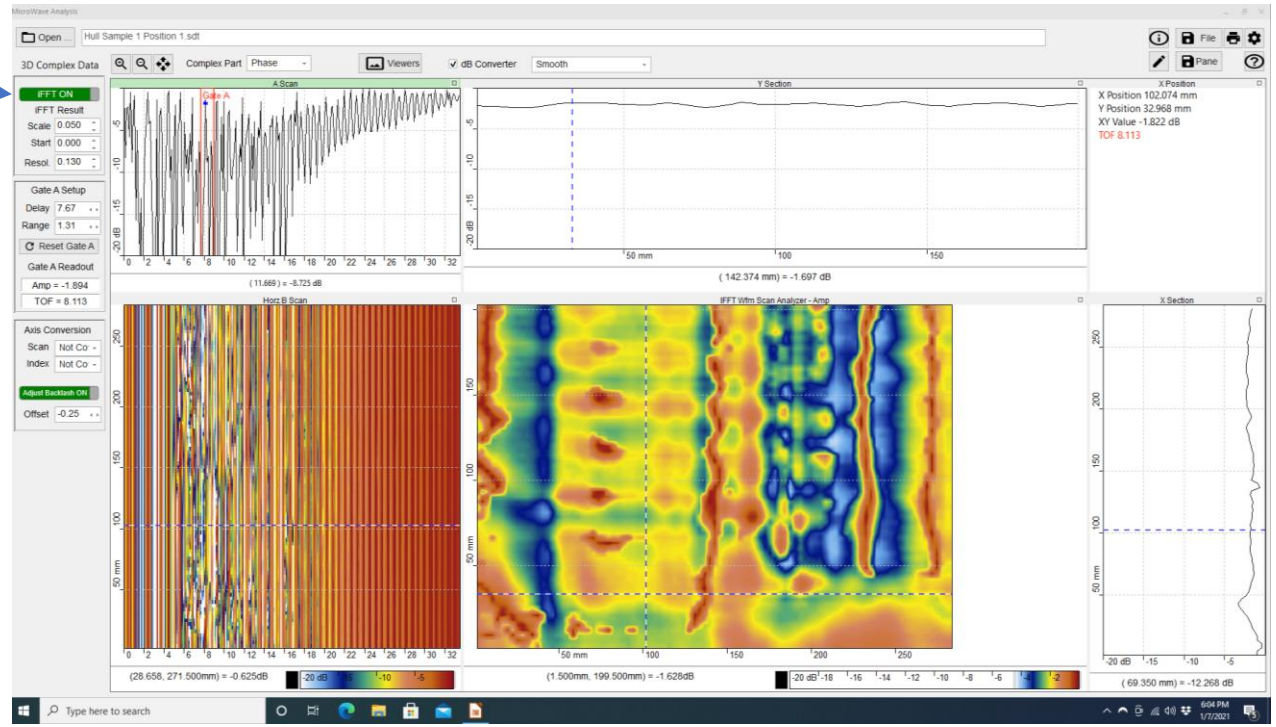
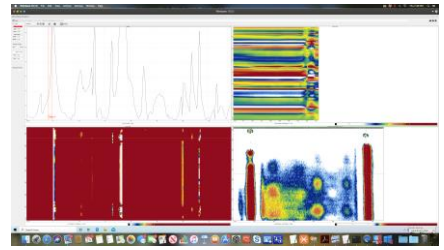
Specialized Analysis Software

"A" Scan View

"Y" Section view

Frequency Sweep allows for IFFT conversion to time/depth domain and easy conversion from frequency to depth





Alternate "B" Horiz and "B" Vertical views

Horizontal "B" (Depth) Scan View

"X" Section View

"C" Scan View

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Sample Creation

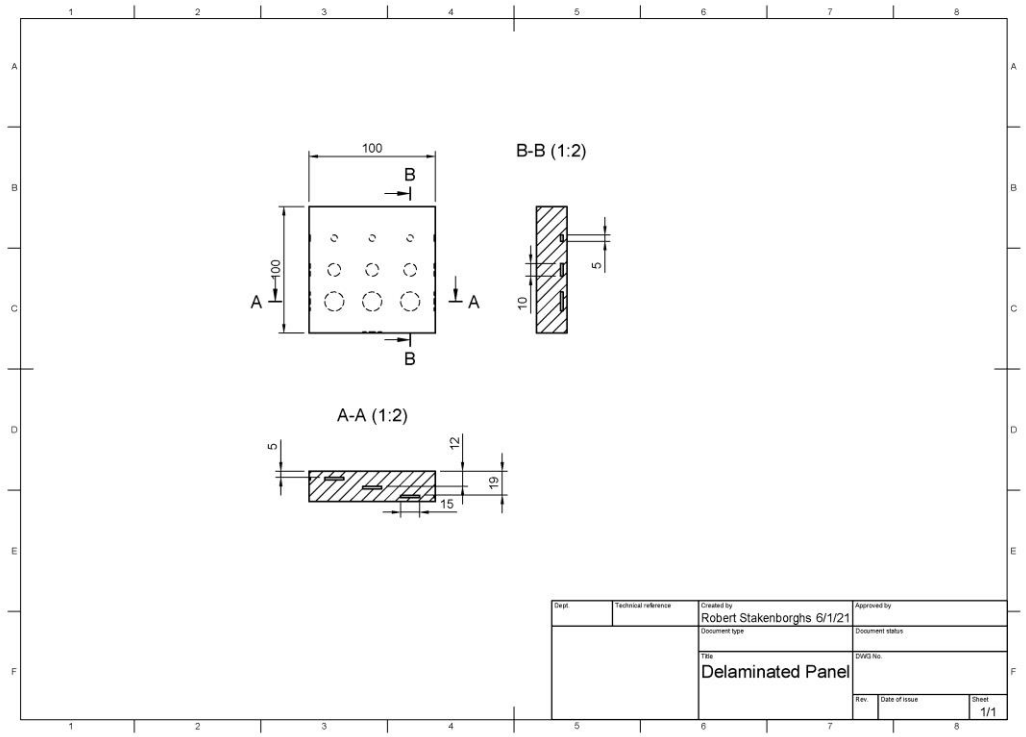
Creating flaws in composite structures can be problematic

Delamination flaws can be problematic because of uncertainty associated with maintaining clearance between layers (i.e. - layer contamination)

- One possible solution his to design a part with a known delamaintion and then 3D print that part.

- 3D printing with fiberglass and other materials are now possible.

Example in PLA



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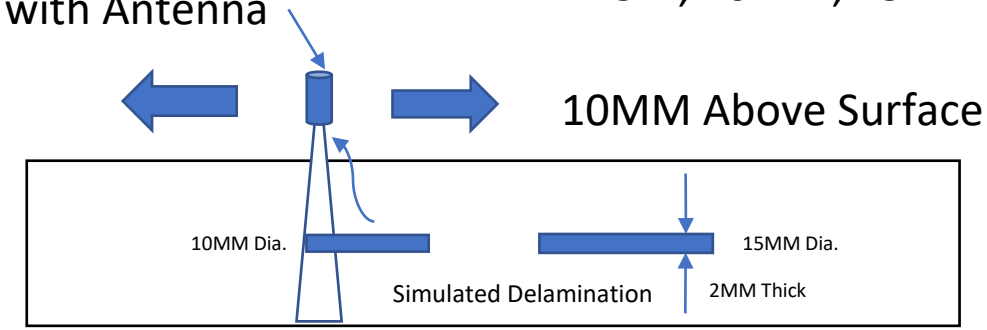
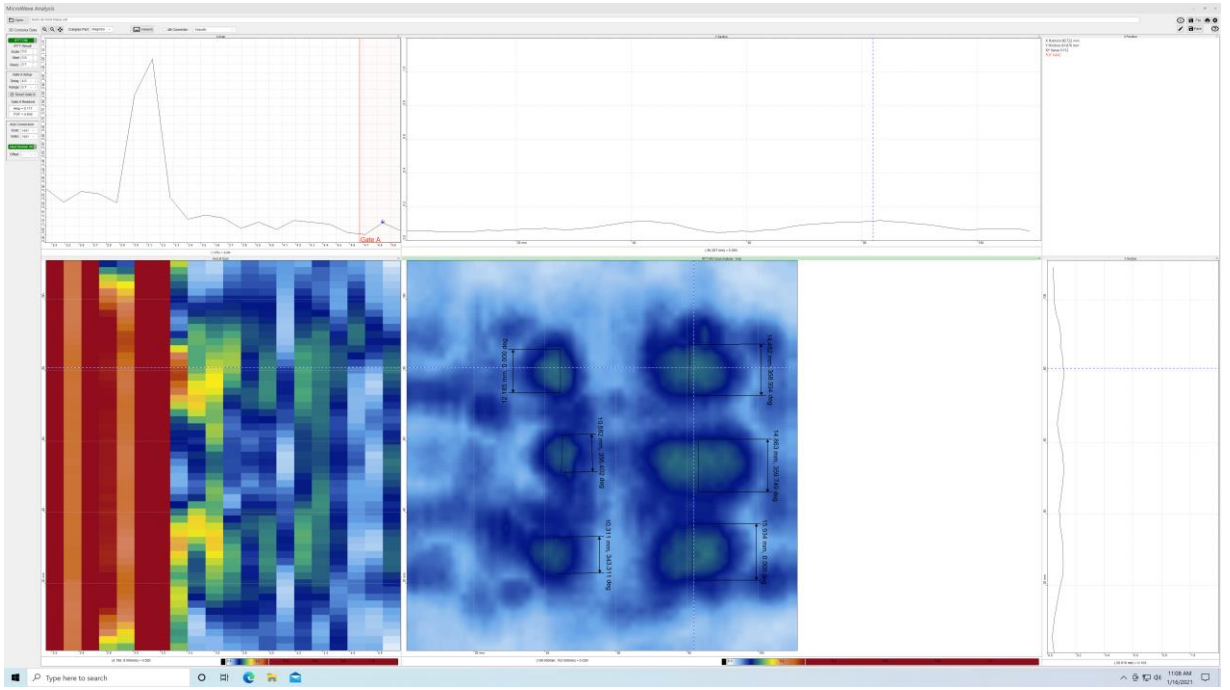
MW Inspection Advanced System

- Inspection Example (3d Print PLA)

25MM Thick Part
3 Depths
5M, 10MM, 15MM

VNA with Antenna





Reflected signal (S_{11}) varies based on complex permittivity beneath antenna

Smallest flaws were not detected and likely were not printed properly.

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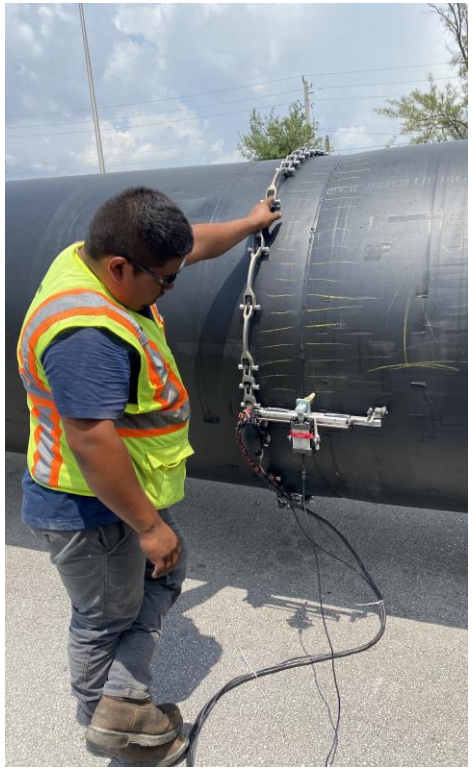
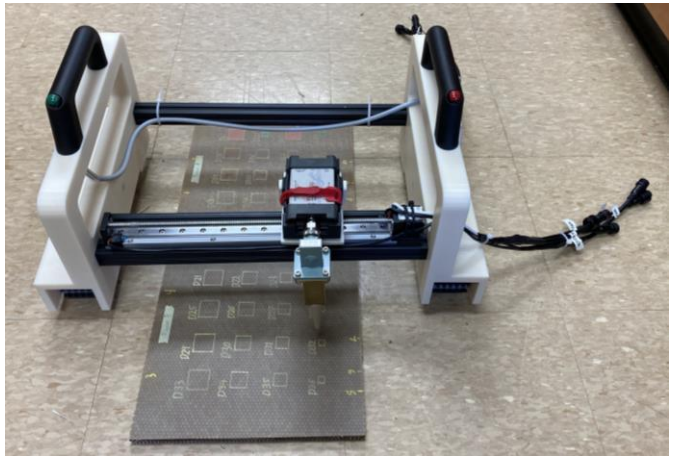
AMWI Field Inspection Equipment

Pipe Scanner (Motorized/manual)



- Motorized Scan Axis
- Manual Index
- Capable of scanning up to 1,000MM Diameter
- Push Button Operation

Motorized Axis Portable Scanner (MAPS)



- Motorized scan axis (Three different lengths 450MM, 300MM, 200MM)
- Manual Index
- Push Button Operation (Allows hands on scanner)
- Built for Up-Tower Wind Turbine Blade Inspection or Large Pipe

AMWI scanning systems use simple to use data acquisition software that is fully compatible with VNA

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Complex Data Analysis

The availability of complex data, that is complex reflection coefficient S_{11} made up of dielectric and loss components allows for further analysis

The availability of sophisticated data allows for analysis for evaluation of located flaws in ways that have not been previously been available for microwave inspection.

Multi-Frequency Data

- Allows for viewing of inspection at various frequencies versus only a single frequency
- Different frequencies interact with material slightly differently providing additional information
- Allows for conversion of frequency based data to time based data using IFFT
- Provides for selection of a best single frequency for SAFT

Complex Reflection Coefficient

- Allows for viewing real and imaginary data as well as calculating true magnitude and phase
- True phase provides a tremendous amount of information about the MUT
- Allows for SAFT analysis

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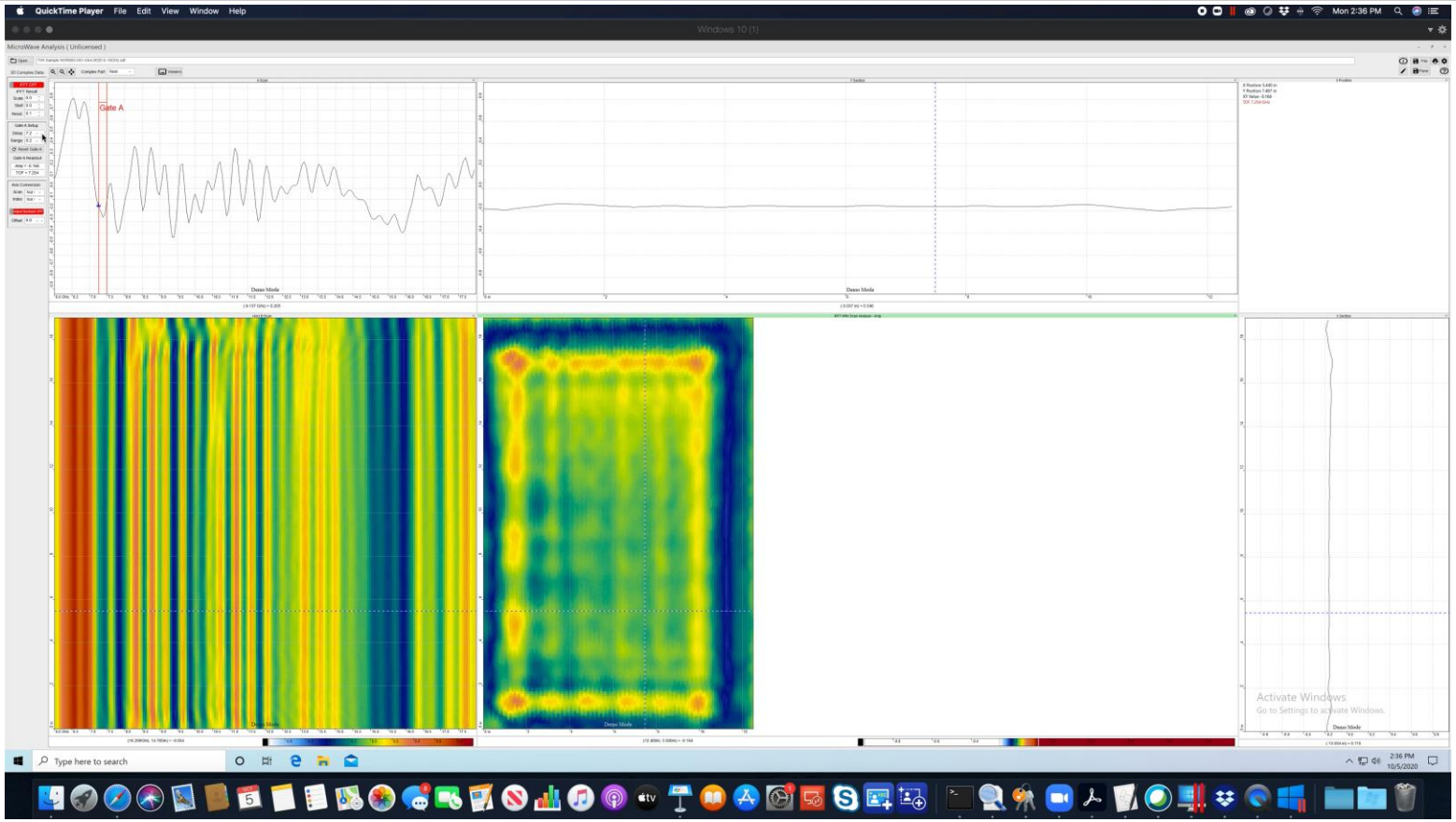
Frequency Variance



Fiberglass panel with back drilled holes of varying size and depth.

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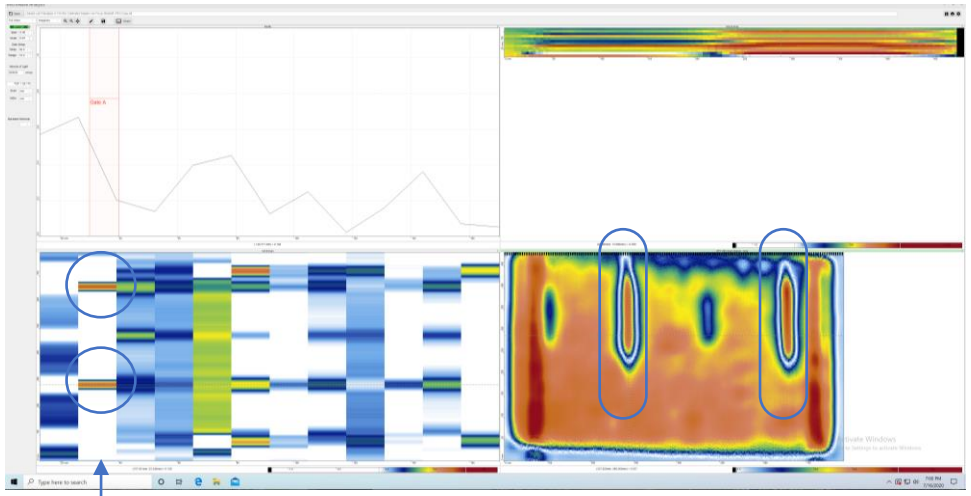
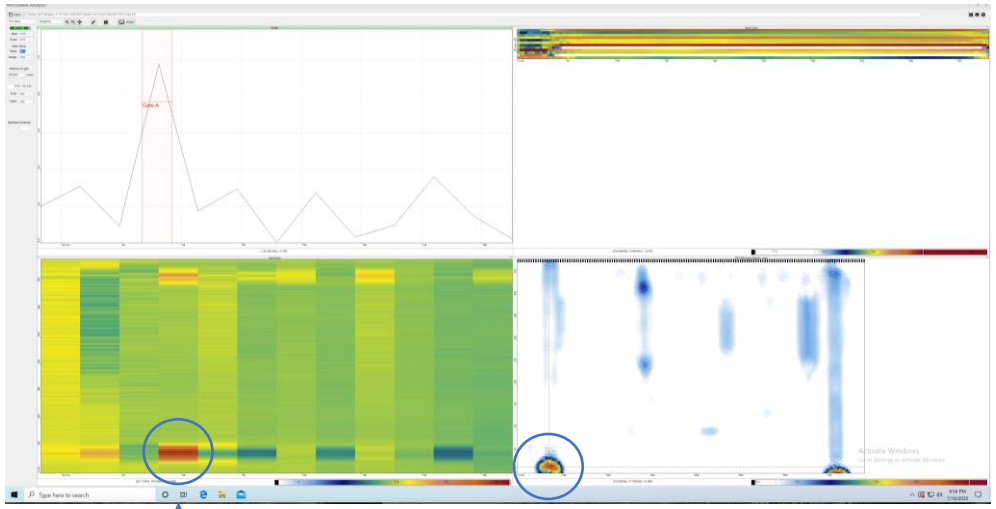
Depth Detection using IFFT



Location Near Side of MUT



Location Far Side of MUT

Depth Capabilities with Proper Calibration
(25MM Thick Fiberglass Part)

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Synthetic Aperture Focusing

- Developed in laboratory setting for microwave inspection
- Using AMWI equipment, SAFT can be performed with field acquired data
- Allows for better resolution of depth than IFFT alone

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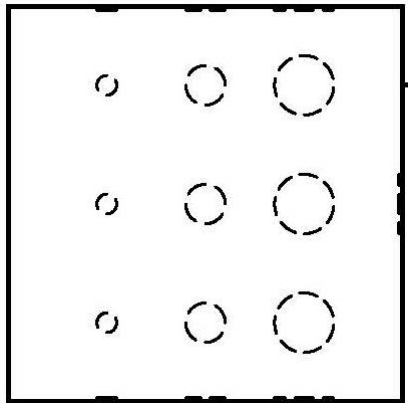
SAFT EXAMPLE

3D Print PLA Sample

Delamination flaws at various depths in part

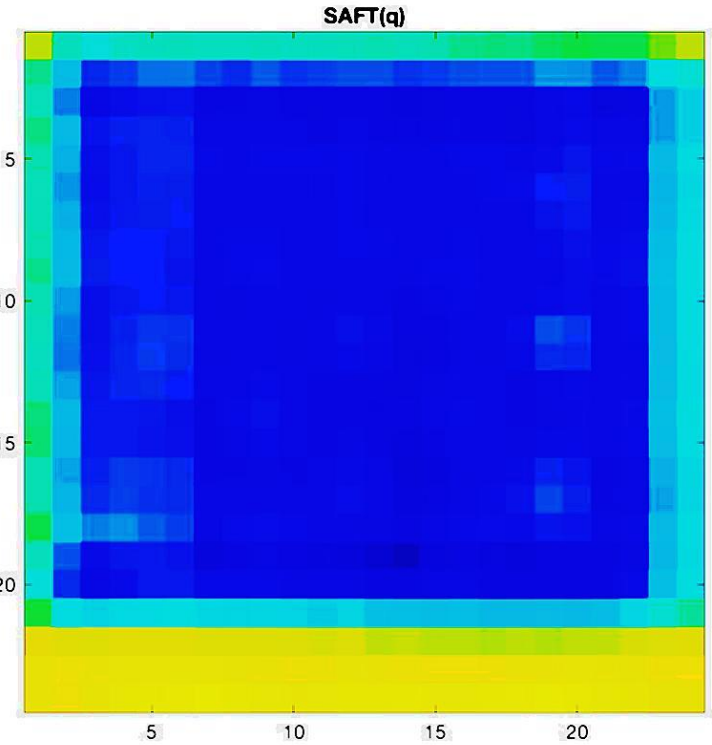
Each image represents approximately 1MM of depth below the antenna

The defects begin to appear at
Approximately (-) 5MM and persist until approximately (-) 12MM. The deepest (Top defects) appear later in the images.



Deepest

Shallowest



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HDPE Butt Fusion Pipe Inspection

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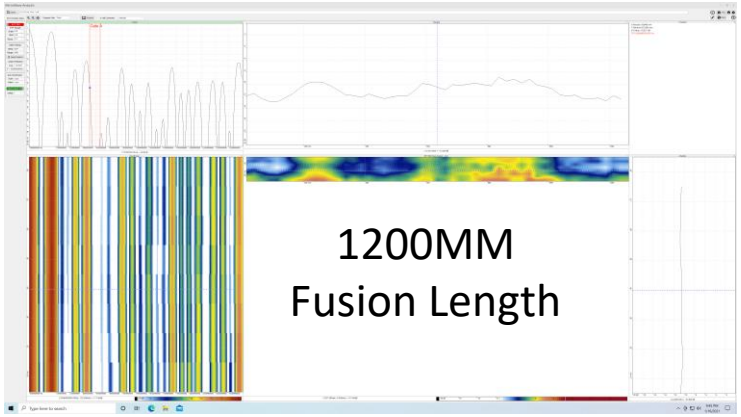
HDPE Pipe Inspection 6GHz to 14GHz

Pipe 14” SDR 11 PE4710

Multiple fusions of various quality

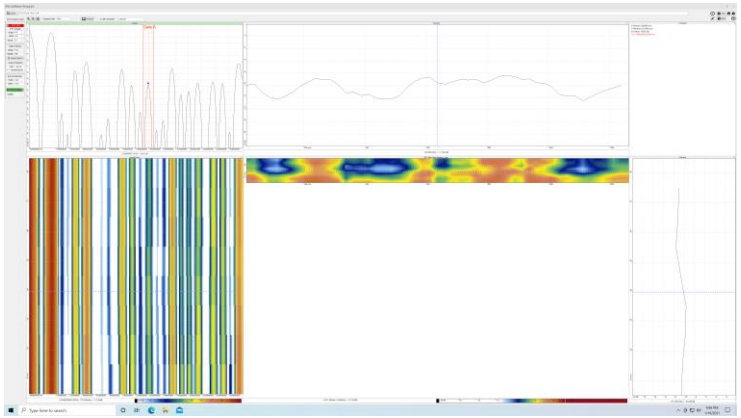
Each frequency provides sights different information

Frequency or image selection based on pre-determined accept/reject criteria selection

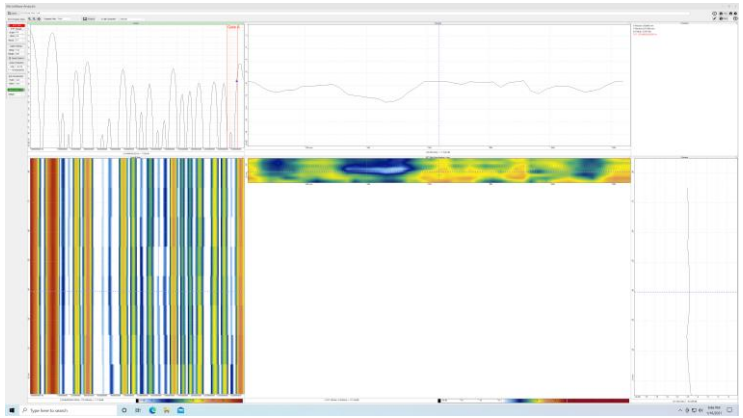


80 MM (40MM Each Side of Fusion)

Frequency 1 - 8.25GHz



Frequency 2 - 10.25GHz



Frequency 2 - 13.25GHz

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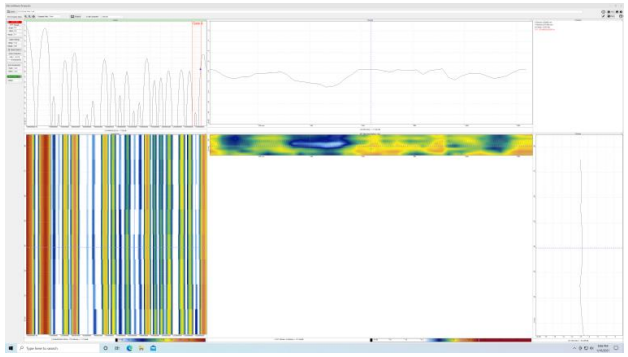
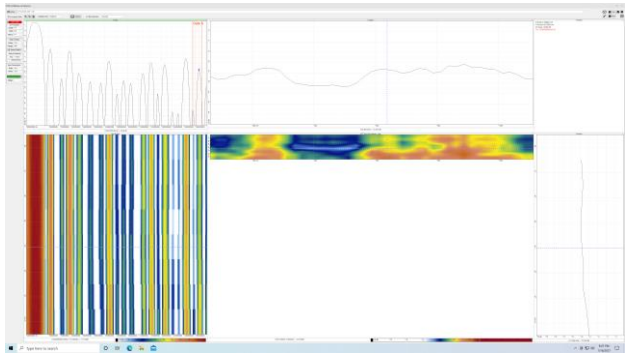
HDPE Inspection Accept/Reject

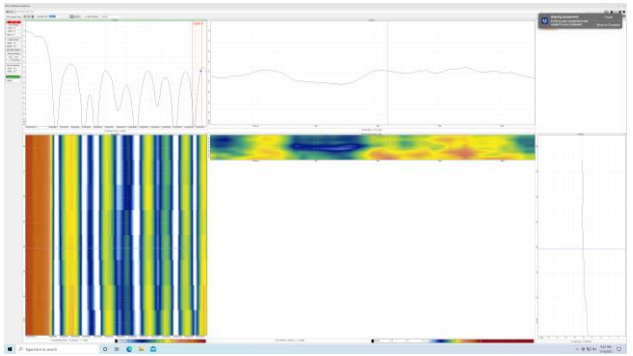
- Different Signal (S_{11}) Parts Displayed at Same Frequency



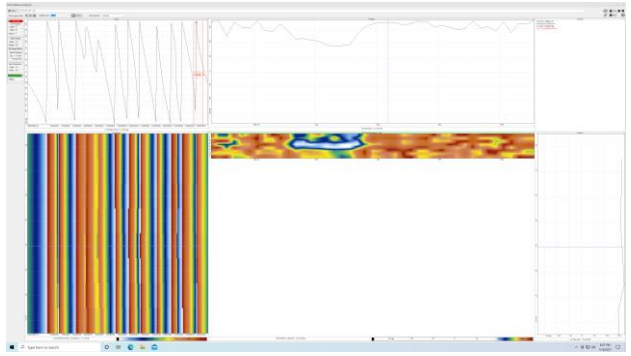
Real



Imaginary



Magnitude



Phase

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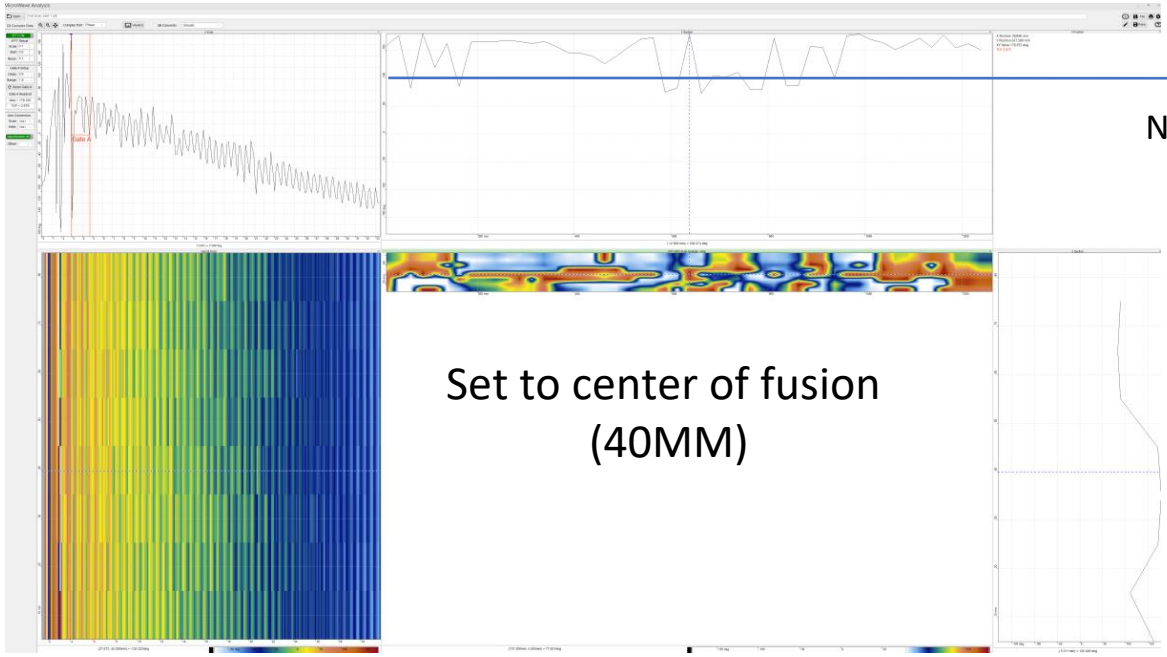
HDPE Accept Reject

Final selection based on mechanical testing of test fusions

Currently, IFFT of PHASE signal seems to provide excellent sensitivity and repeatability of signal

IFFT of Phase



Procedure (Preliminary based on small sample set)

- Set image to IFFT of Phase
- Set “X” Section to 40 MM (Fusion Center)
- Set Accept/Reject to 100 Degrees Phase
- Above - Acceptable
- Below - Reject

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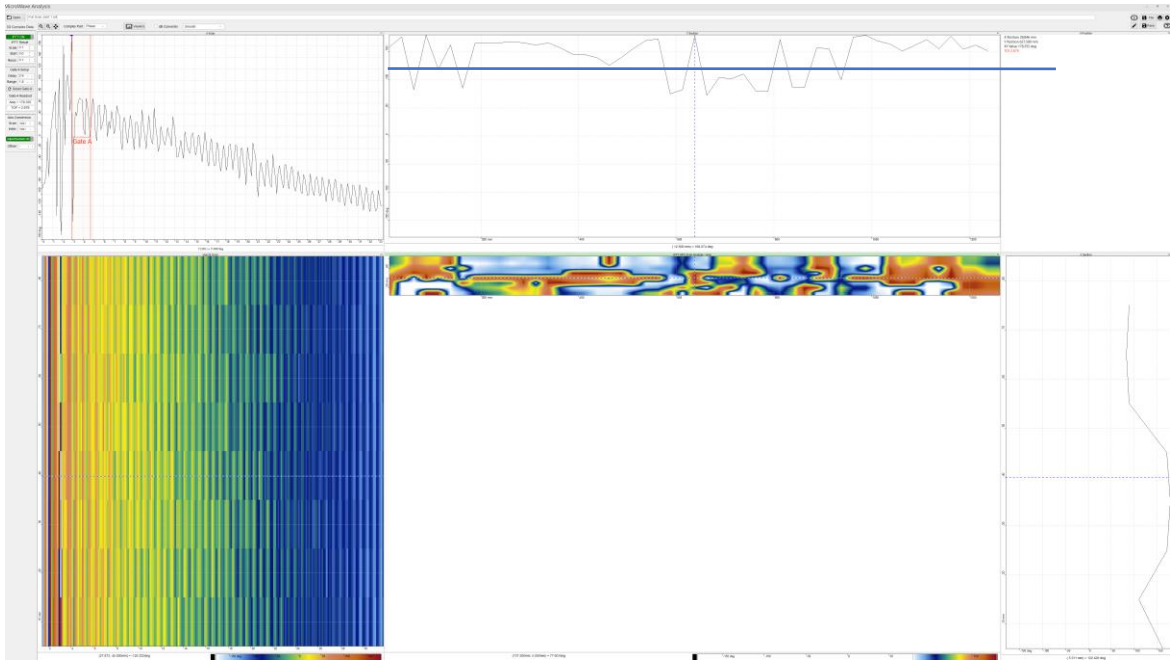
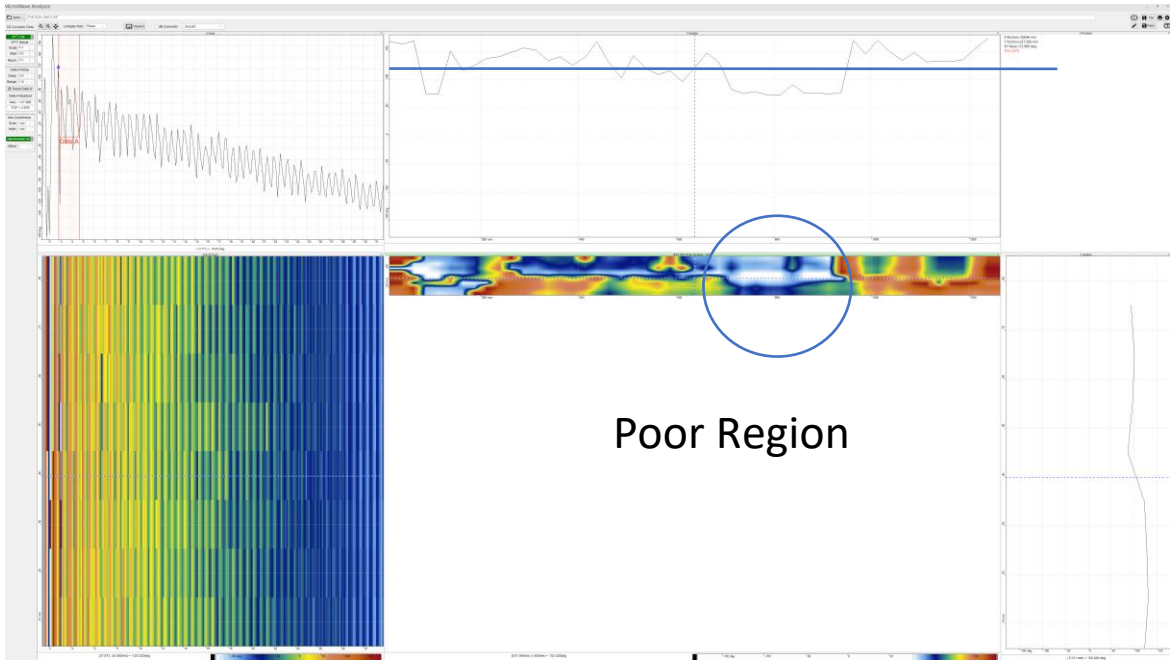
Sample Set Fusions 1 and 2



PASS



REJECT

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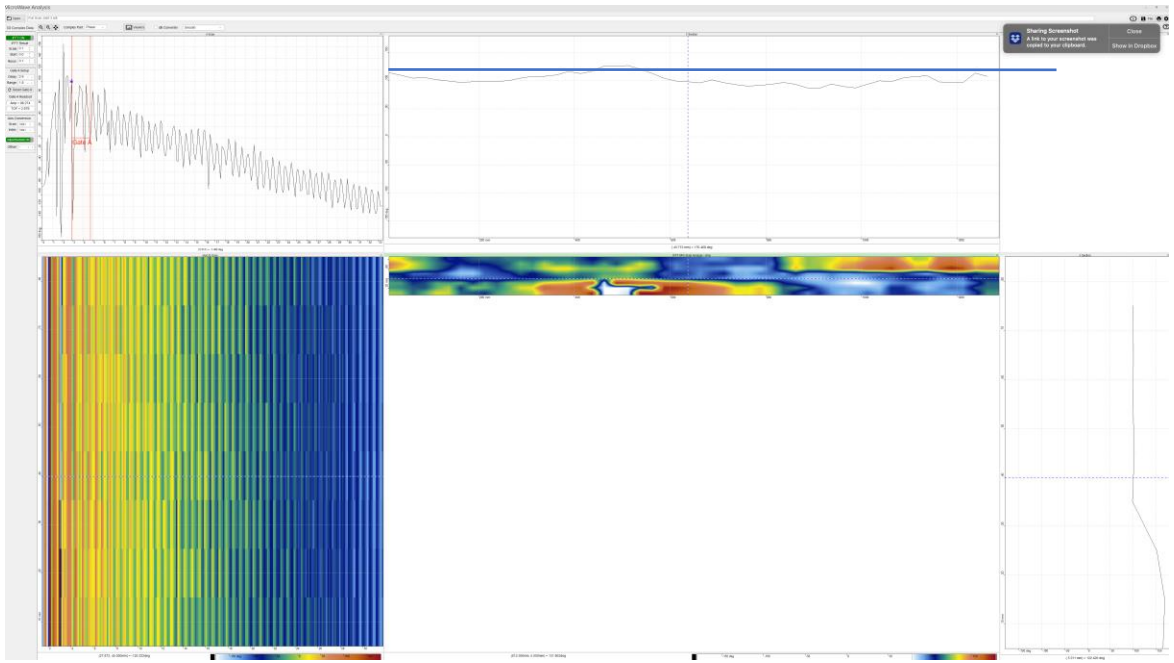
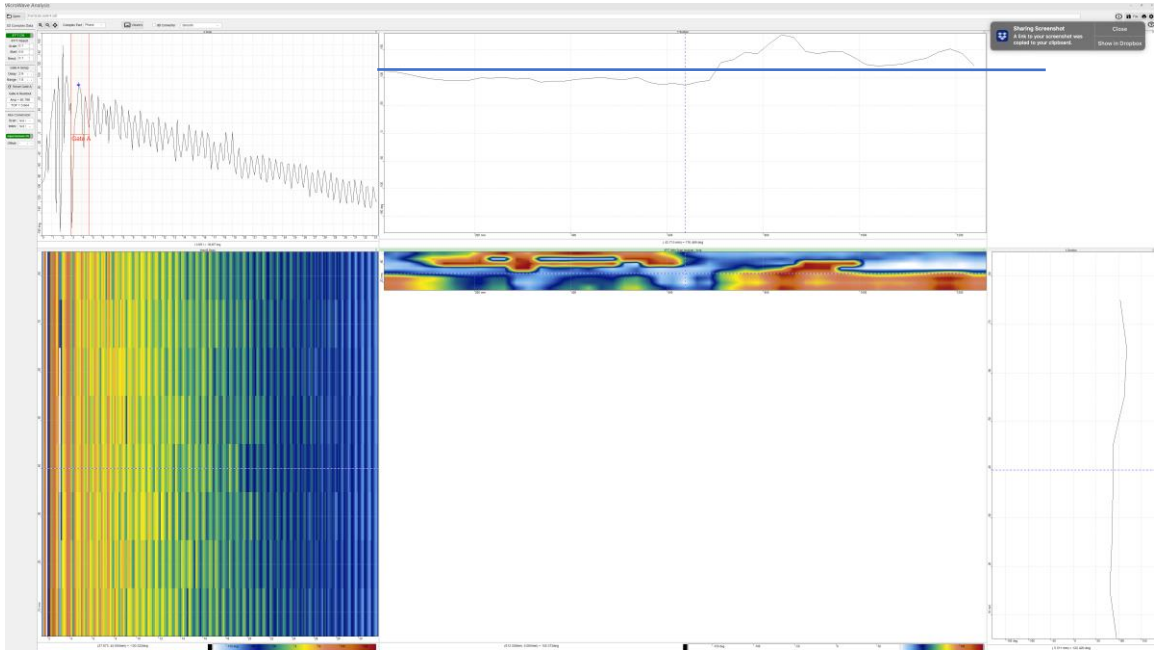
Sample Set Fusions 3 and 4



REJECT



REJECT

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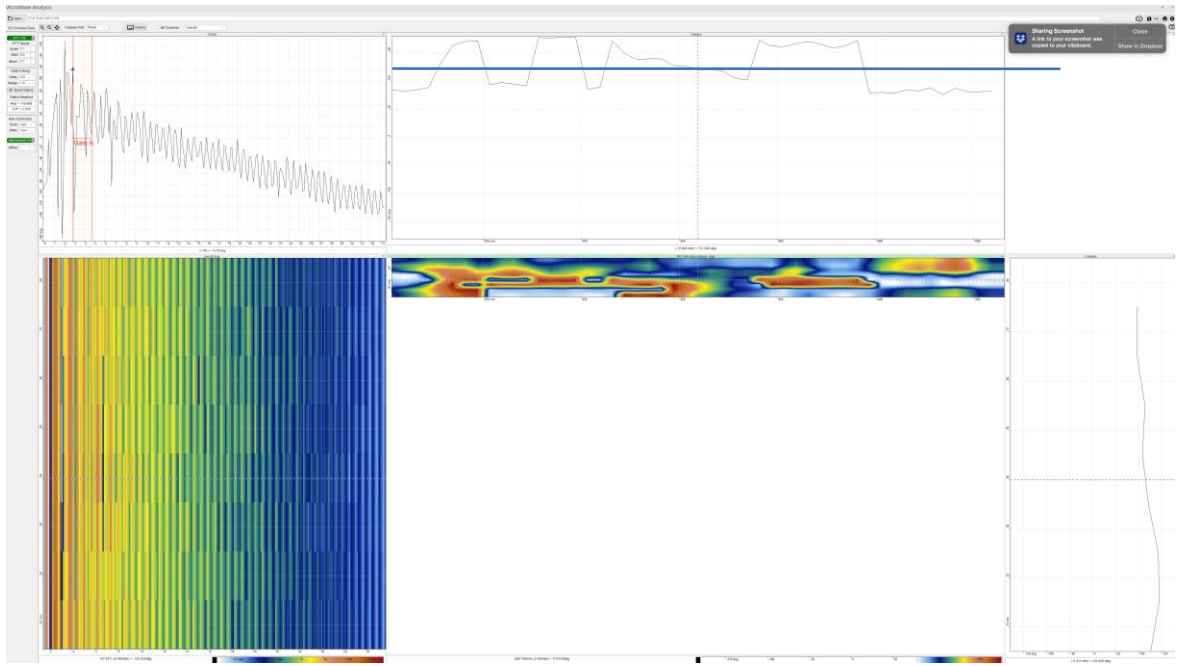
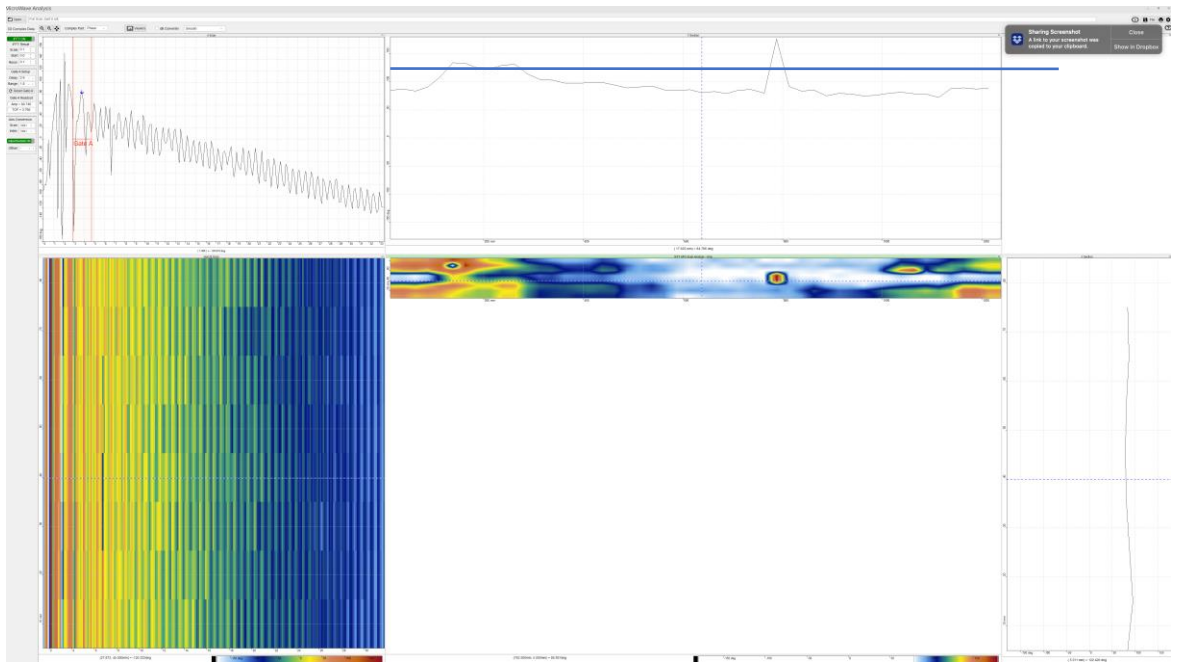
Sample Set Fusions 5 and 6



PASS



REJECT

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FUTURE PLANS

AMWI is advancing the technology of microwave inspection for all applications.

ADVACED MICROWAVE IMAGING

THE FUTURE OF MICROWAVE INSPECTION

Active Programs in AMWI

- Improve spatial and depth resolution using advanced analytical algorithms
  - MUSIC (**MU**ltiple **SI**gnal **C**lassification)
  - 3D Hologram of Part using SAFT as a stepping stone
- Produce new scanning platforms to enhance areas of usefulness
  - Microwave Inspection of Carbon Fiber
  - Hand held thickness gun (HDPE and Fiberglass)
  - Fully motorized pipe scanner
- Take advantage of new sensor packages
  - Direct Time of Flight Sensor Package
  - ID Inspection pipe PIG using TOF device
  - Lightweight 3-D printed antenna parts for drone mounted volumetric inspection equipment

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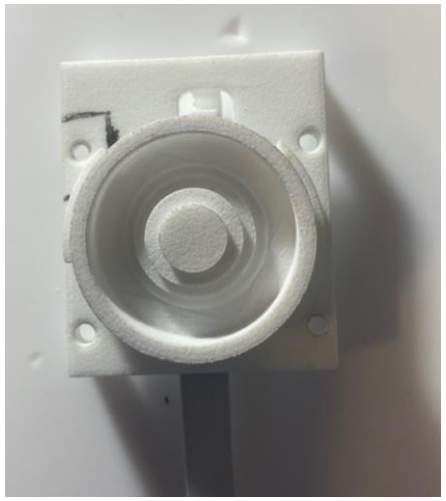
Time of Flight Microwave

Time of flight sensor is the one of the latest developments in MW inspection

Allows for true TOF detection capability



- Similar to UT Time Based Inspection
  - Microwave signal pulse generated at transmit antenna
  - Return reflected signal measured at receive antenna
  - Receive signal coherent with transmit signal
  - Time measured in Pico Seconds (10^{-12} Seconds)
- Speed of light 3^8 Meters per Second
- Distance resolution on the order of 0.3 MM (possible, depends on signal amplitude)

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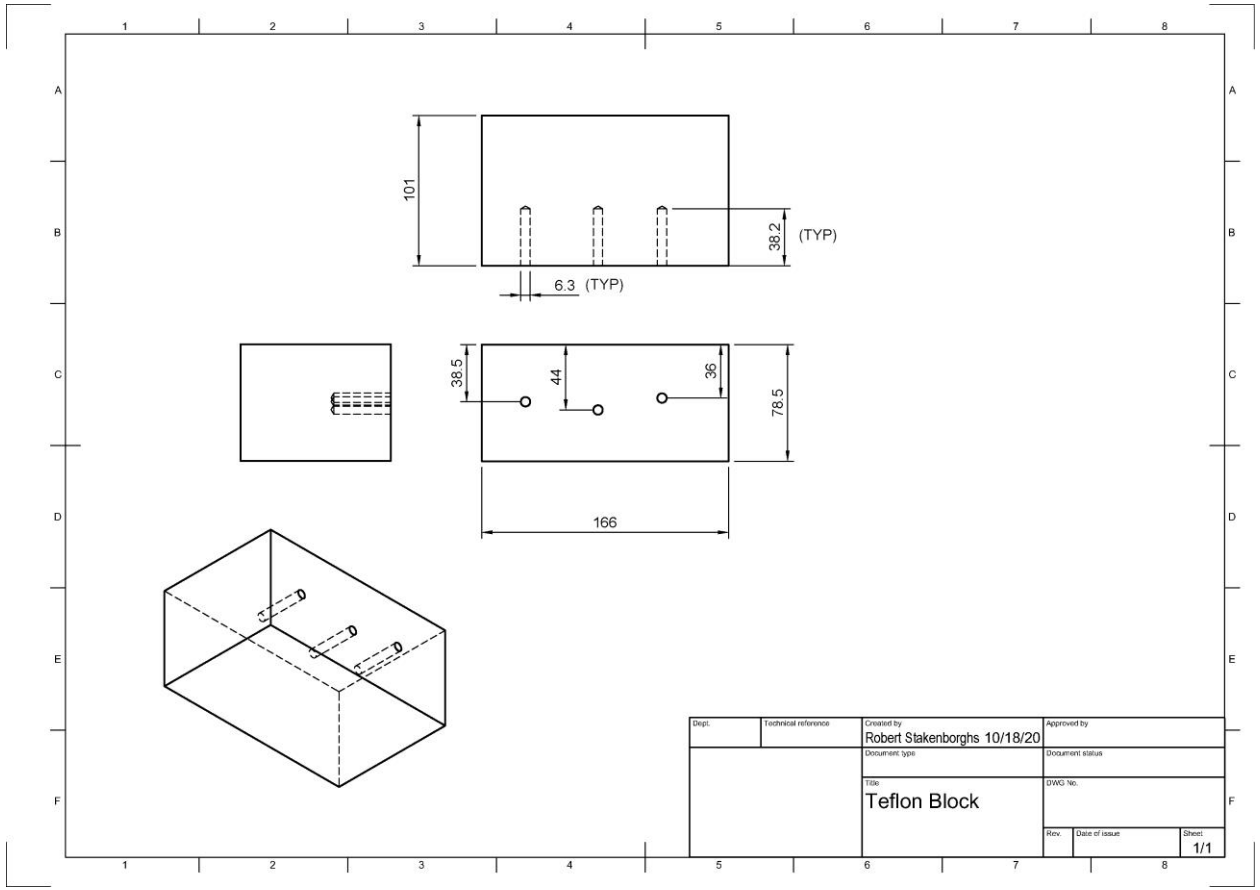
TOF Example

Teflon Block (Dielectric Constant = 2.1)



Depth Info
Back Wall = 78.5MM
Flaw 1 = 38.5 MM
Flaw 2 = 44MM
Flaw 3 = 36MM

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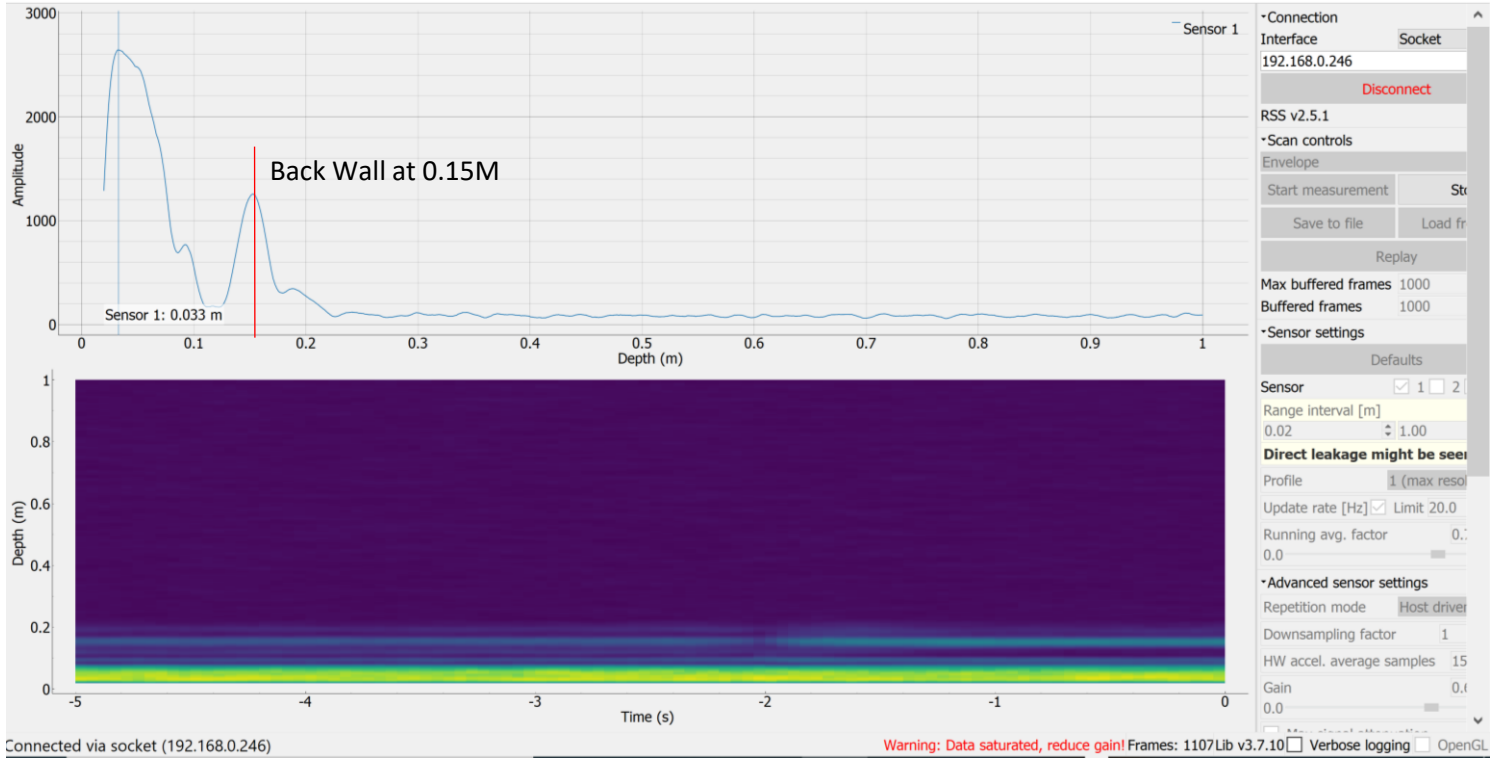
Back Wall Reflection Actual Depth = 78.5MM

Depth equals reflected signal (0.15M) minus front wall (0.033M) divided by square root of dielectric constant (1.45) equals 80.7MM



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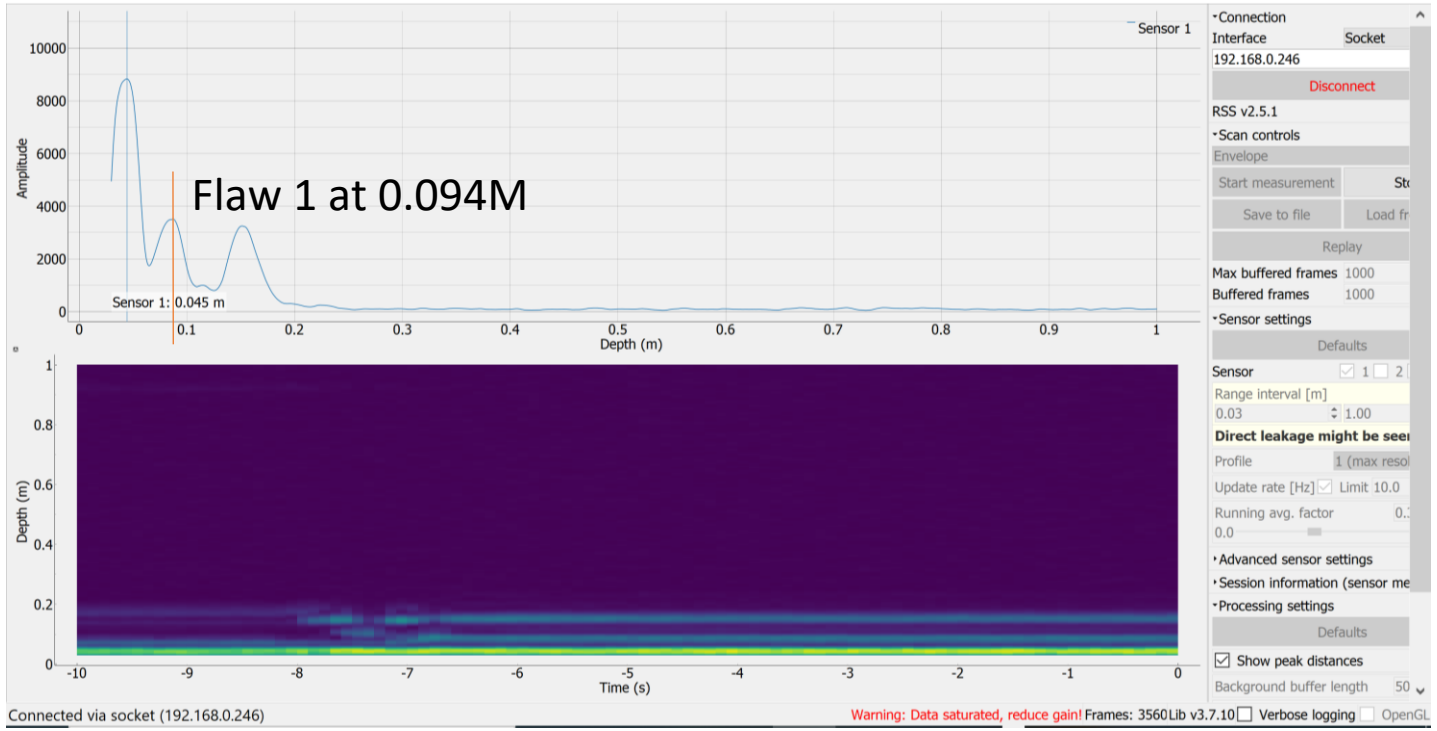
Flaw 1 (Left Hole) Actual Depth =38.5MM

Measured Depth =
(0.094M - 0.045M)/1.45
= 33.7MM



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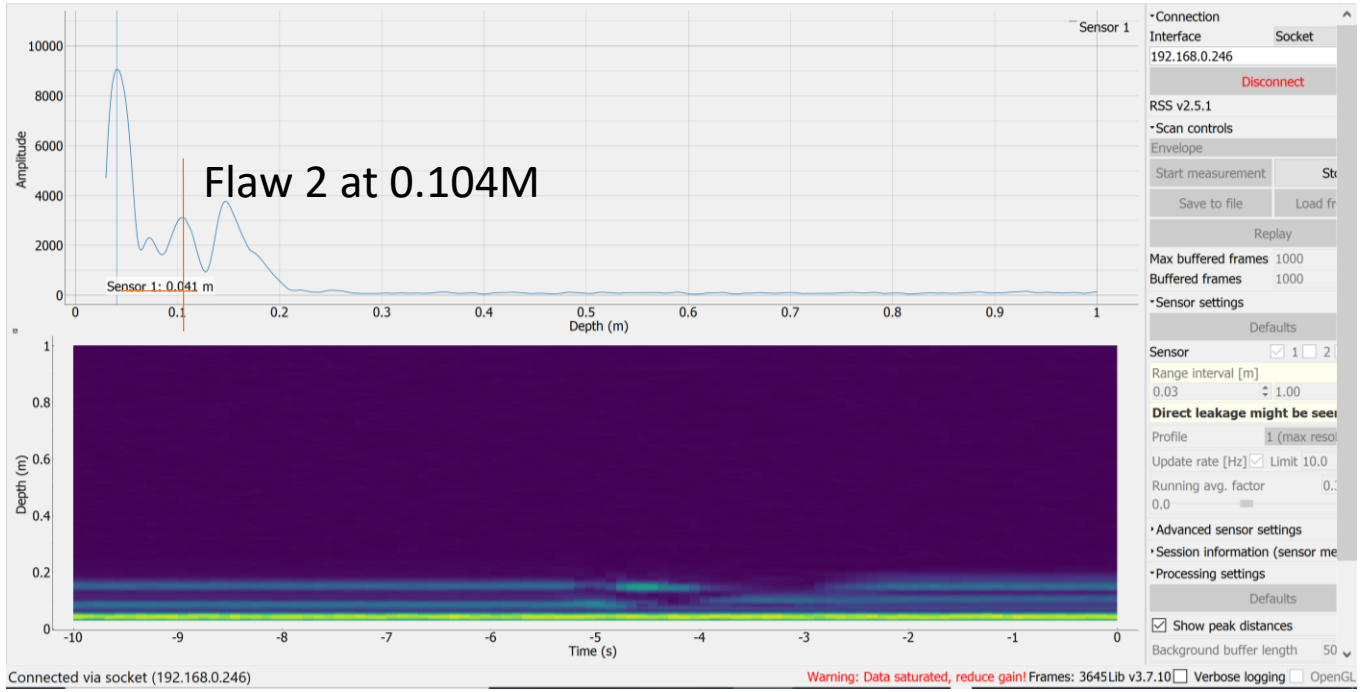
Flaw 2 Actual Depth = 44MM

Measured Depth =
(0.104M - 0.041M)/1.45
= 45MM



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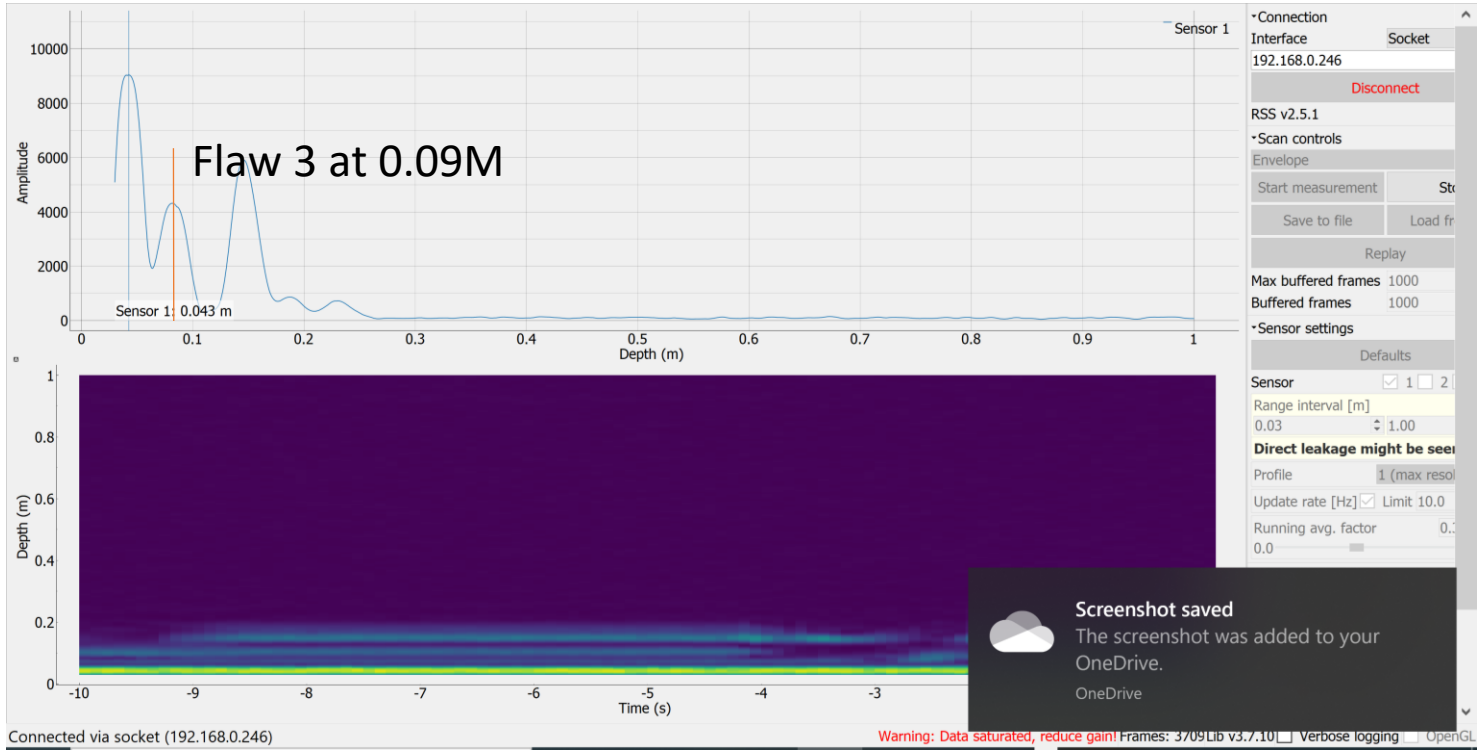
Flaw 3 (Right Hole) Actual Depth = 36MM

Measured Depth =
(0.09M - 0.043M)/1.45
= 32.4MM



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Comparison of Actual to Time of Flight Measured Flaw

ACTUAL LOCATION				MEASURED LOCATION			
1	2	3	4	1	2	3	4
Back Wall = 78.5MM	Flaw 1 = 38.5MM	Flaw 2 = 44MM	Flaw 3 = 36MM	Back Wall = 80.7 (+2.8%)	Flaw 1 = 33.7MM (-12.5%)	Flaw 2 = 45MM (+2.3%)	Flaw 3 = 32.4MM (-10%)

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Q & A

What can we answer for you?

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INSPECTION TECHNIQUES

MICROWAVE NDT INSPECTION TECHNIQUES FOR POWER GENERATION AND SPECIALTY APPLICATIONS

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With increasing use of nonmetallic materials in a variety of power generation applications, new opportunities are driving research and development of microwave inspection technologies.

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ADVANCED MATERIALS & PROCESSES | SEPTEMBER 2020

Microwave (MW) nondestructive testing (NDT) is defined as nondestructive inspection of a material using electromagnetic energy in the microwave frequency range as the interrogating medium. The microwave frequency range exists between radio waves and far infrared in the 300 MHz to 300 GHz frequencies. These frequencies roughly correspond to wavelengths between 1 m and 1 mm in a vacuum, respectively.

MW inspection operates in a similar fashion to ground penetrating radar (GPR). That is, the inspection device emits an electromagnetic energy beam in the microwave frequency range and then records the reflected signals from the material under test (MUT). See Fig. 1. These reflected signals are then represented visually, and the image interpreted based on its appearance. The two parameters that determine electromagnetic field propagation, as well as reflection and absorption, are the electrical permittivity and magnetic permeability of the space. This means the method can be used to penetrate any dielectric material for volumetric inspection as well to inspect the surface of metals. Today, MW NDT is commonly used in the inspection of rubber expansion joints in power plants, high density polyethylene (HDPE) butt fusion and electrofusion, fiberglass piping and joints, ceramic materials, and other specialty applications[2-4].

Fig. 1 — Microwave examination of Kevlar panel.

MICROWAVE INSPECTION STANDARDS

For any nondestructive testing method to be successfully used in industrial applications, the equipment needs to be standardized via national and/or international standards. These standards are developed to govern equipment calibration as well as provide information on training and certification of users and specific procedures for various materials. The following list identifies some codes that have been issued or are in progress to date:

- ASNT Recommended Practice No. SNT-TC-1A - 2016 Edition
- ASME Section III Appendix XXVI - HDPE Inspection 2017 Edition
- ASTM E3101-18 "Standard Practice for Microwave Examination of Polyethylene Butt Fusion Joints"
- ASTM E3102-18 "Standard Practice for Microwave Examination of Polyethylene Electrofusion Joints used in Piping Application"
- ISO - Microwave Inspection of HDPE Butt and Electrofusion Joints (in progress)
- ASTM - Standard Practice for Microwave Inspection of Fiber Reinforced Polymer Products (in progress)
- ASME Section V Article on Microwave Inspection (in progress)

Many of these standards are in development or have recently been updated, indicating the growth of new applications in this field.

HISTORICAL MICROWAVE RESEARCH

The Electric Power Research Institute (EPRI) has been involved in active microwave research projects since approximately 2005 when inspection of HDPE pipe fusions was emerging as a best practice in the nuclear power plant arena. This was followed by experimenting with microwave inspection on a sampling of HDPE fusions and inspecting rubber expansion joints in power plants (Fig. 2)[4-7]. These early research efforts were followed by several new projects based on industry input. Many of these were associated with fiberglass pipe inspection and carbon fiber pipe repair inspection. However, the largest project to date is focused on developing MW approaches for inspecting composite wind turbine blades.

INSPECTION OF WIND TURBINE BLADES

Utility-scale wind turbine blades are primarily made of fiberglass reinforced polymer (FRP) with various core materials as a small percentage of the total composition. Over time, blade

Fig. 2 — Microwave inspection of high-density polyethylene.

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