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High Accuracy Measurement of Prepreg Level of Impregnation using Non-Contact Ultrasound

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The Ultran Group, Inc.

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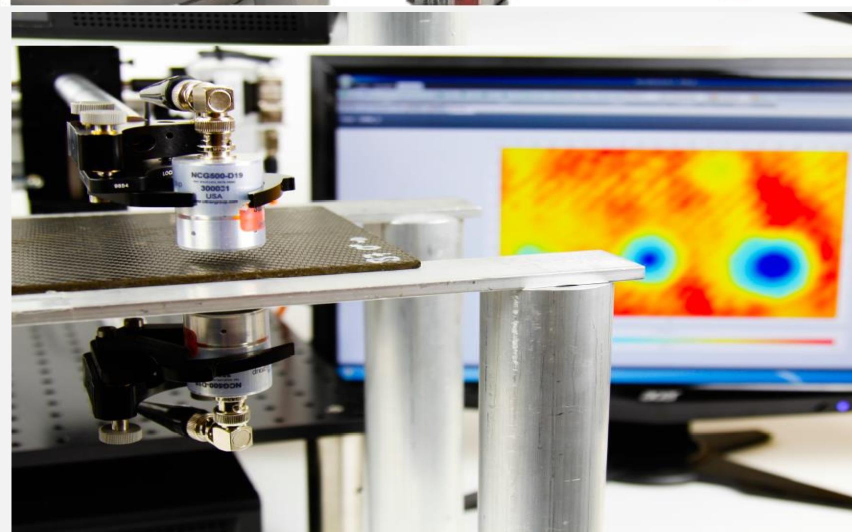
Project Introduction

Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 1

The Ultran Group is the pioneer of non-contact ultrasound and provides inspection systems for customers worldwide

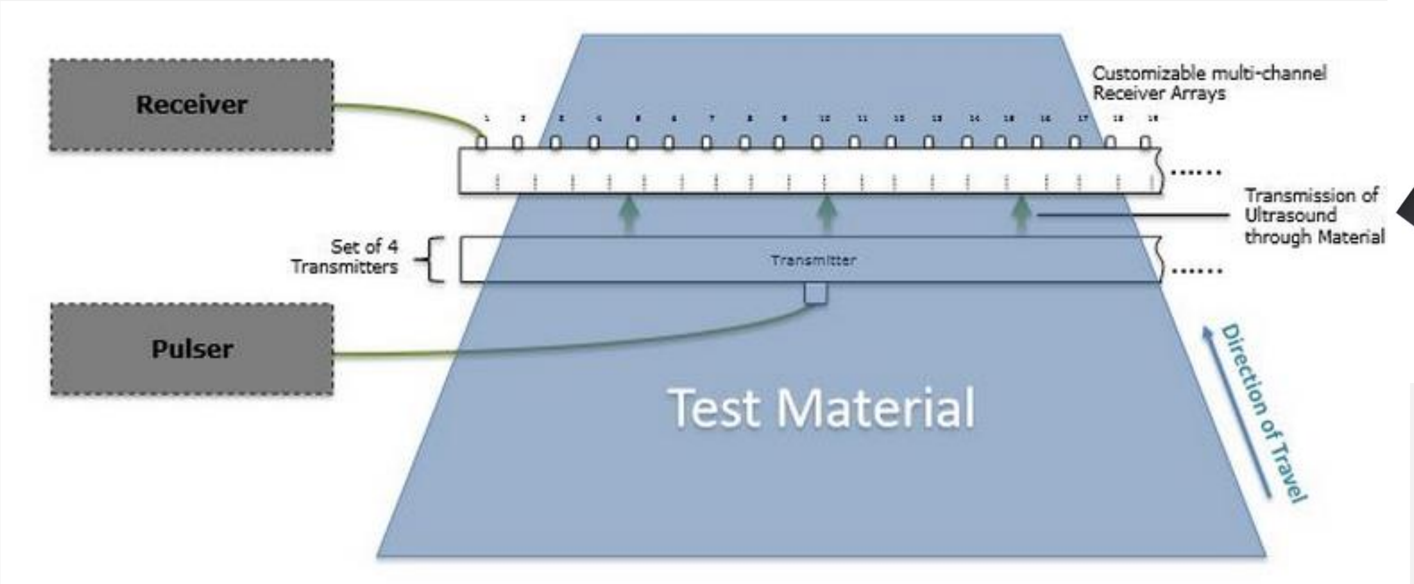
- The Ultran Group was founded in 1977
- Headquartered in State College, PA
- Additional offices in Hoboken, NJ and Minneapolis, MN
- Developed leading ultrasonic products, including transducers and systems for R&D and production quality control
- Initial advancements in non-contact (air-coupled) ultrasound were made in the late 1990s and optimized through the mid-2000s*
- Global presence with exports accounting for over half of sales
- Sales to numerous fortune 500 companies and major aerospace corporations



*US and International Patents

The Ultran Group supplies online NCU analysis systems for prepreg inspection

<u>Representation of Multi-Channel Online System for Continuous Inspection</u>



Modular 4-channel NCU Array

Designed and Produced
by The Ultran Group

Aurora Flight Sciences

- Design, analysis, testing, and manufacture of military and commercial manned and unmanned aerial vehicles.
- Headquartered in Manassas, VA
- Composites manufacturing facilities (WV & MS)
  - Lean aerospace manufacturing
  - Commercial & military manned & unmanned aircraft
  - >200,000 SF capacity
  - 7-axis Electroimpact AFP machine
  - 16' x 40' autoclave
  - NDI, Trimming, Machining, etc.
- R&D Center in Cambridge, MA

Our project team is composed of inspection experts, composite manufacturing specialists, and leading statistical researchers

Core Team Members

- **Kashyap Patel**, The Ultran Group (Principal Investigator)
- **Konstantine Fetfatsidis**, Aurora Flight Sciences – **D30.03 Subcommittee Member**
- **Anuj Bhardwaj**, The Ultran Group (Program Manager)

Supporting Groups

- McGill University, Center for Composite Research: Professor Pascal Hubert, Marc Palardy-Sim
- The Pennsylvania State University, Statistics Department
- Harvard University, Center for Nanoscale Systems
- Dr. Schenk of America, Optical Inspection Equipment & Analysis

SBIR Project Overview
Sponsored by U.S. Air Force Research Laboratory

- The Ultran Group was awarded a Phase I SBIR grant on August 1, 2014 to demonstrate feasibility of prepreg LOI measurement using NCU
    - Project conducted in partnership with Aurora Flight Sciences, Inc. – manufacturer of composite aerospace parts and UAVs
- Effort includes establishment of ASTM standard method for prepreg LOI measurement
    - ASTM adopted methods will become industry standard for measurement and certification of prepreg LOI
    - Future work will ensure that standard method is applicable to a wide variety of prepreg products
    - SBIR effort so far has proven feasibility and accuracy of prepreg LOI measurement to greater than 1% accuracy
- Tests conducted upon Cytec OOA IM7/5320-1 prepreg material provided for the SBIR effort.
- **Draft ASTM Standard has been balloted**

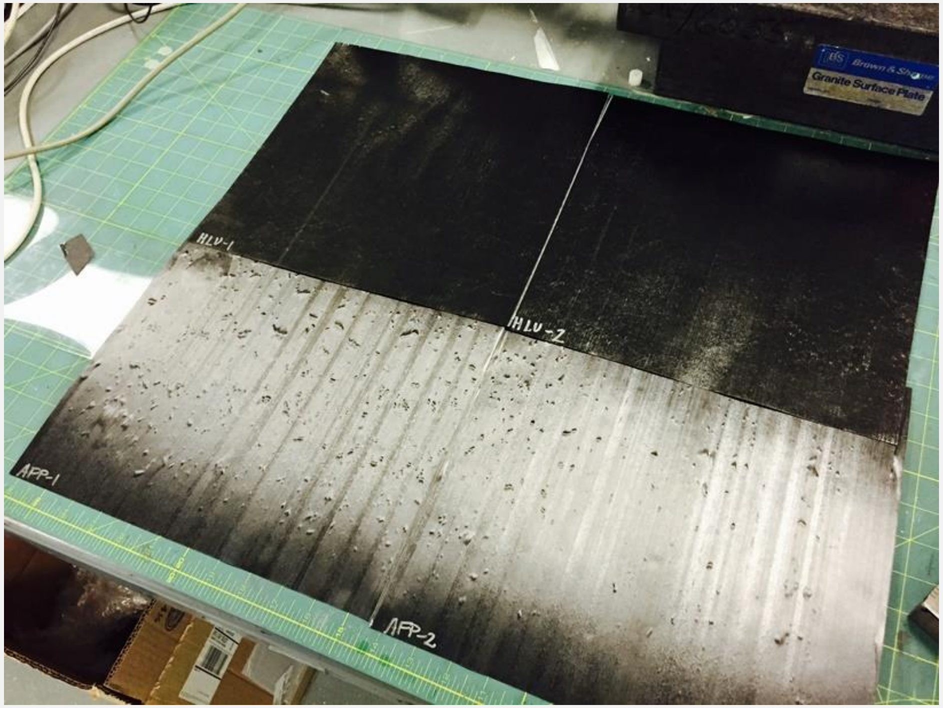
Methods of Analysis

- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 2

Prepreg material was provided by Cytec for the SBIR effort

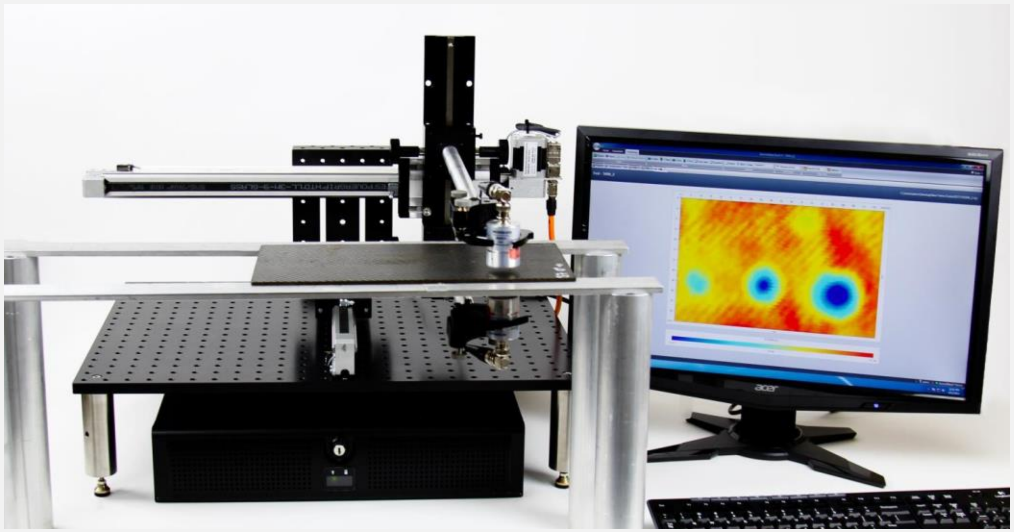
Prepreg Samples provided at 3 level of impregnation - cut in half to create 12" x 12" squares. Material Composition: IM7/5320-1

Material Type	Label	Size
Hand Layup (Low LOI)	HLU-1	12" x 12"
	HLU-2	
Automated Tape Layup	ATL-1	12" x 12"
	ATL-2	
Automated Fiber Placement	AFP-1	12" x 12"
	AFP-2	



Images were captured using the U710 Imaging system

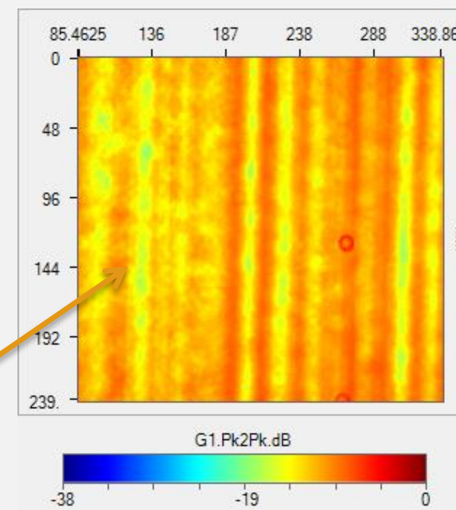
Ultran U710 Analysis System and Corresponding Imaging and Data



Scan Statistics	
Average Amplitude (dB)	-13.57
Standard Deviation	1.71
Highest Amplitude (dB)	-9.95
Lowest Amplitude (dB)	-20.59

Test area imaged for each sample – four corners marked and orientation saved

Image Capture and Scan Statistics



The first main set of analysis was to determine the optimal frequency range for analysis

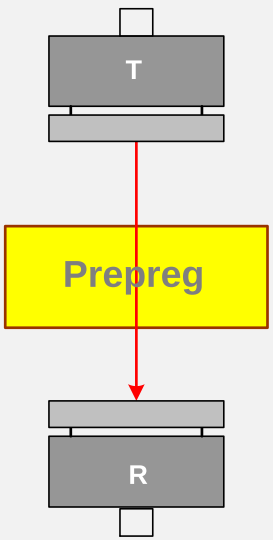
Settings and Transducer Types for Frequency Analysis

Frequency	NCU Transducer Model	Transmitter Transducer Serial Number	Receiver Transducer Serial Number	Active Diameter of Transducer	Gain	HPF	LPF
50 kHz	NCG50-D50	350175	350174	50 mm	50 dB	40 kHz	1000 kHz
100 kHz	NCG100-D25	370066	370065	25 mm	40 dB	40 kHz	1000 kHz
200 kHz	NCG200-D25	370061	370062	25 mm	40 dB	40 kHz	800 kHz
350 kHz	NCG350-D13	320094	320009	13 mm	52 dB	40 kHz	1000 kHz
500 kHz	NCG500-D19	300031	300284	19 mm	60 dB	40 kHz	1000 kHz
700 kHz	NCT700-D19	370396	370397	19 mm	62 dB	40 kHz	1000 kHz
1 MHz	NCT1-D13	300671	280251	13 mm	64 dB	40 kHz	1000 kHz
2 MHz	NCT2-D13	340324	340323	13 mm	84 dB	800 kHz	2000 kHz

- 8 Frequencies analyzed from **50 kHz to 2 MHz in through transmission**
- Two 12” x 12” samples analyzed at each level of impregnation (HLU, ATL, AFP)
  - 48 scans conducted for frequency analysis
  - Samples were also scanned with backing paper on at 3 frequencies: 200 kHz, 500 kHz, and 1 MHz. 18 additional scans performed (**66 total**)

Analysis was conducted in through transmission with transducers of varying size and frequency

Transducers used for analysis



Direct transmission route

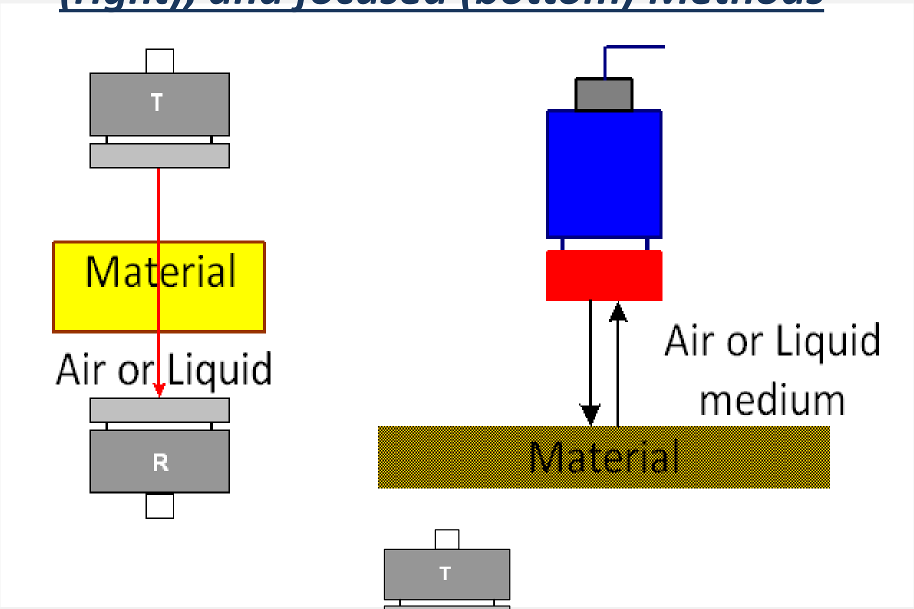
For the second set of analysis, additional variables were considered to determine the optimal test method

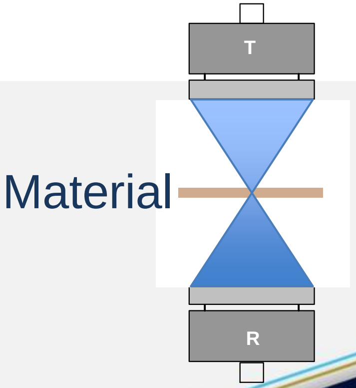
Additional Variables Considered

Focused ultrasound vs. Planar: The previous analysis was conducted using planar transducers. Focused ultrasound will provide higher spatial resolution as the spot size is significantly reduced (potentially <1mm)

Surface reflection data: Prior analysis was conducted using through transmission mode. While through transmission may provide the core information regarding LOI, reflection data may prove useful complementarily

Through Transmission (left), Reflection (right), and focused (bottom) Methods





The combinations of test conditions were arranged using a DOE test matrix

DOE Test Matrix		
Factors	Levels	Values
Ultrasonic Frequency	3	500 kHz, 700 kHz & 1 MHz
Focus Parameter	2	Focused & Planar
Inspection Mode	3	Top reflection, bottom reflection, & through transmission
LOI	3	High, Medium, & Low

- Test matrix consisted of 4 variables at multiple levels with a single replicate (4 samples)
- **Total scans performed = 216**
- Increased sample size to obtain more accurate correlation

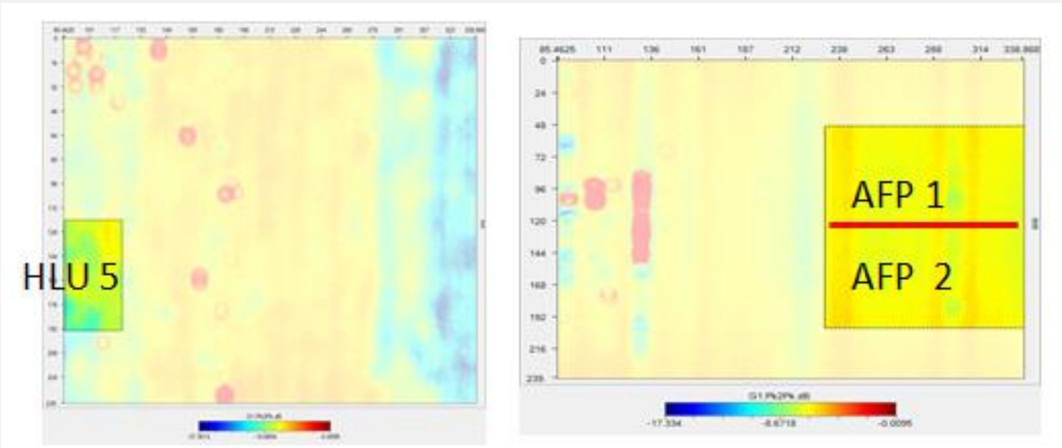
Initial tests conducted with paper backing to simulate inline test conditions

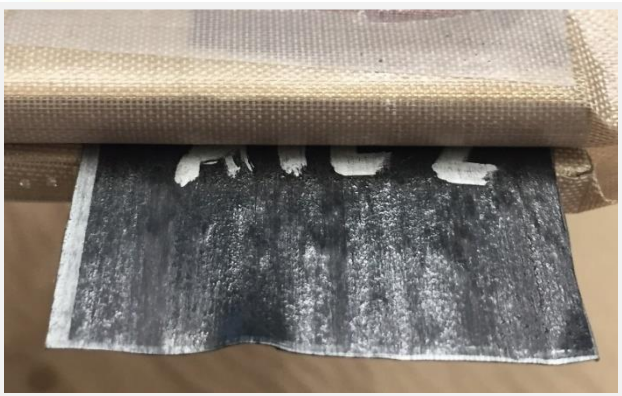
- Ultran was advised to consider conditions where the prepreg paper backing is not removed
  - Analysis with paper backing is required for measurement online during manufacturing
- Majority of analysis conducted has been performed upon prepreg with no backing to allow for ideal conditions which are viable for an offline test
- Initial analysis conducted upon first set of IM7/5320-1 samples provided by Cytec (designated for frequency analysis)
- Additional analysis will be conducted a wider variety of materials

Secondary test methods

- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 3

Use of a guided water pickup test can be used to create a very accurate correlation function between NCU transmittance and prepreg LOI*





Guided Water Pickup Test

- Larger areas of samples are imaged using NCU
- Areas with high uniformity are selected to test for water pickup
  - Test accuracy of standard water pickup test is greatly improved by choosing areas of high uniformity
  - High uniformity allows water to flow unrestricted through sample
  - Accuracy improved from +/- 5% to approximately +/-1%
- Following water pickup the samples are weighed to determine level of impregnation

*US Patent Pending

X-ray MicroCT is used as another method to qualitatively analyze porosity of prepreg

MicroCT Imaging System at Harvard University

Cross Section View in MicroCT of IM7/5320-1 Prepreg Sample*

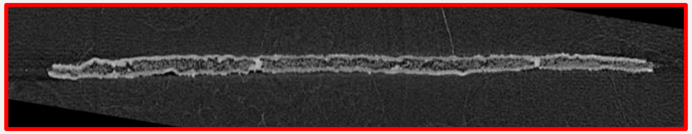


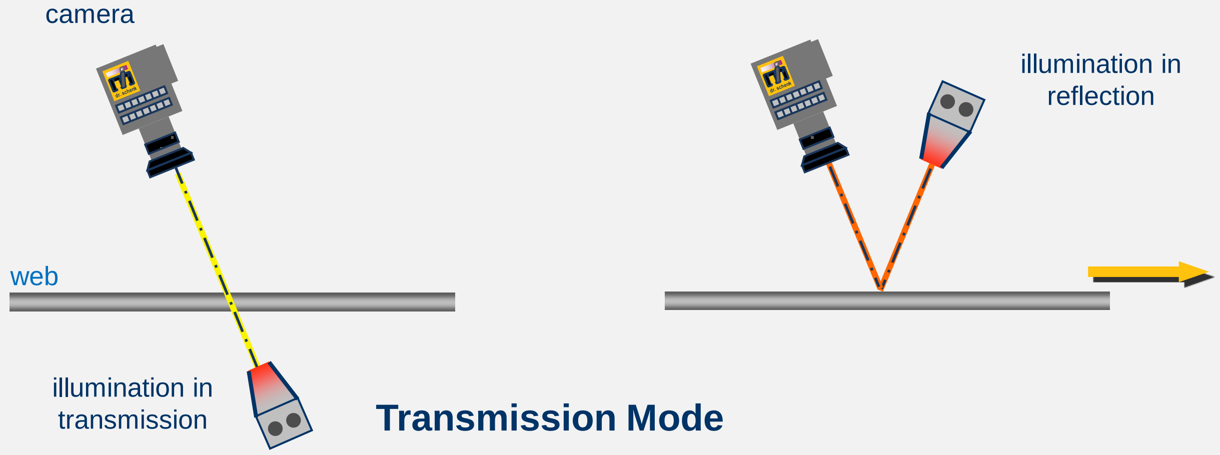
*Image produced by McGill University

- Aurora Flight Sciences has conducted MicroCT analysis at the Harvard University Center for Nanoscale Systems
  - Multi-layer laminates of cured CFRP have been successfully analyzed using MicroCT to detect porosity variation and delamination
- We have also begun working with Professor Pascal Hubert at McGill University in Montreal, Canada
  - Professor Hubert and his student, Marc Pallardy-Sim have extensive experience analyzing composite materials using MicroCT
  - Their research center, the Structured Composites Material Laboratory, at McGill has analyzed select material which we have provided to them

We conducted experiments with Dr. Schenk, an optical inspection technology company, to study relationship between NCU and surface photography

Optical analysis conducted in reflection and through transmission modes

Reflection Mode



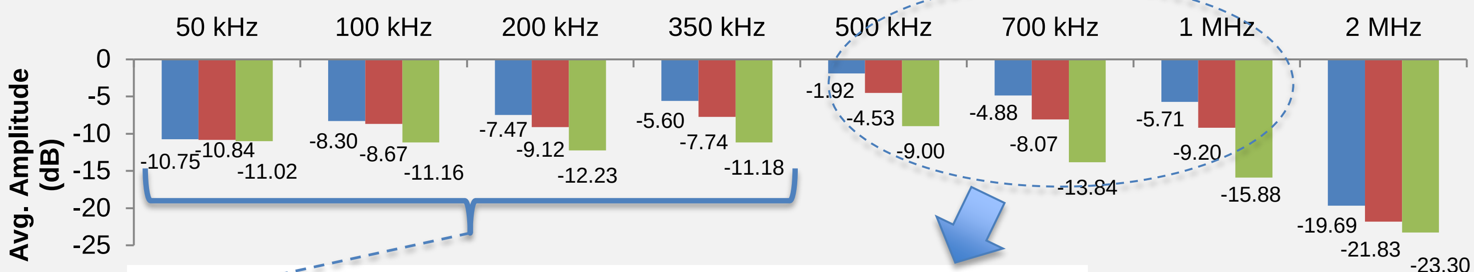
Transmission Mode

NCU LOI Measurement Results & Accuracy

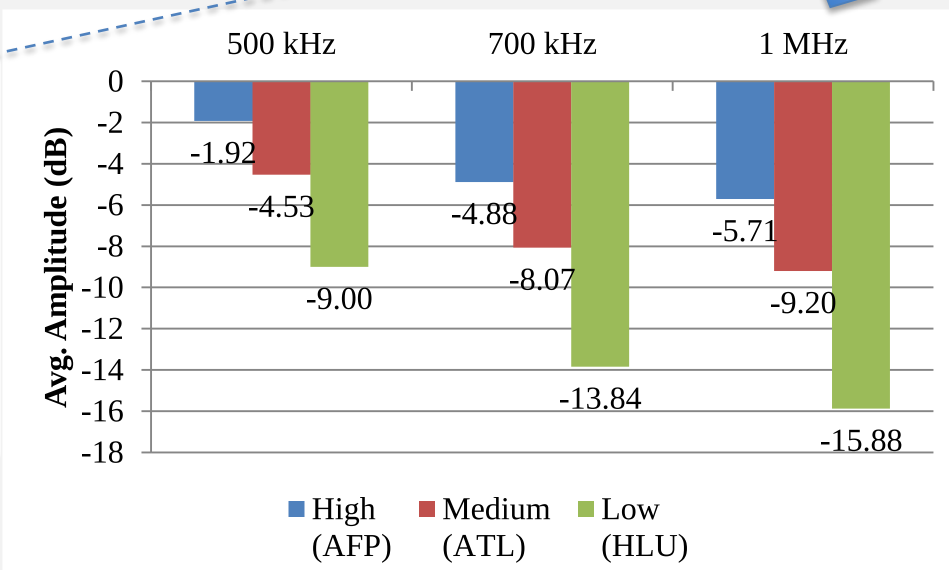
- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 4

Following frequency analysis, it was determined that optimal frequencies of measurement are from 500 kHz to 1 MHz

Sensitivity of Ultrasonic Transmittance to Prepreg LOI Variation at frequencies from 50 kHz to 2 MHz



Lower frequencies exhibited some saturation in measurement and lower sensitivity to change in LOI. 2 MHz exhibited some areas of no signal amplitude

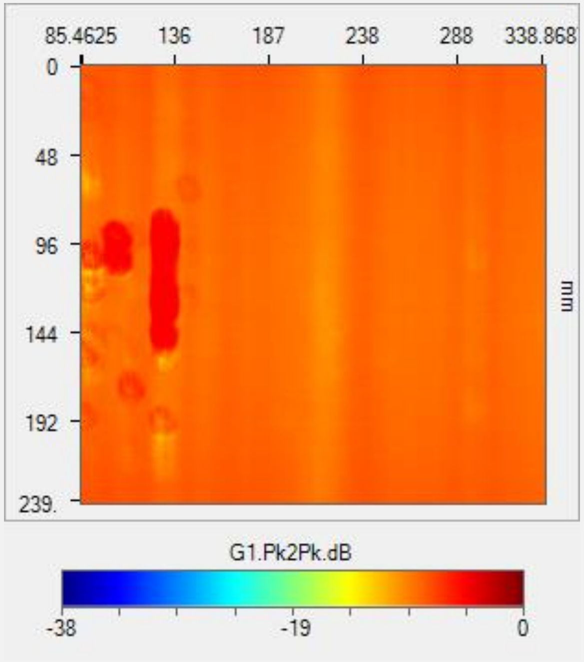


Highest sensitivity and correlation to prepreg LOI variation found at 500 kHz, 700 kHz, and 1 MHz

A clear reduction in signal amplitude is present when the level of impregnation drops

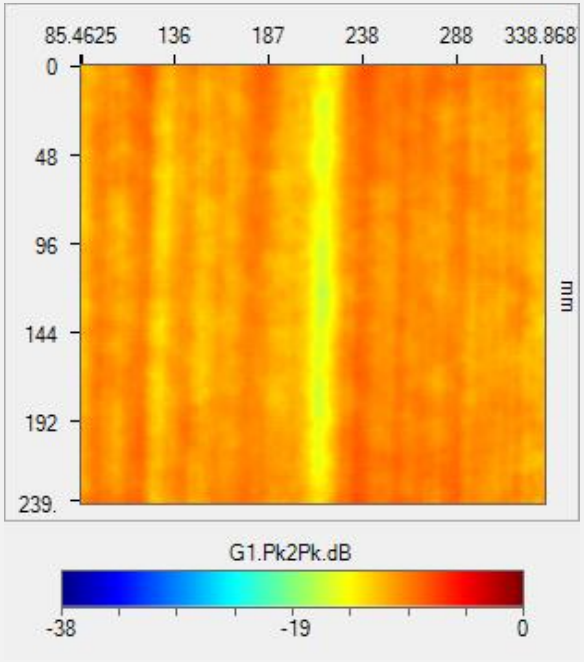
Ultrasonic C-scan Images of AFP, ATL, and HLU Samples at 700 kHz in Through Transmission

AFP



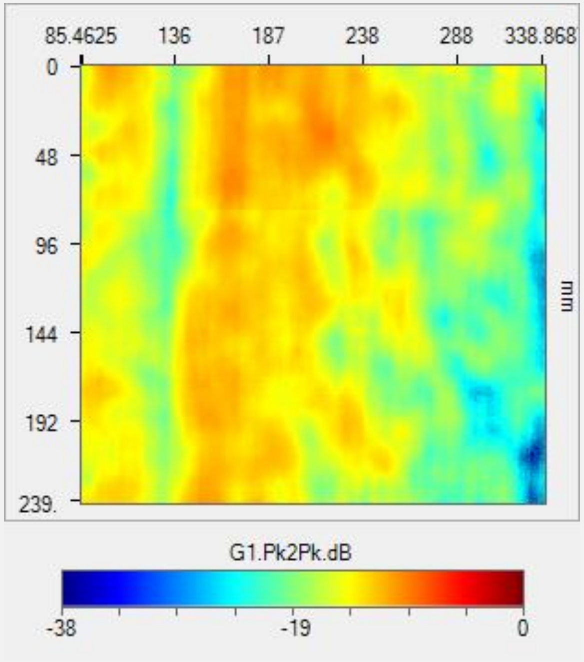
Ave. Ultrasound Signal: -4.64 dB

ATL



Ave. Ultrasound Signal: -8.15 dB

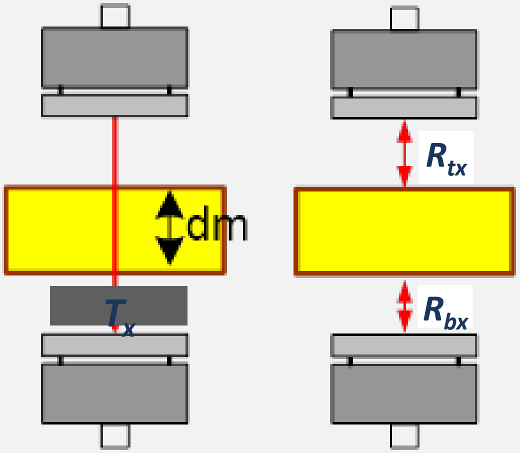
HLU



Ave. Ultrasound Signal: -12.78 dB

By adding new input variables acquired by NCU, accuracy of prepreg LOI measurement can be increased*

Schematic of Reflection and Transmission Signals



Additional Variables of NCU Analysis

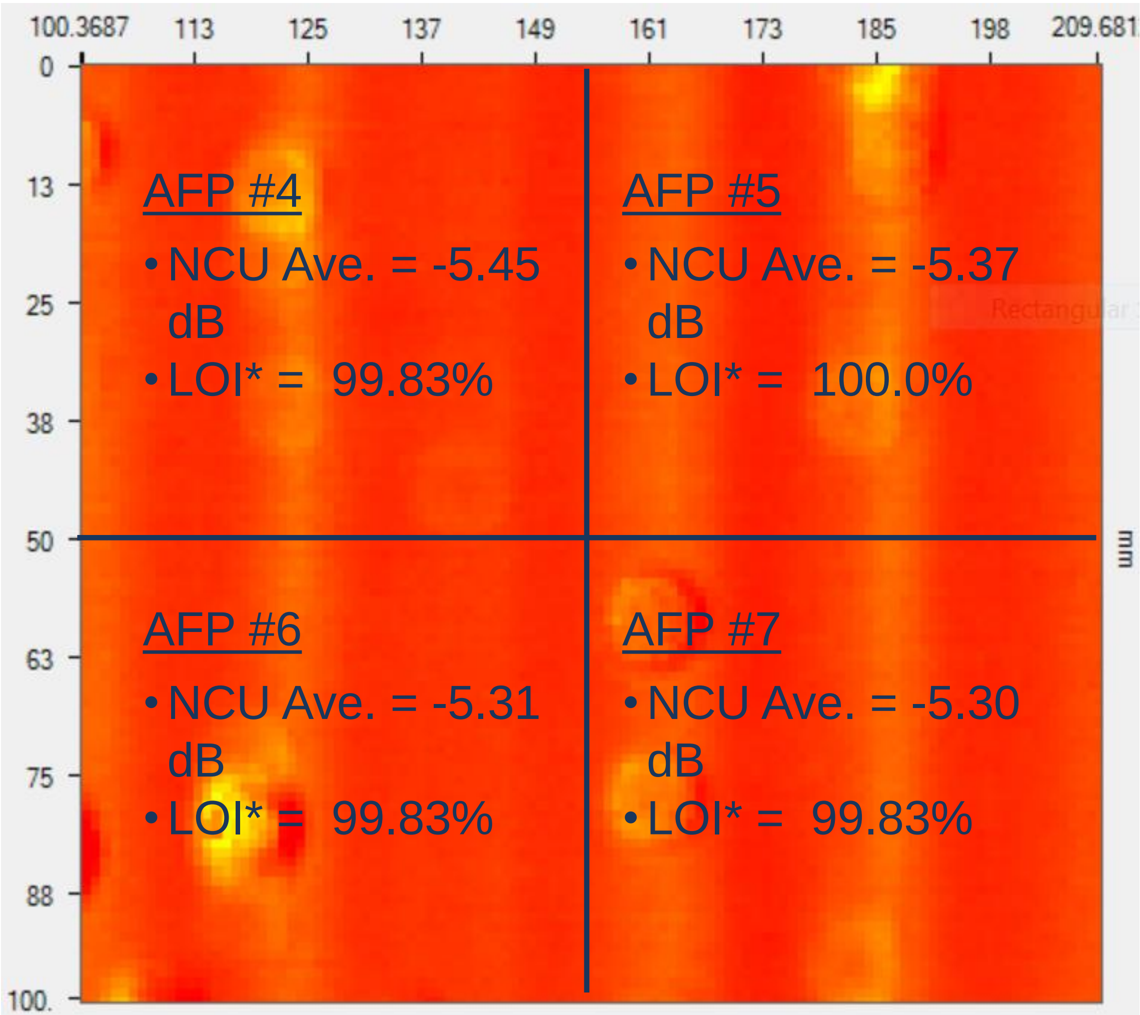
T_x: NCU Transmittance (planar)
T_{xfo}: NCU Transmittance (focused)
R_{tx}: NCU Reflectance (top surface)
R_{bx}: NCU reflectance (bottom surface)
T_{xf1}: NCU Transmittance (frequency 1)
T_{xf2}: NCU Transmittance (frequency 2)
V: Velocity
Fp: Peak Frequency
Fb: Signal Bandwidth

- Prior correlation functions considered only one variable; T_x at 1 frequency
- Analysis can include correlation functions with numerous variables, including reflectance values and transmission/reflection at different frequencies
- A correlation function can include limitless variables as follows (linear example):

$$\%imp = m(T_x) + n(R_{tx}) + j(T_{xf1}) + k(T_{xf2}) + l(F_b)..... + b$$

*US Patent Pending

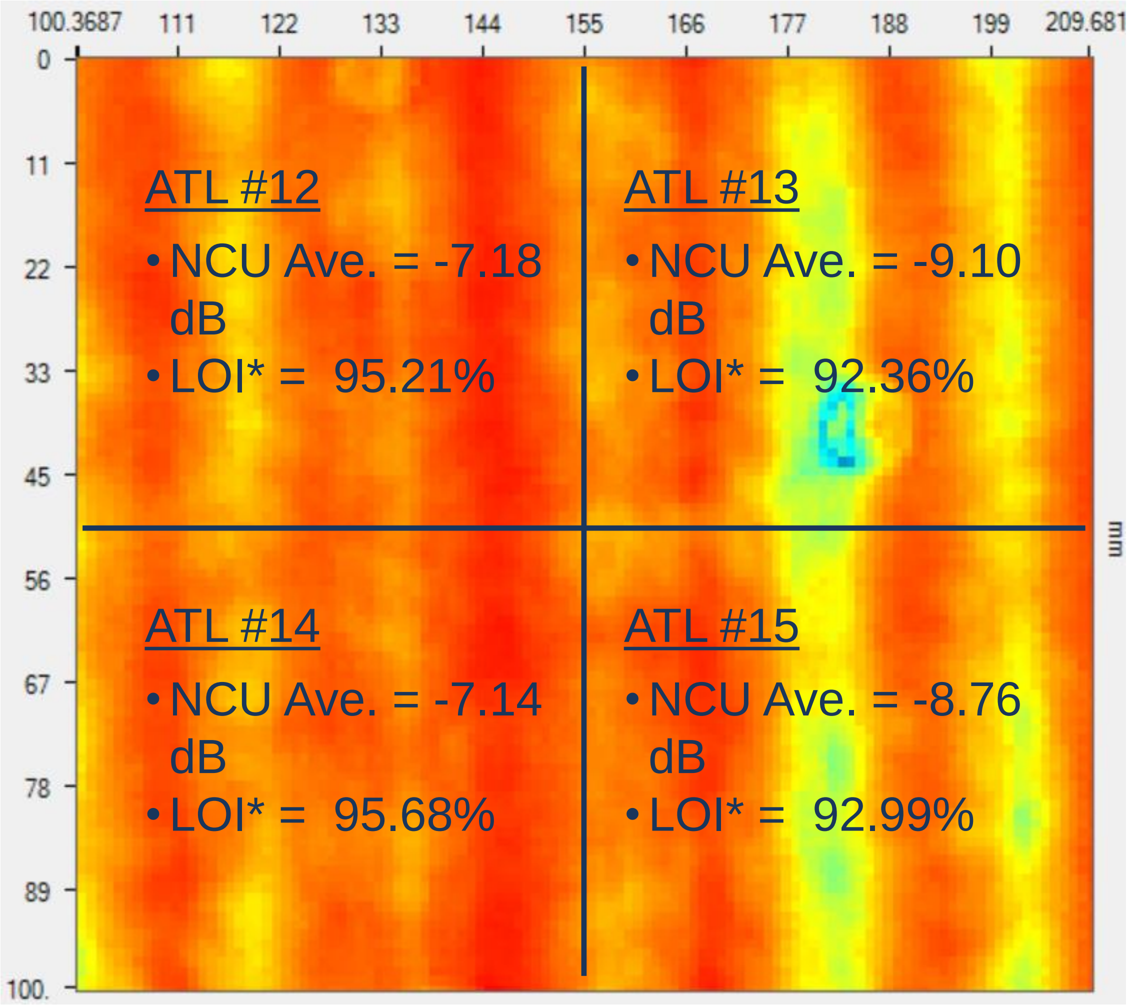
AFP (High LOI) Samples 5-8: NCU Image at 1 MHz through transmission (single variable only)



- AFP samples are nearly 100% impregnated
- NCU average values are very high, showing high transmittance through well-impregnated material
- Localized striping pattern is noticed. Likely caused by ridges in nip rolls used to infuse resin

*Actual level of impregnation as measured by guided water pickup test

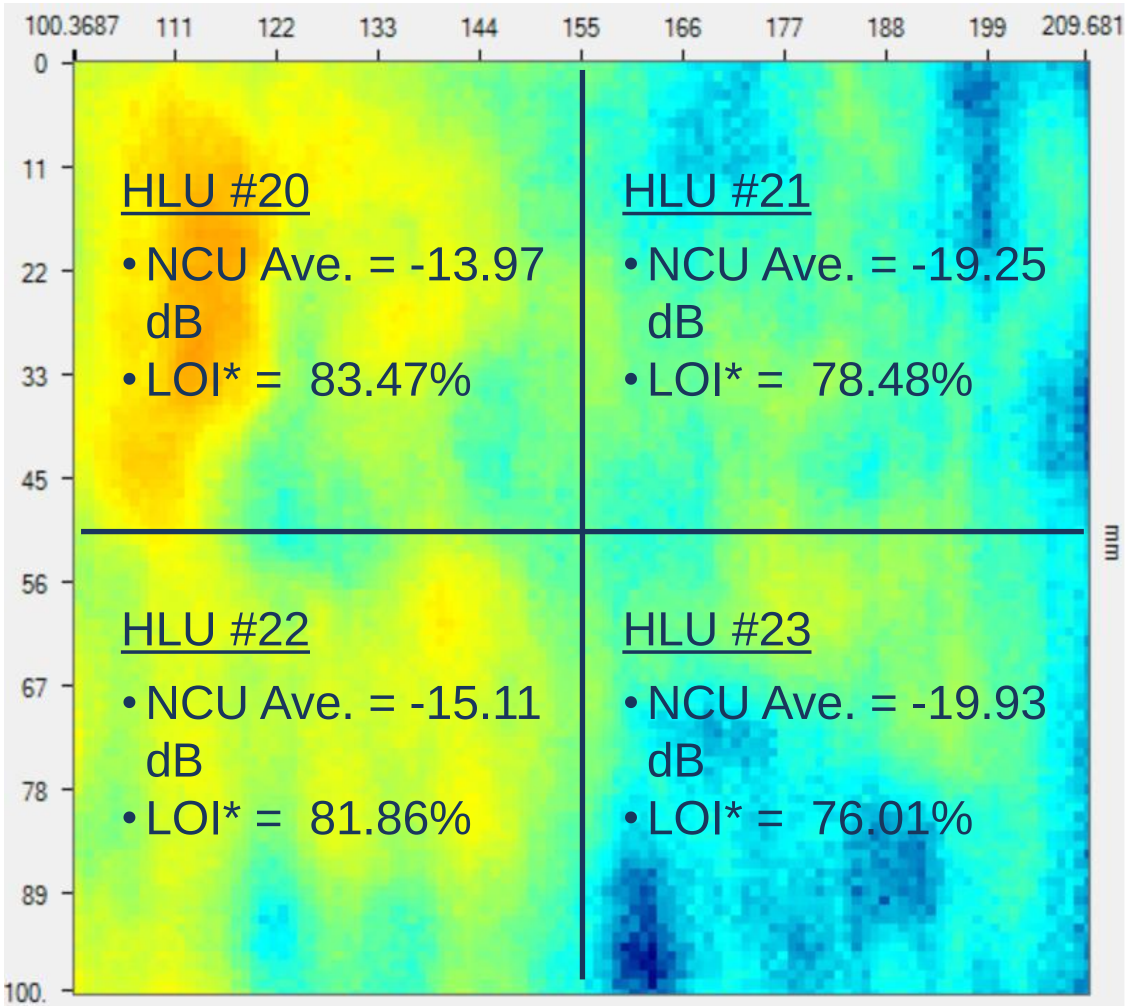
ATL (Medium LOI) Samples 13-16: NCU Image at 1 MHz through transmission (single variable only)



- ATL samples are impregnated between 92-96%
- NCU average values reflect even minute variations in LOI
- Localized striping pattern is noticed. Likely caused by ridges in nip rolls used to infuse resin

*Actual level of impregnation as measured by guided water pickup test

HLU (Low LOI) Samples 21-24: NCU Image at 1 MHz through transmission (single variable only)



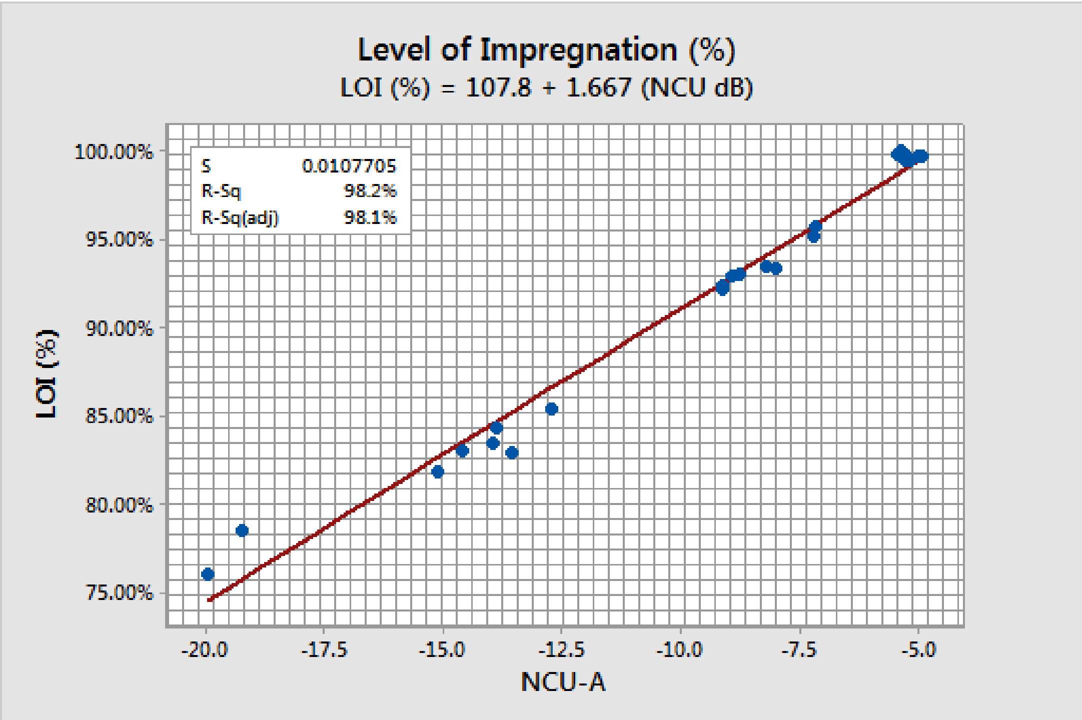
- HLU samples are impregnated between 76-84%
- Higher variation within and between samples is detected in NCU
- NCU data can clearly detect localized variation in LOI

*Actual level of impregnation as measured by guided water pickup test

4

LOI correlation to NCU transmittance at 1 MHz (single variable)

Graphical and Tabular representation of NCU Transmittance vs. Prepreg LOI (single variable) †



Prepreg Type	Sample #	NCU Tx (dB)	GWPU (%)	LOI (%)
AFP	1	**-4.99**	0.34%	**99.66%**
	2	**-5.27**	0.50%	**99.50%**
	3	**-4.94**	0.34%	**99.66%**
	4	**-5.18**	0.51%	**99.49%**
	5	**-5.45**	0.17%	**99.83%**
	6	**-5.37**	0.00%	**100.00%**
	7	**-5.31**	0.17%	**99.83%**
	8	**-5.30**	0.17%	**99.83%**
ATL	9	**-8.19**	6.59%	**93.41%**
	10	**-8.93**	7.11%	**92.89%**
	11	**-7.98**	6.69%	**93.31%**
	12	**-9.13**	7.86%	**92.14%**
	13	**-7.18**	4.79%	**95.21%**
	14	**-9.10**	7.64%	**92.36%**
	15	**-7.14**	4.32%	**95.68%**
	16	**-8.76**	7.01%	**92.99%**
HLU	17	**-12.70**	14.63%	**85.37%**
	18	**-13.89**	15.65%	**84.35%**
	19	**-13.56**	17.06%	**82.94%**
	20	**-14.58**	17.01%	**82.99%**
	21	**-13.97**	16.53%	**83.47%**
	22	**-19.25**	21.52%	**78.48%**
	23	**-15.11**	18.14%	**81.86%**
	24	**-19.93**	23.99%	**76.01%**

† Data filtered to remove pinhole effect

- There is a very strong and direct relationship between NCU transmittance and prepreg LOI
- **R^2 = 98.2%, S = 1.08% (error of measure)**
- The accuracy of the correlation function can be increased further by adding additional transmittance variables (i.e. multiple frequencies)*

*US Patent Pending

Inclusion of multiple variables (i.e. more than 1 frequency & focused + planar) and separating functions by product type can increase correlation and accuracy of measurement*†

	1 MHz Planar (single Variable)	1 MHz & 500 kHz Planar	1 MHz Planar & 500 kHz Focused	1 MHz planar & 1 MHz focused
Linear Function (single equation)	**R^2 = 98.16%** **S = 1.08%**	**R^2 = 98.40%** **S = 1.03%**	**R^2 = 98.27%** **S = 1.07%**	**R^2 = 98.79%** **S = 0.89%**
Quadratic Function (single equation)	**R^2 = 99.43%** **S = 0.61%**	**R^2 = 99.57%** **S = 0.56%**	**R^2 = 99.52%** **S = 0.59%**	**R^2 = 99.67%** **S = 0.49%**
Linear Function (three equations)††	**R2 = 99.59%** **S = 0.53%**	**R^2 = 99.67%** **S = 0.49%**	**R2 = 99.77%** **S = 0.43%**	**R^2 = 99.59%** **S = 0.55%**

While inclusion of variables enhance accuracy, the best combination of accuracy and ease of measurement is 1 MHz planar with 3 linear correlation functions for IM7/5320-1 prepreg

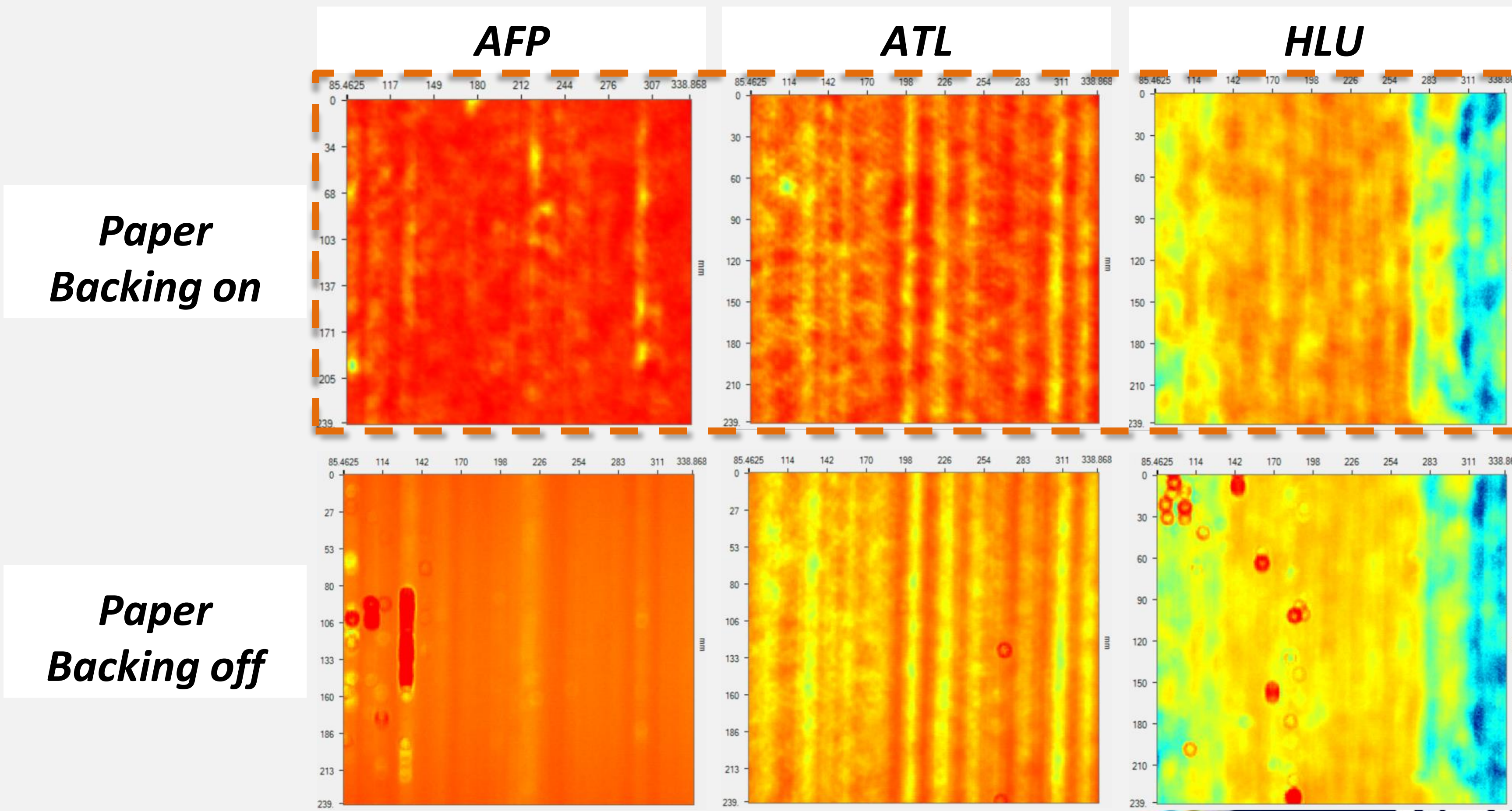
† † Separate equation is applied to each AFP, ATL, and HLU

*US Patent Pending

† Data filtered to remove pinhole effect

Initial analysis upon samples with paper backing demonstrate similar ability to measure varying levels of impregnation

C-scan Images of Samples with and without Paper Backing (1 MHz transmission) – From Initial Frequency Analysis

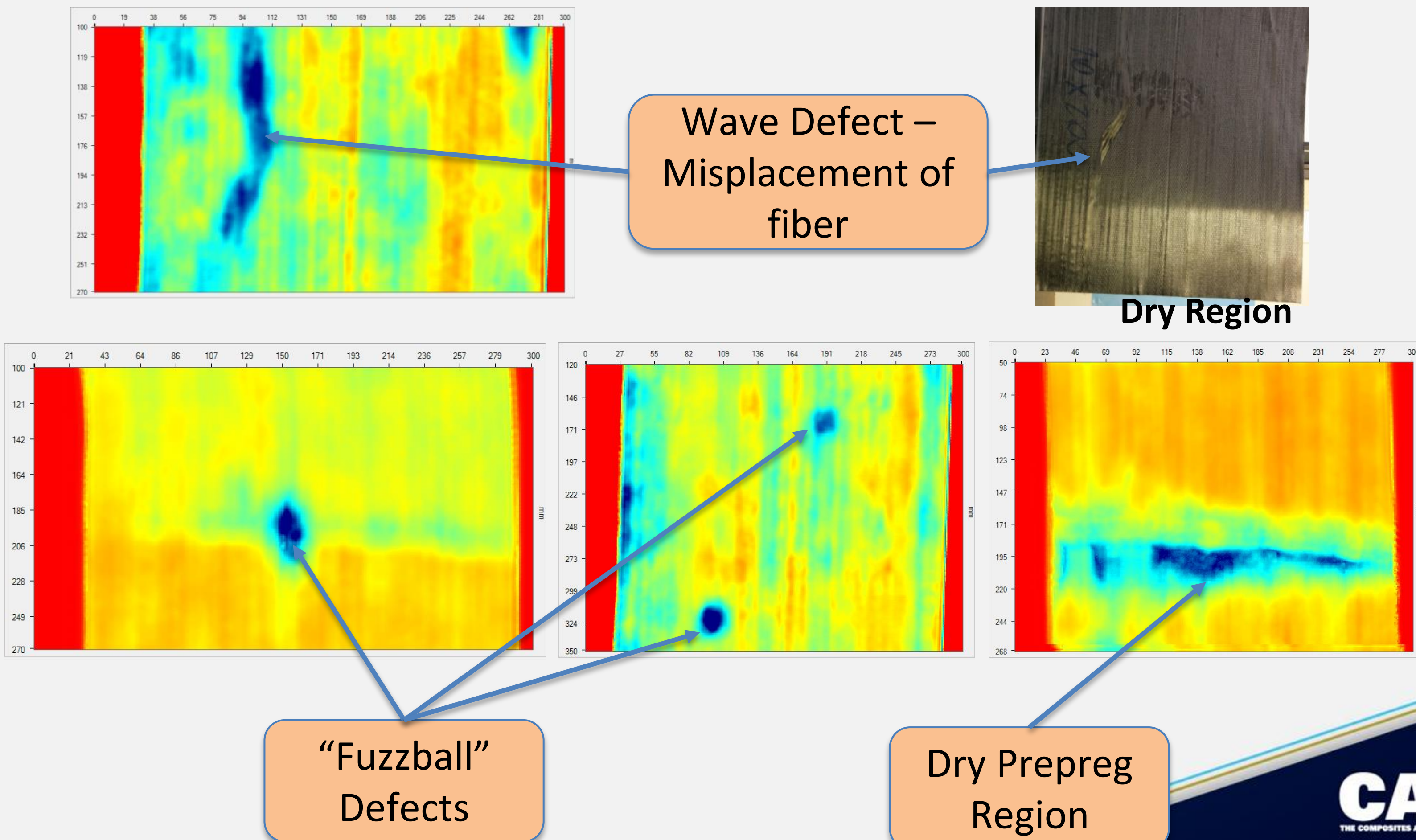


Other Prepreg products

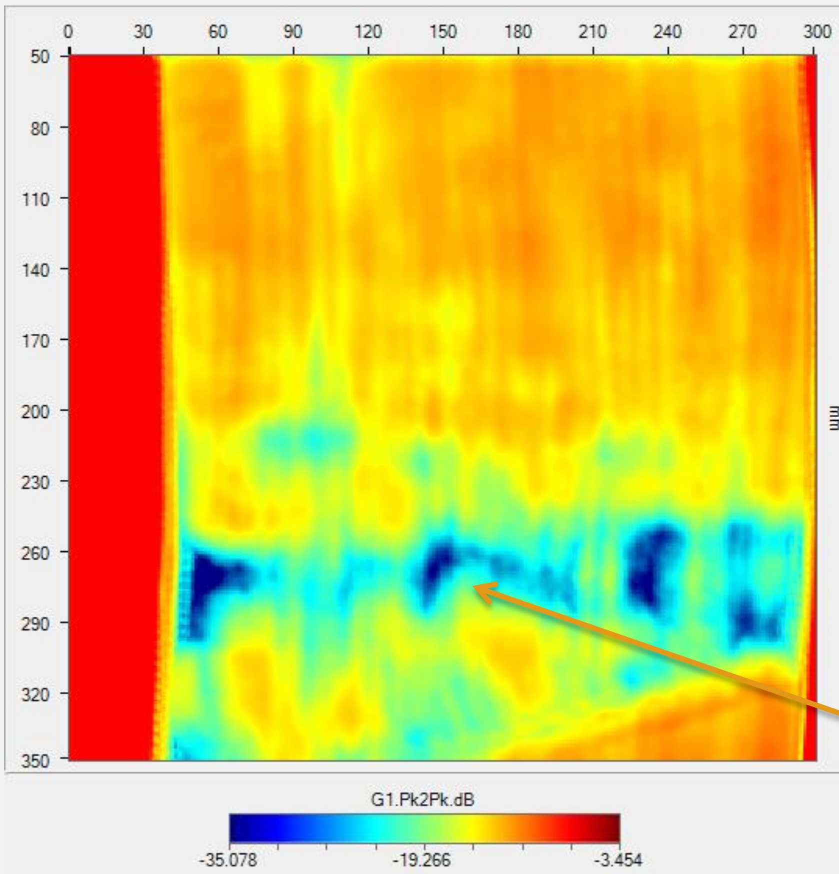
- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 5

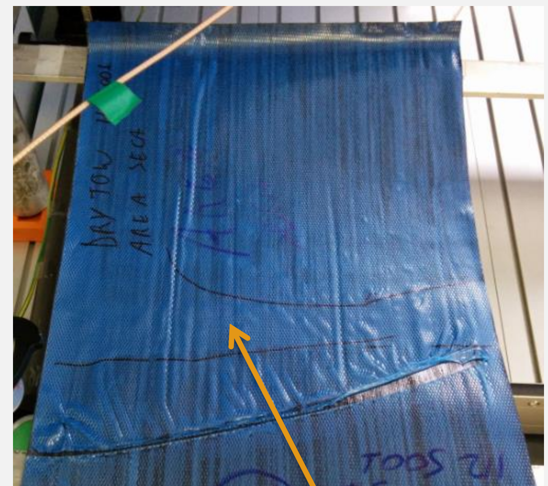
Certain analysis has also been conducted upon other prepregs, such as wind turbine blade material

Wind Turbine Grade Carbon Fiber Prepreg with Various Defects



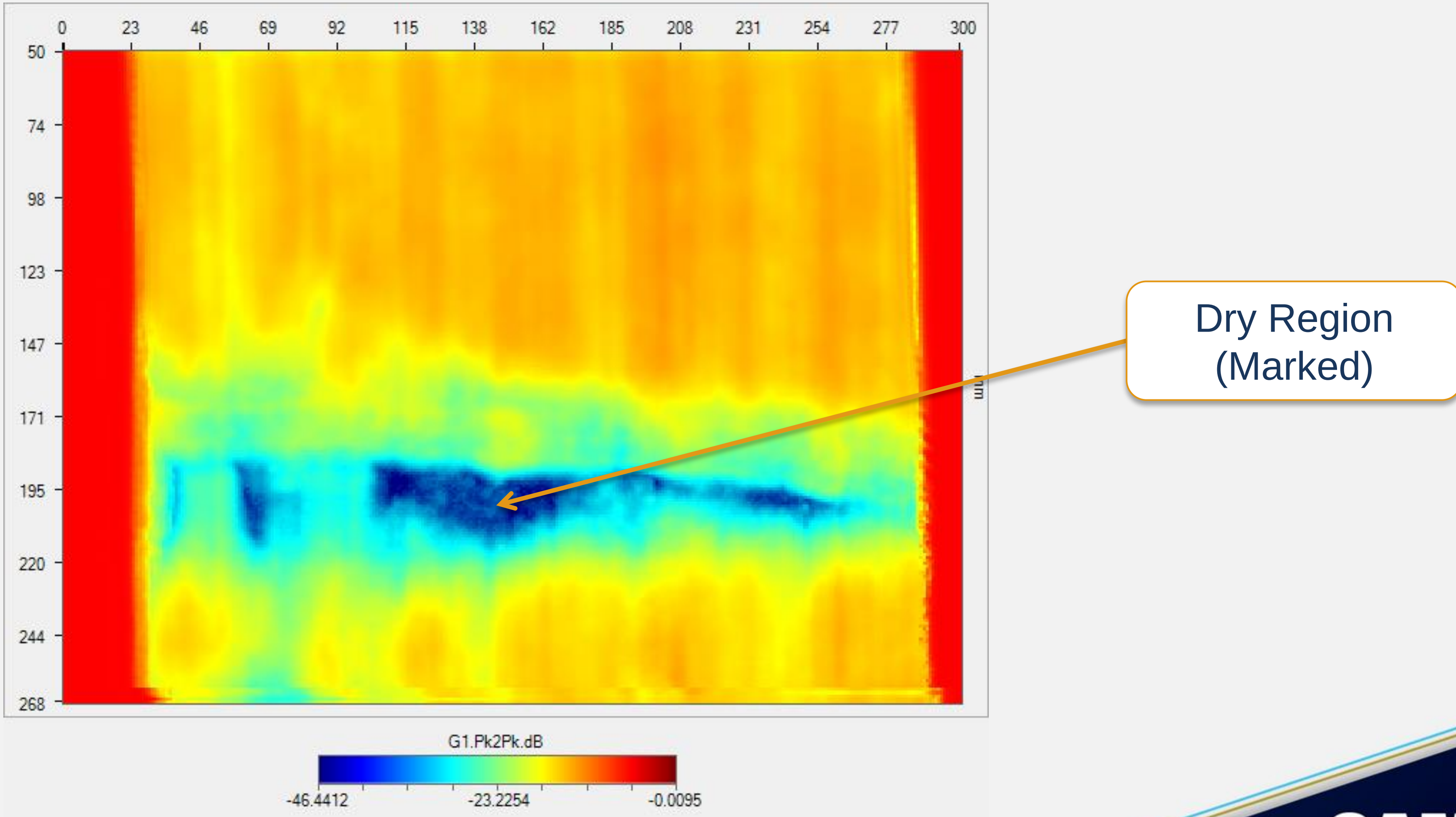
Porosity (inversely related to LOI) is measured using NCU in wind turbine prepreg





Dry Region (Marked)

Additional wind turbine blade prepreg with dry region (blue)



Over a number of years, Ultran has applied NCU to inspect various prepreg materials

- Majority of analysis has been conducted upon unidirectional carbon fiber prepreg material for aerospace applications
  - However, some analysis has also been conducted upon additional materials, such as glass fiber, fabric-based prepreg, and material for other industry applications
- The Ultran Group will incorporate testing of additional materials into the development plan for the ASTM standard method

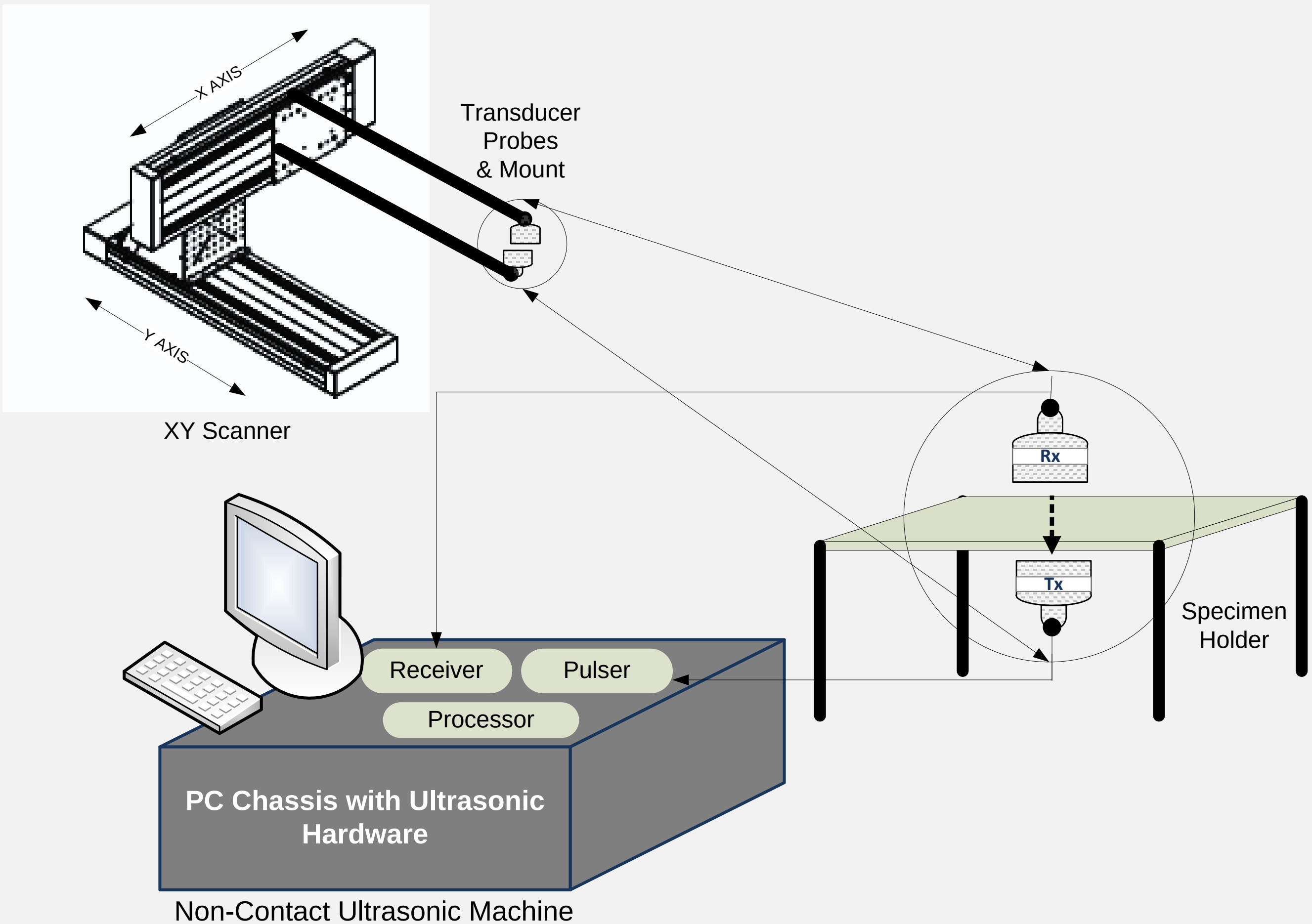
Draft ASTM Standard Method

- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 6

A method for prepreg LOI measurement has been balloted with ASTM subcommittee D30

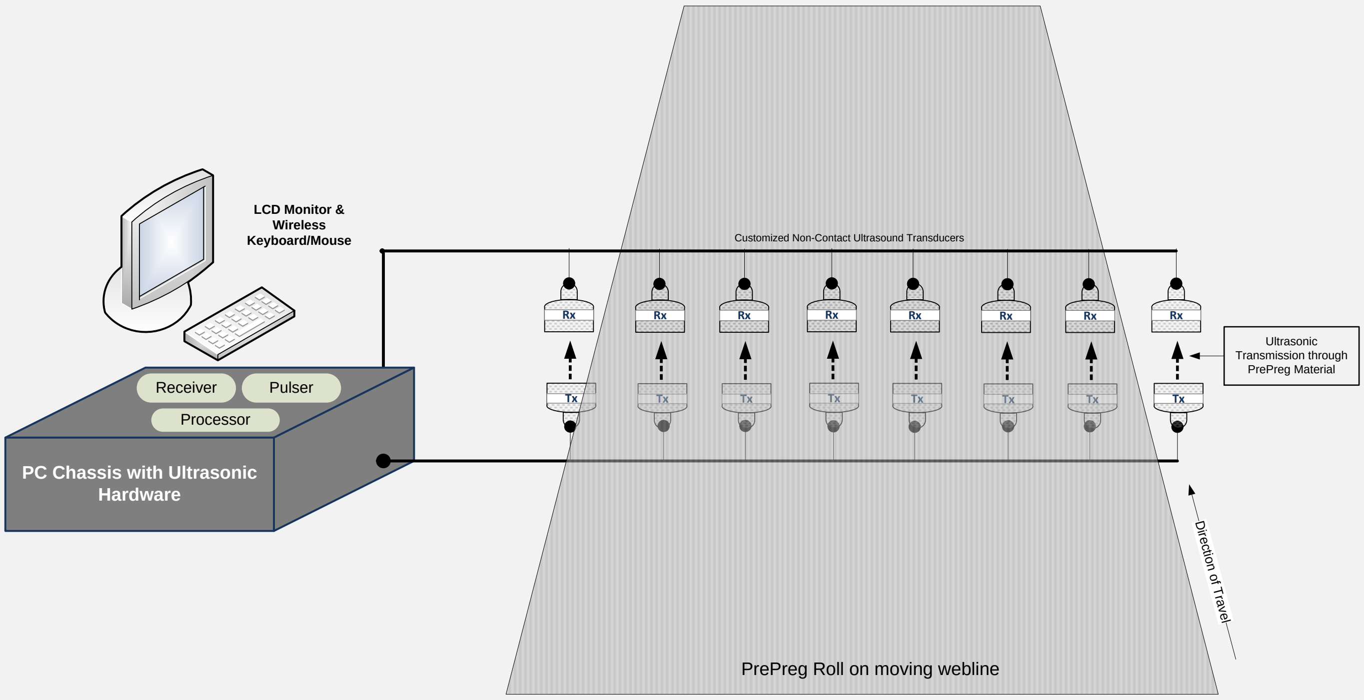
- Draft standard method balloted on May 5, 2015 in upcoming review cycle
- Standard includes Procedure A and Procedure B, for offline and on-line processes, respectively
- We will work with the ASTM subcommittee D30 to review and iterate the proposed standard method and initiate round robin testing with industry partners
- Acceptance of ASTM standard is planned in upcoming 12-18 months

An offline test can be conducted using a 2-dimensional non-contact ultrasonic imaging device with two transducers



- Qualification of prepreg LOI can be conducted using an NCU imaging device
- Two transducers designed for operation at 1 or 2 frequencies will be used
- Analysis and post-processing software should provide a test report with image and LOI values & statistics

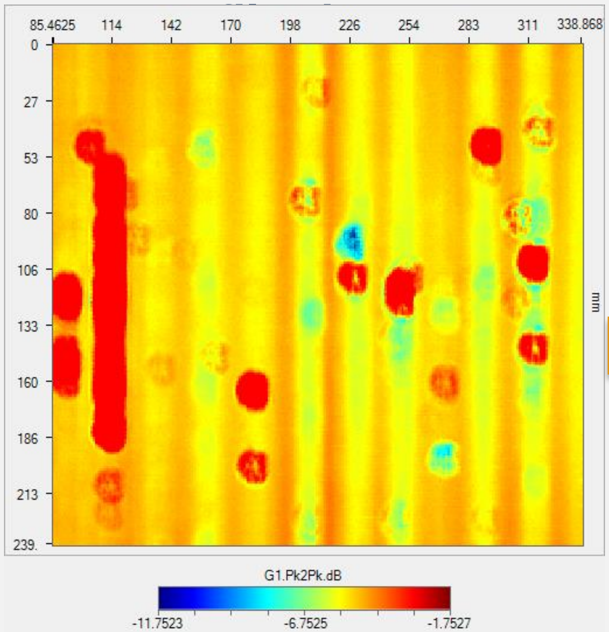
For manufacturers of prepreg, an online standard will also be implemented for continuous inspection and qualification during production



- The online standard method will include multiple transducers (at least 2-3 pairs to cover the web width)
- The analysis will be conducted in a similar mode to the offline test
- Inspection will be continuous and a report can be generated for an entire roll or mfg. run

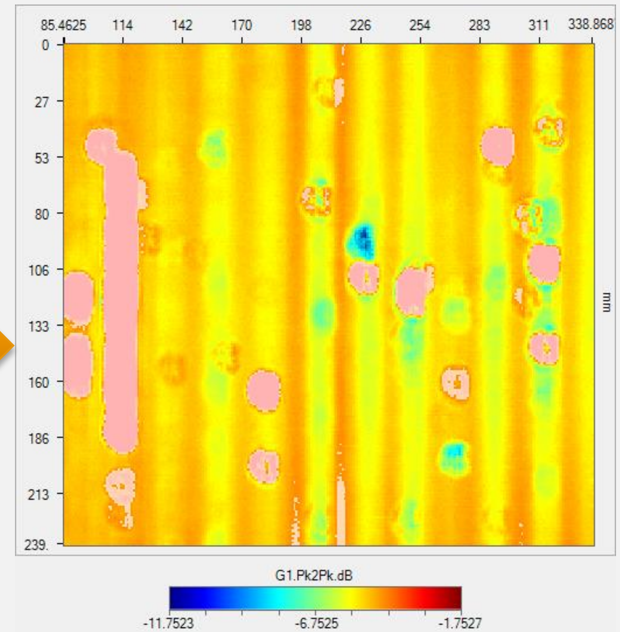
Pin-hole effects and other artifacts can be filtered out in post-processing

AFP C-scan without



NCU Ave. = -4.40 dB
Standard Dev. = 1.24 dB

AFP C-scan with



NCU Ave. = -4.72 dB
Standard Dev. = 0.59 dB

By eliminating artifacts created by air gaps between fibers, we can more accurately measure LOI. The average transmittance is slightly reduced while standard deviation is significantly lowered

Our recommendation for LOI measurement of IM7/5320-1 is through transmission at 1 MHz with planar transducers

- Results demonstrate high accuracy of measurement (approximately 0.5% error) when imaging in through transmission at 1 MHz
- Initial data from analysis with paper backing demonstrate no loss in measurement accuracy
  - Data from results without paper backing can be processed to improve accuracy (i.e. removal of pin-hole areas)
- Off-line measurement standard will include X-Y imaging of samples (at least 4” x 4”) using 1 MHz NCU transducers in through transmission
  - Analysis can possibly be conducted with paper backing (further testing required)
  - On-line measurement standard will be conducted using 1 MHz NCU transducers in through transmission with paper backing
- The next set of analysis conducted will involve testing under multiple conditions upon samples with paper backing
  - This test will be conducted in similar fashion as recent tests

Other considerations for Standard Method Development

- Multiple companies with NCU products and services exist
  - The Ultran Group is a pioneer of NCU and has high performing products, however other companies can also supply solutions
  - Currently proposed method (designed mainly for IM7/5320-1) includes inspection at 1 MHz. This is relatively high frequency for NCU, which other companies will likely develop capability for in upcoming years
    - Method may be revised for lower frequency to accompany more attenuative prepregs
- Round robin testing
  - Certain companies are already using NCU and can immediately support round robin testing
  - Ultran will partner with additional prepreg manufacturers for method development and round robin testing
  - Currently open to working with additional suppliers – Systems can be loaned or provided on a rental basis

Additional steps for ASTM standard implementation for universal measurement

- Additional testing will be conducted upon unidirectional as well as woven carbon fiber prepreg products
  - Glass fiber and other prepreg types can also be considered
  - Materials will be tested with and without paper backing
- The implemented standard test method will be capable of measuring all relevant aerospace materials
- The Ultran Group standard product, U710, can be used to conduct the offline test method
  - Other 3rd party hardware may also have this capability
- We can also supply online test measurement systems to comply with the ASTM online method
- Software will be further developed to conduct standard tests and produce reports for offline and online methods
- Hardware development (system and transducer) can be considered but may not be necessary

Additional Observations

- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation 7

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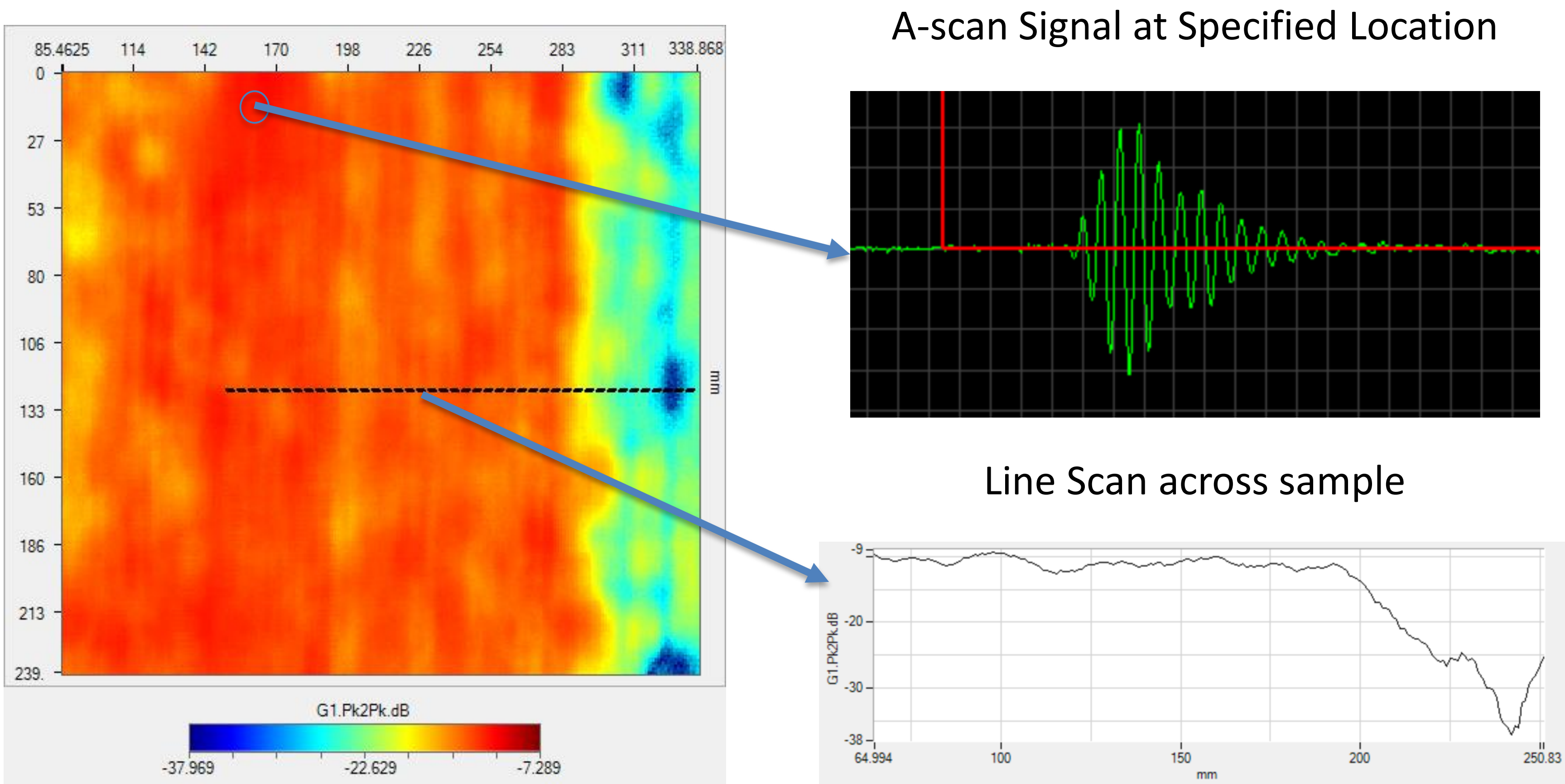
Signal strength through prepreg sample

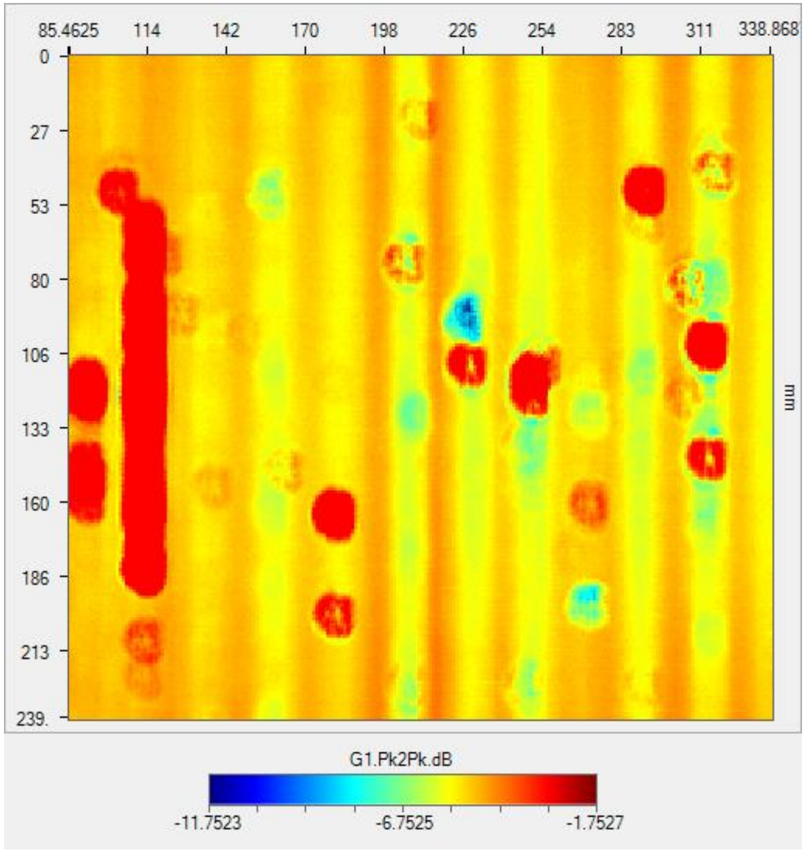
HLU C-scan



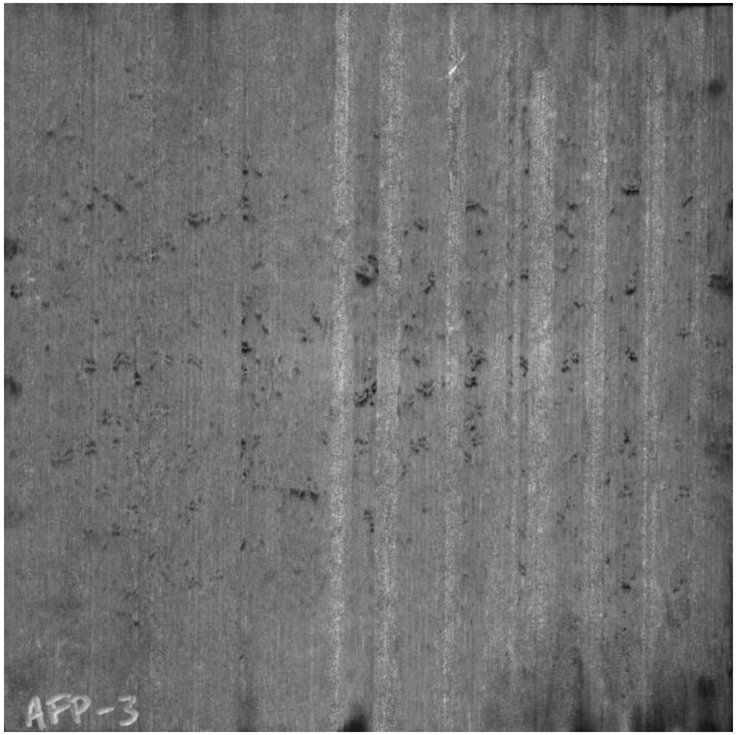
- The recorded signal (A-scan at 1 MHz), which makes up each point in the 2-dimensional (C-scan) image, has a very high signal to noise ratio; SNR = 30 for above A-scan (29 dB). Higher SNRs measured in AFP and ATL materials
- This demonstrates that the integrity of our ultrasonic measurements is very high

Sample AFP on tighter color palette with reflection image

AFP C-scan

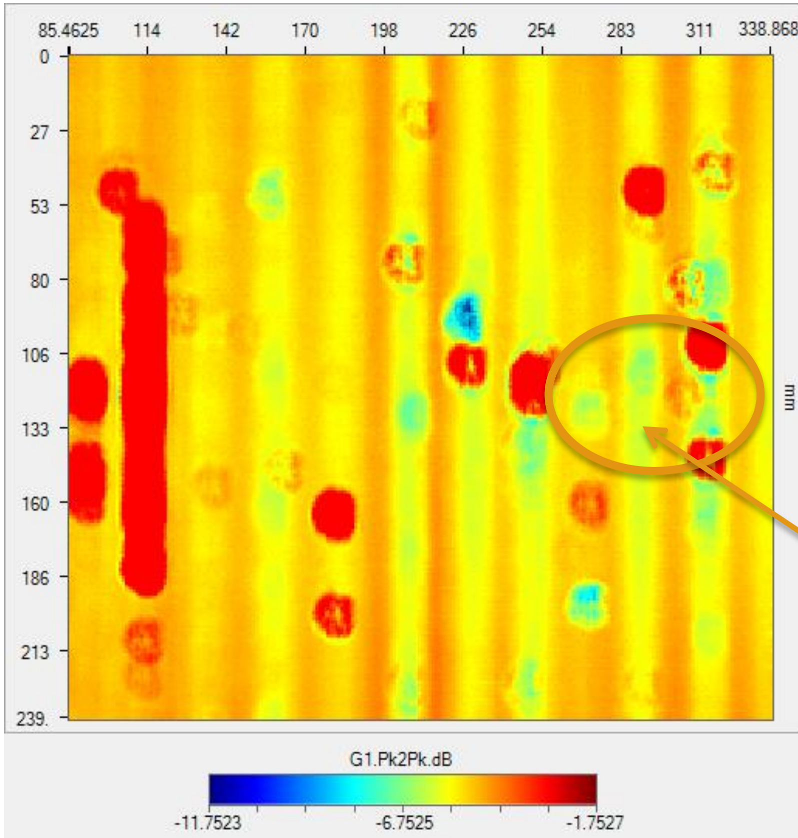


AFP Optical Image

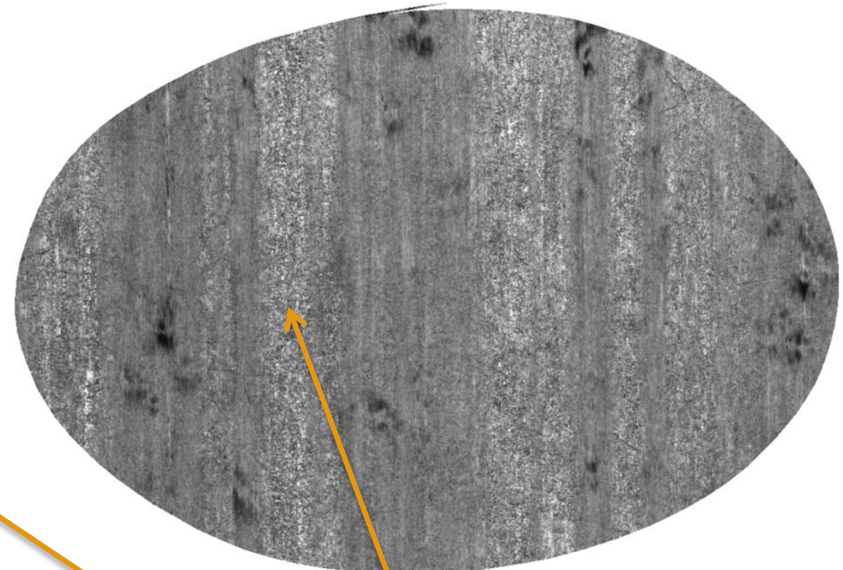


Sample AFP on tighter color palette with reflection image

AFP C-scan



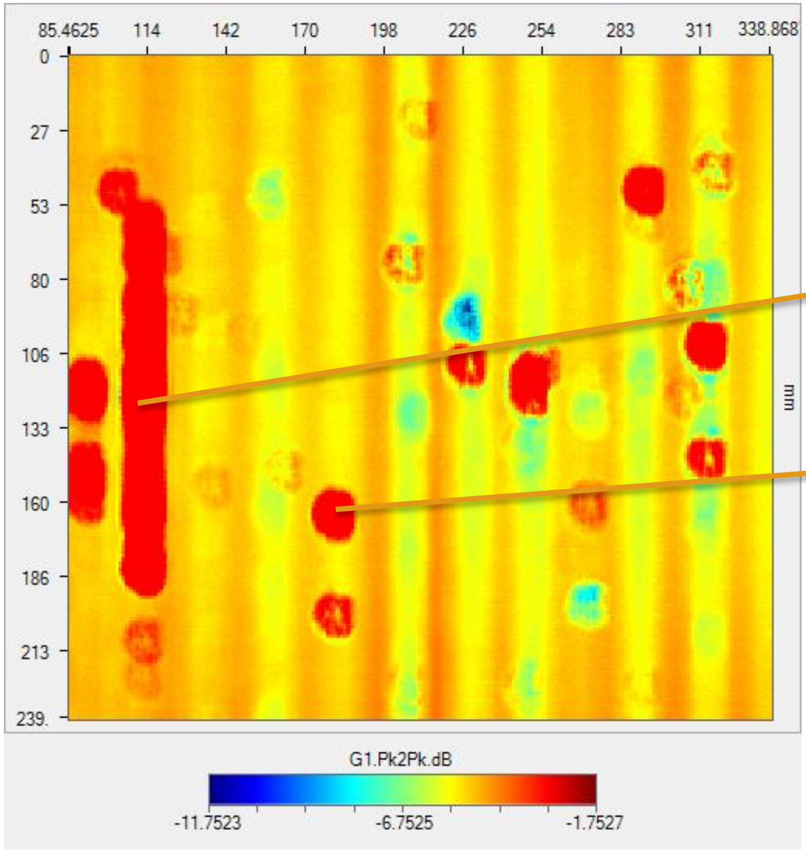
AFP Reflection Image



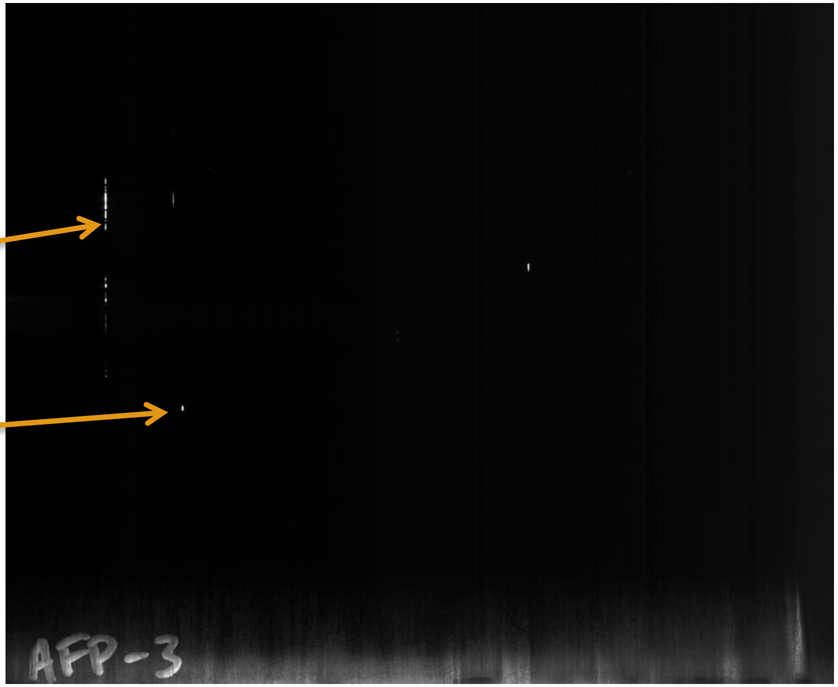
Low transmittance stripes appear “shiny” in optical image. May be due to resin which was not impregnated into fiber bed (still remaining on prepreg surface)

Sample AFP on tighter color palette with transmission image

AFP C-scan



AFP Transmission Image



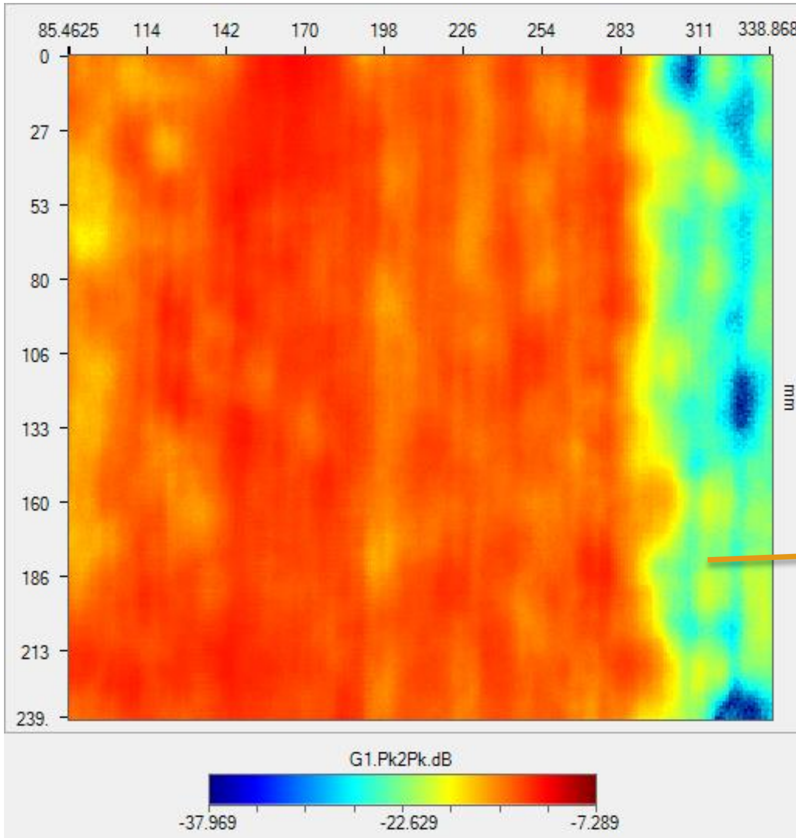
Right-side image demonstrates pin-holes and lines which allow for very high transmittance in NCU (red dots and line on left side of sample)

Photograph depicting “pin-hole” air gaps in prepreg)

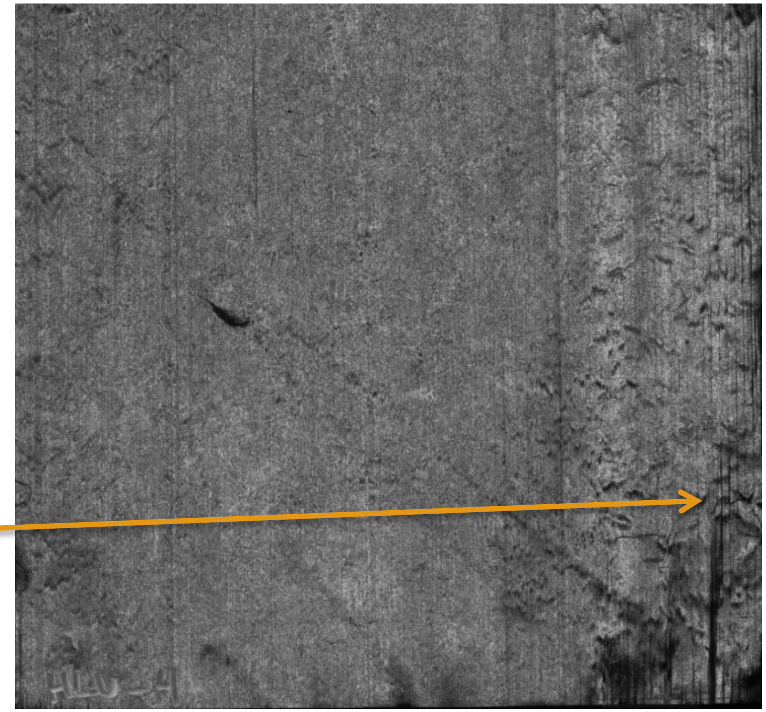
The presence of pin-holes allows for abnormally high ultrasonic transmission, which must be filtered out in real-time or post-processing

Sample HLU on tighter color palette with reflection image

HLU C-scan



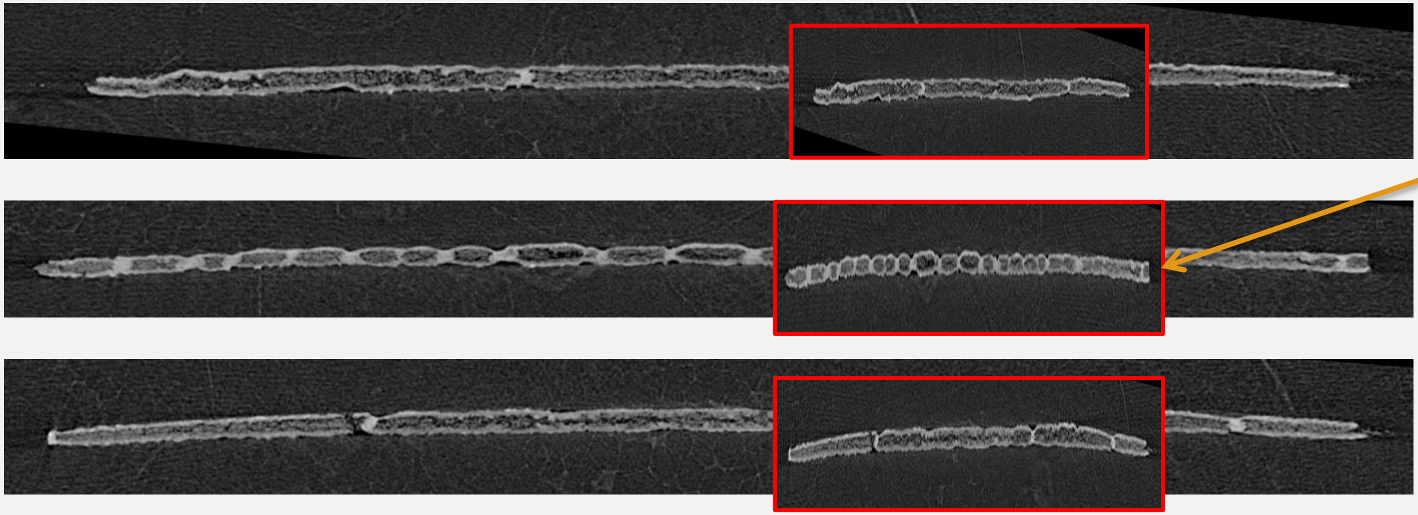
HLU Optical Image



Section on right side of sample appears optically shiny, while transmittance is especially low. This may be due to resin which is not properly impregnated in this region, and remains upon the sample surface

Images captured using MicroCT allow us to observe cross-sectional images of the fiber construction and surrounding resin

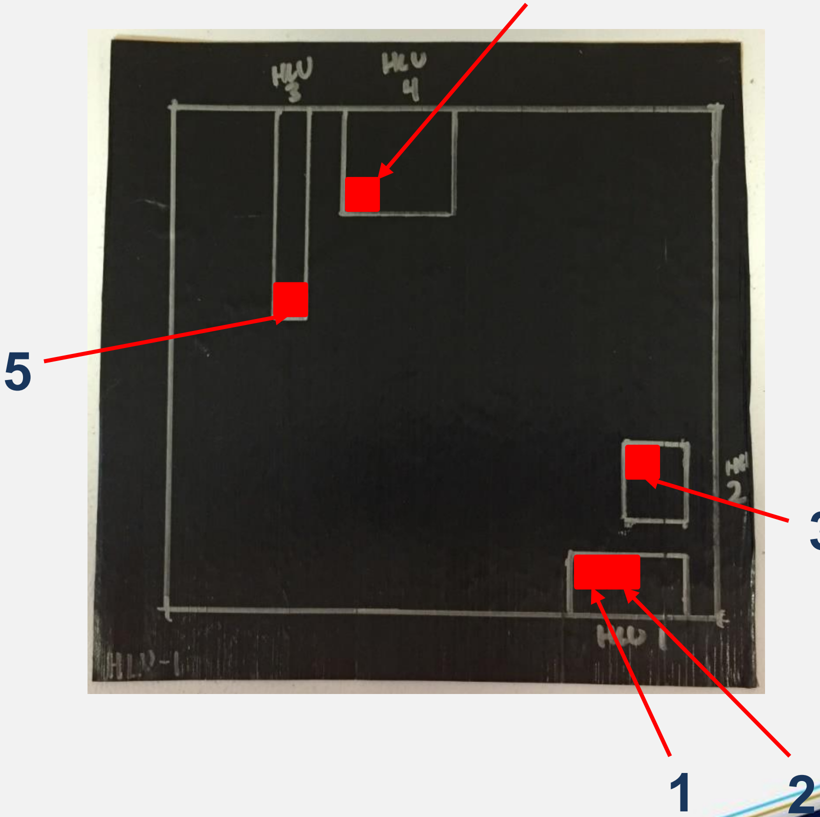
Cross-Sectional Images from MicroCT performed at McGill University (HLU Sample) – 6.9 µm/pixel resolution



Weaving pattern with areas of dry fiber

The Structure and Composite Materials Research Laboratory at McGill has analyzed samples of uncured prepreg, but handling material presents challenging

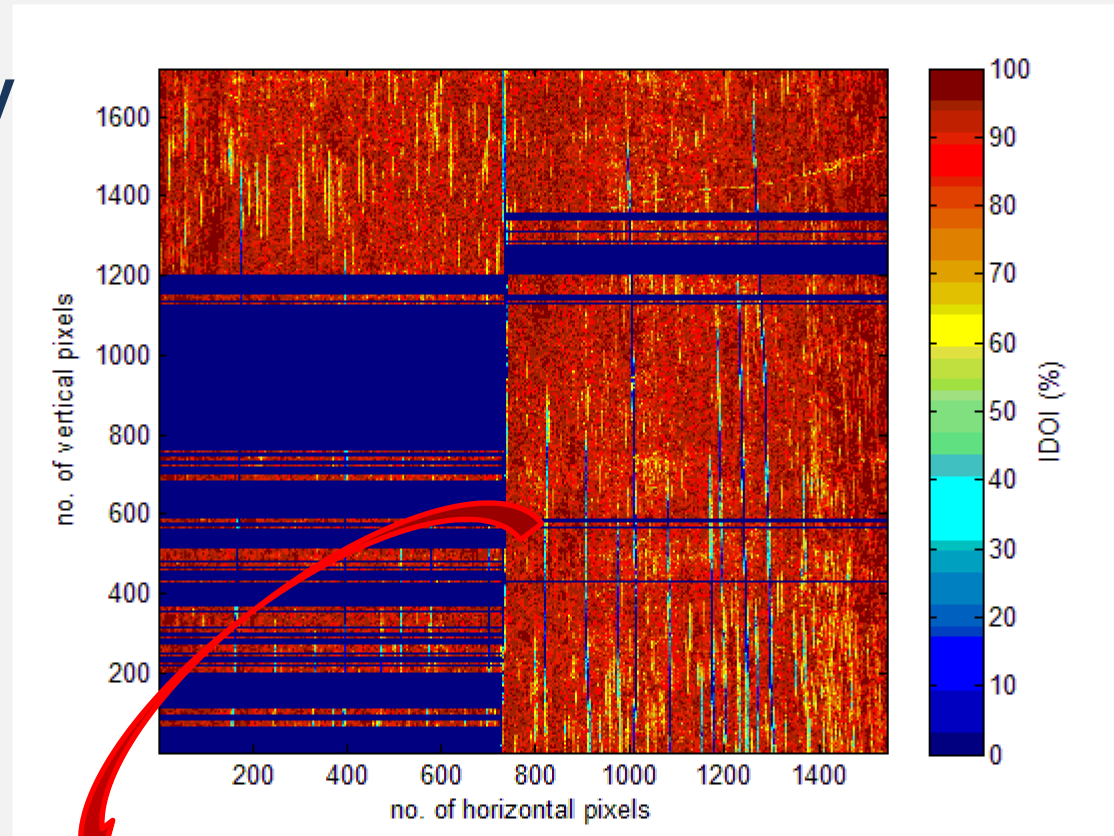
- Small square sections (12.5 x 12.5 mm) are cut from prepreg samples and placed between sheets of styrofoam
- Prepreg material was too "fresh" and damaged during the cutting process

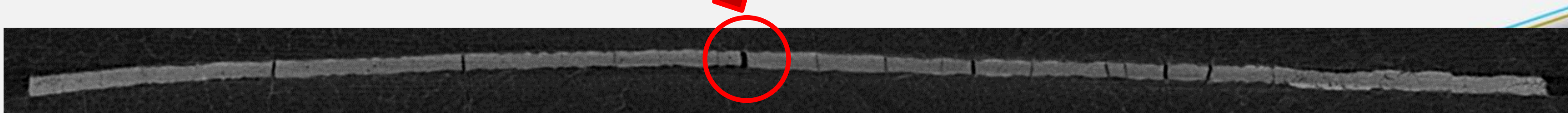


Cracking occurred during handling of certain samples

Comments and Image provided by McGill University – ATL Sample

- **Material was very dry**
- **Cracking occurred while cutting which caused problem in MATLAB code identify entire prepreg**



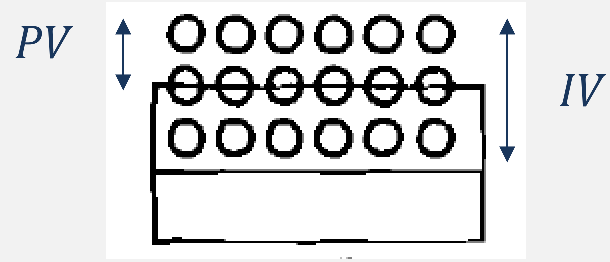


The research group at McGill University has developed a method for attempting to calculate prepreg LOI but challenges in post processing may affect accuracy

Methodology provided by McGill (Pascal Hubert and Marc Palardy-Sim)

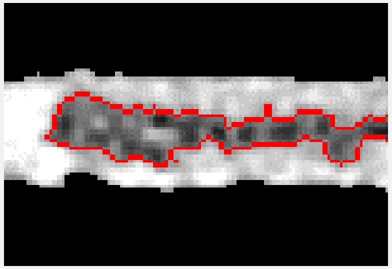
From Thorfinnson and Biermann [1]

$$DOI = \frac{IV - PV}{IV}$$



We've modified this approach

$$DOI = 1 - \frac{A_{dry\ fibre}}{A_{total}}$$



Appendix I

- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation

The correlation between NCU transmittance and Prepreg LOI was highest at 1 MHz for the initial analysis

Correlation Results between LOI measured from Guided Water Pickup Test and NCU Transmittance at 500 kHz, 700 kHz, and 1 MHz

Freq.	R^2 Value for Linear Correlation	Linear Correlation Equation
500 kHz	89.81 %	LOI (%) = 101.92 + 2.128 * (NCU dB)
700 kHz	92.71 %	LOI (%) = 107.54 + 1.857 * (NCU dB)
1 MHz	96.30 %	LOI (%) = 109.31 + 1.759 * (NCU dB)

Regression Analysis: LOI (%) versus NCU-A *1MHz Planar Single Linear Function* †

2nd set of analysis

Regression Analysis: LOI (%) versus NCU-A
1MHz (Planar) Linear

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.135961	0.135961	1172.03	0.000
NCU-A	1	0.135961	0.135961	1172.03	0.000
Error	22	0.002552	0.000116		
Total	23	0.138513			

Model Summary

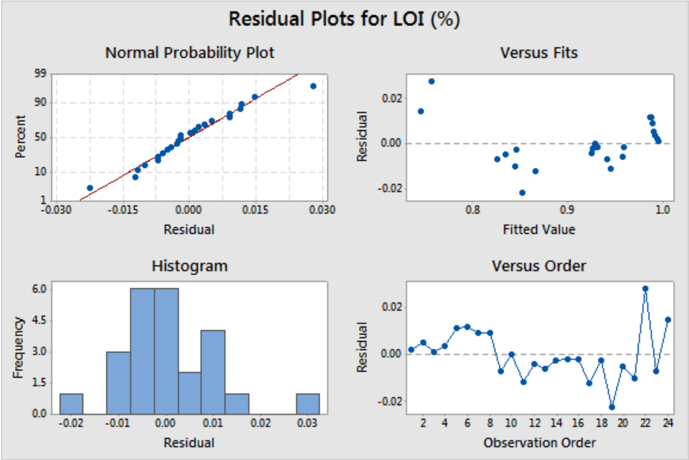
S	R-sq	R-sq(adj)	R-sq(pred)
0.0107705	98.16%	98.07%	97.46%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.07780	0.00518	208.03	0.000	
NCU-A	0.016672	0.000487	34.23	0.000	1.00

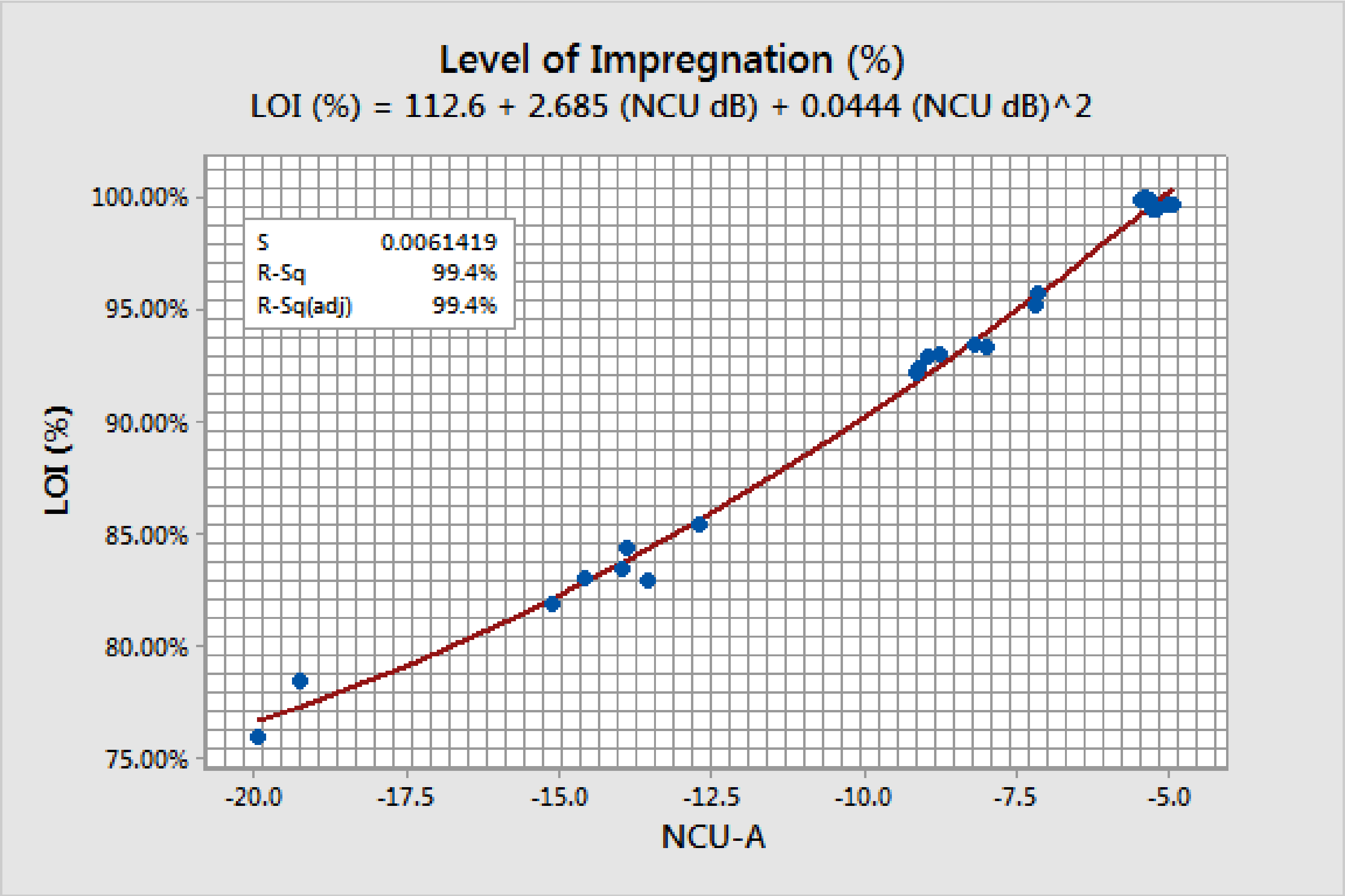
Regression Equation

LOI (%) = 1.07780 + 0.016672 NCU-A



† Data filtered to remove pinhole effect

Graph and Statistics from 1 MHz through transmission (single variable) with single quadratic correlation function †



† Data filtered to remove pinhole effect

Regression Analysis: LOI (%) versus NCU-A
1MHz Planar with Single Quadratic Function †

Regression Analysis: LOI (%) versus NCU-A, NCU-A^2
1MHz (Planar) Quadratic

Analysis of Variance

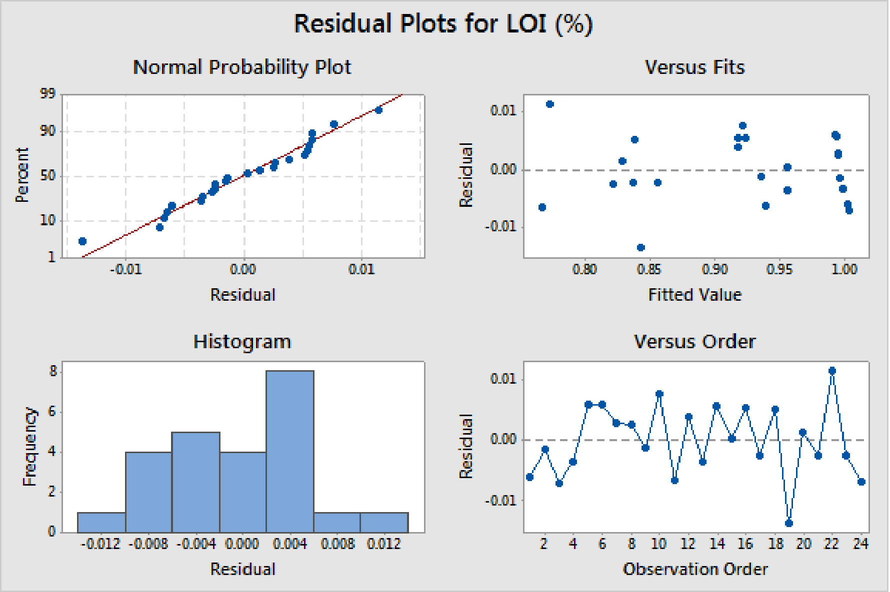
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.137721	0.068860	1825.40	0.000
NCU-A	1	0.011841	0.011841	313.89	0.000
NCU-A^2	1	0.001760	0.001760	46.65	0.000
Error	21	0.000792	0.000038		
Total	23	0.138513			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0061419	99.43%	99.37%	99.06%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value
Constant	1.12557	0.00759	148.24	0.000
NCU-A	0.02685	0.00152	17.72	0.000
NCU-A^2	0.000444	0.000065	6.83	0.000



Regression Equation

LOI (%) = 1.12557 + 0.02685 NCU-A + 0.000444 NCU-A^2

† Data filtered to remove pinhole effect

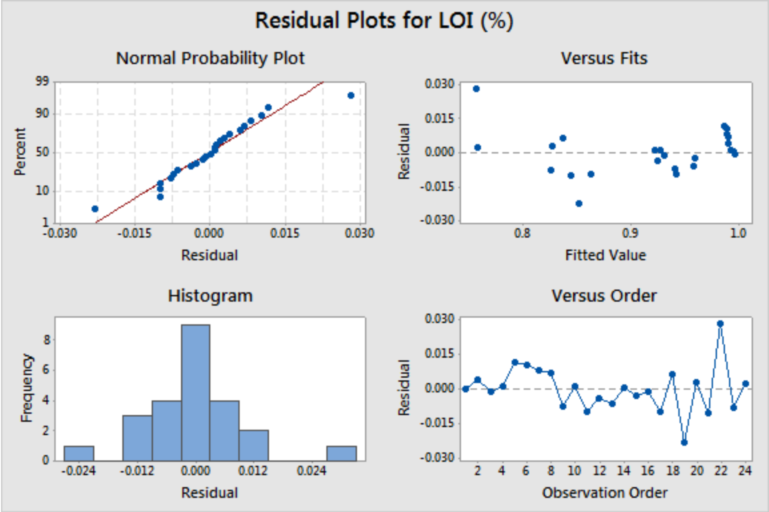
Regression Analysis: LOI (%) versus NCU-A *1 MHz Planar + 500 kHz Planar with Single Linear Function* †

Regression Analysis: LOI (%) versus NCU-A, NCU-G

1MHz (Planar) + 500 kHz (Planar) Combo

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.136298	0.068149	646.04	0.000
NCU-A	1	0.002827	0.002827	26.80	0.000
NCU-G	1	0.000337	0.000337	3.19	0.088
Error	21	0.002215	0.000105		
Total	23	0.138513			



Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0102707	98.40%	98.25%	97.77%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.07793	0.00494	218.16	0.000	
NCU-A	0.02540	0.00491	5.18	0.000	111.66
NCU-G	-0.01104	0.00617	-1.79	0.088	111.66

Regression Equation

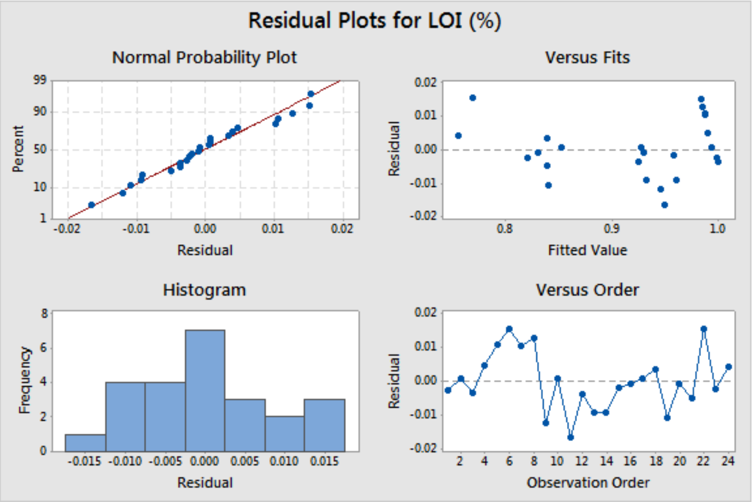
LOI (%) = 1.07793 + 0.02540 NCU-A - 0.01104 NCU-G

† Data filtered to remove pinhole effect

Regression Analysis: LOI (%) versus NCU-A
1MHz Planar + 1 MHz focused with Single Linear Function †

Regression Analysis: LOI (%) versus NCU-A, NCU-B
1MHz (Planar) + 1MHz (Focused) Combo

```
Analysis of Variance

Source        DF    Adj SS    Adj MS  F-Value  P-Value
Regression     2  0.136832  0.068416   854.96    0.000
  NCU-A        1  0.000000  0.000000     0.00    0.995
  NCU-B        1  0.000872  0.000872    10.89    0.003
Error         21  0.001680  0.000080
Total         23  0.138513


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0089455  98.79%     98.67%      98.21%

Coefficients

Term           Coef  SE Coef  T-Value  P-Value     VIF
Constant     1.3284   0.0761    17.47    0.000
NCU-A       0.00003  0.00506     0.01    0.995  156.34
NCU-B       0.01959  0.00593     3.30    0.003  156.34


Regression Equation

LOI (%) = 1.3284 + 0.00003 NCU-A + 0.01959 NCU-B
```



† Data filtered to remove pinhole effect

Regression Analysis: LOI (%) versus NCU-A

1MHz Planar with three Linear Functions (one function per product) †

Regression Analysis: LOI (%) versus NCU-A, PrePreg-L1 1MHz (Planar) - Linear & Individuel Equation

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.137943	0.045981	1612.93	0.000
NCU-A	1	0.007526	0.007526	264.01	0.000
PrePreg-L1	2	0.001982	0.000991	34.76	0.000
Error	20	0.000570	0.000029		
Total	23	0.138513			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0053393	99.59%	99.53%	99.24%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.05785	0.00418	253.06	0.000	
NCU-A	0.011596	0.000714	16.25	0.000	8.74
PrePreg-L1					
ATL	-0.02661	0.00346	-7.70	0.000	2.23
HLU	-0.06025	0.00772	-7.81	0.000	11.15

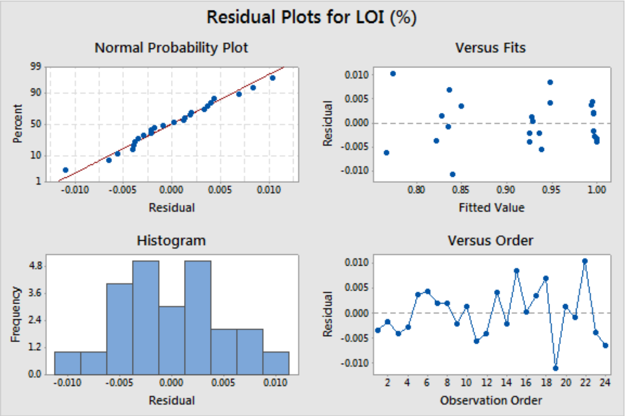
Regression Equation

PrePreg-L1

AFP LOI (%) = 1.05785 + 0.011596 NCU-A

ATL LOI (%) = 1.03125 + 0.011596 NCU-A

HLU LOI (%) = 0.9976 + 0.011596 NCU-A



† Data filtered to remove pinhole effect

Regression Analysis: LOI (%) versus NCU-A *1MHz Planar 500 kHz focused three Linear Functions (one function per product)* †

Regression Analysis: LOI (%) versus NCU-A, NCU-H, PrePreg-L1 1MHz (Planar) + 500 kHz (Focused) – Linear & Individual

Analysis of Variance

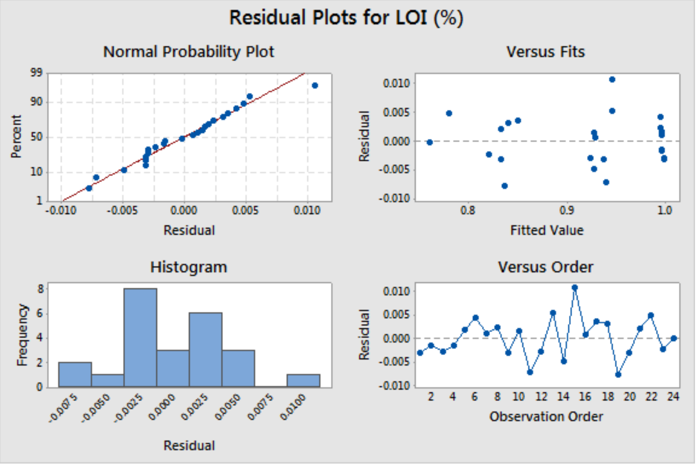
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.138096	0.034524	1574.78	0.000
NCU-A	1	0.000044	0.000044	1.99	0.175
NCU-H	1	0.000154	0.000154	7.01	0.016
PrePreg-L1	2	0.001983	0.000991	45.22	0.000
Error	19	0.000417	0.000022		
Total	23	0.138513			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0046822	99.70%	99.64%	99.47%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.04989	0.00474	221.40	0.000	
NCU-A	0.00409	0.00290	1.41	0.175	187.97
NCU-H	0.00812	0.00307	2.65	0.016	134.51
PrePreg-L1					
ATL	-0.03033	0.00334	-9.08	0.000	2.72
HLU	-0.07217	0.00813	-8.88	0.000	16.08



Regression Equation

PrePreg-L1

AFP LOI (%) = 1.04989 + 0.00409 NCU-A + 0.00812 NCU-H

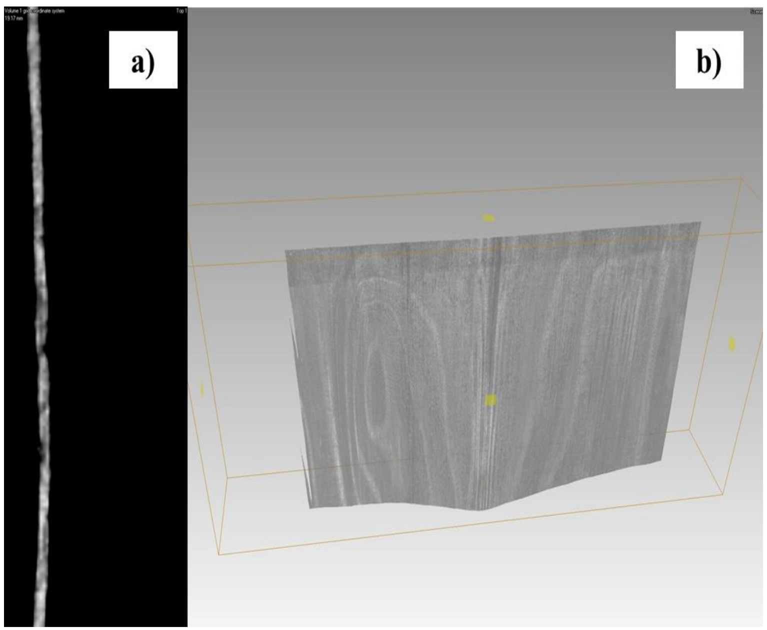
ATL LOI (%) = 1.01956 + 0.00409 NCU-A + 0.00812 NCU-H

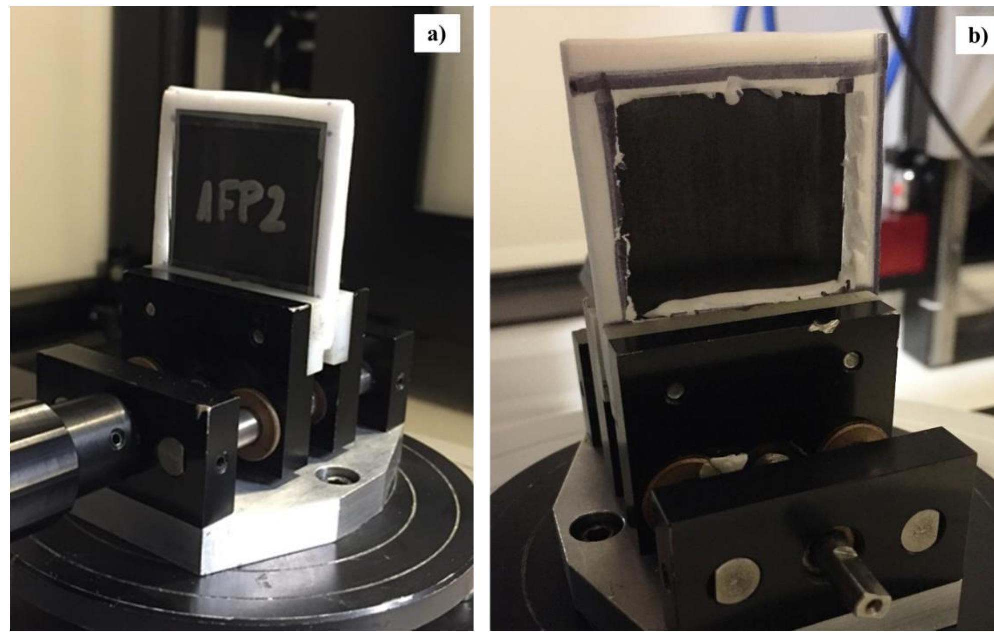
HLU LOI (%) = 0.9777 + 0.00409 NCU-A + 0.00812 NCU-H

† Data filtered to remove pinhole effect

MicroCT results from initial analysis – from Aurora/Harvard

<u>Low resolution MicroCT image of single ply prepreg (left) and setup (right) – Image created by Aurora Flight Sciences with Harvard Ctr. For Nanoscale Development</u>

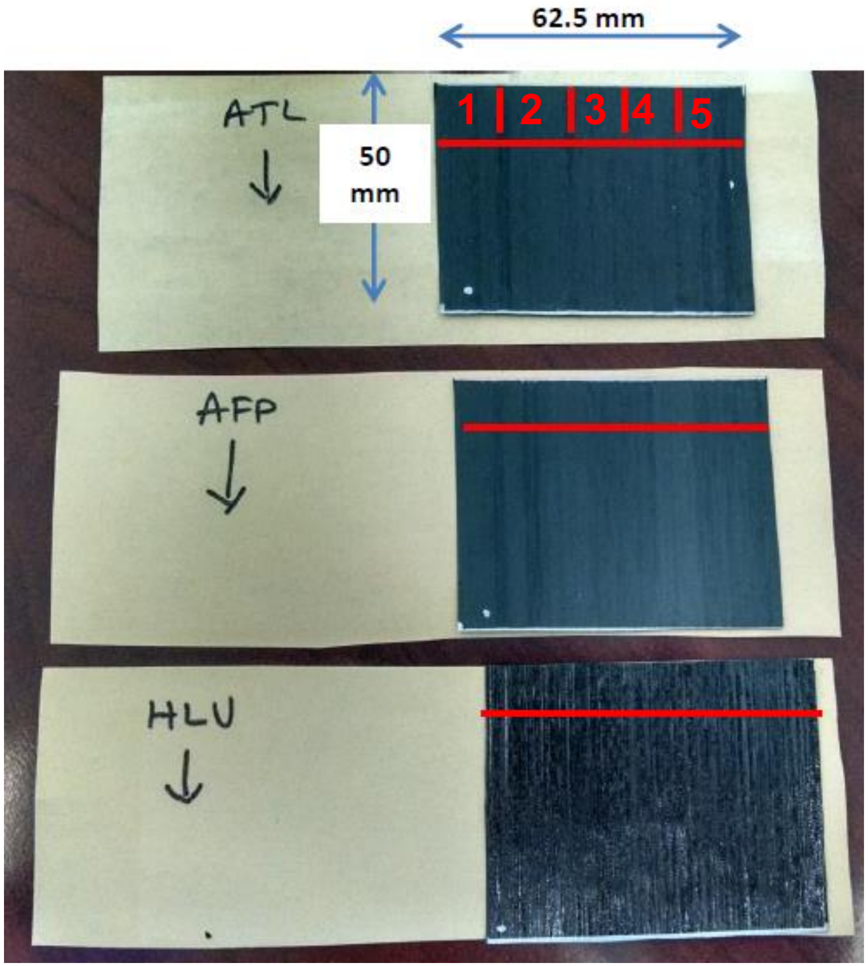




Results from initial frequency analysis sample set. Low resolution data did not provide conclusive results for analysis

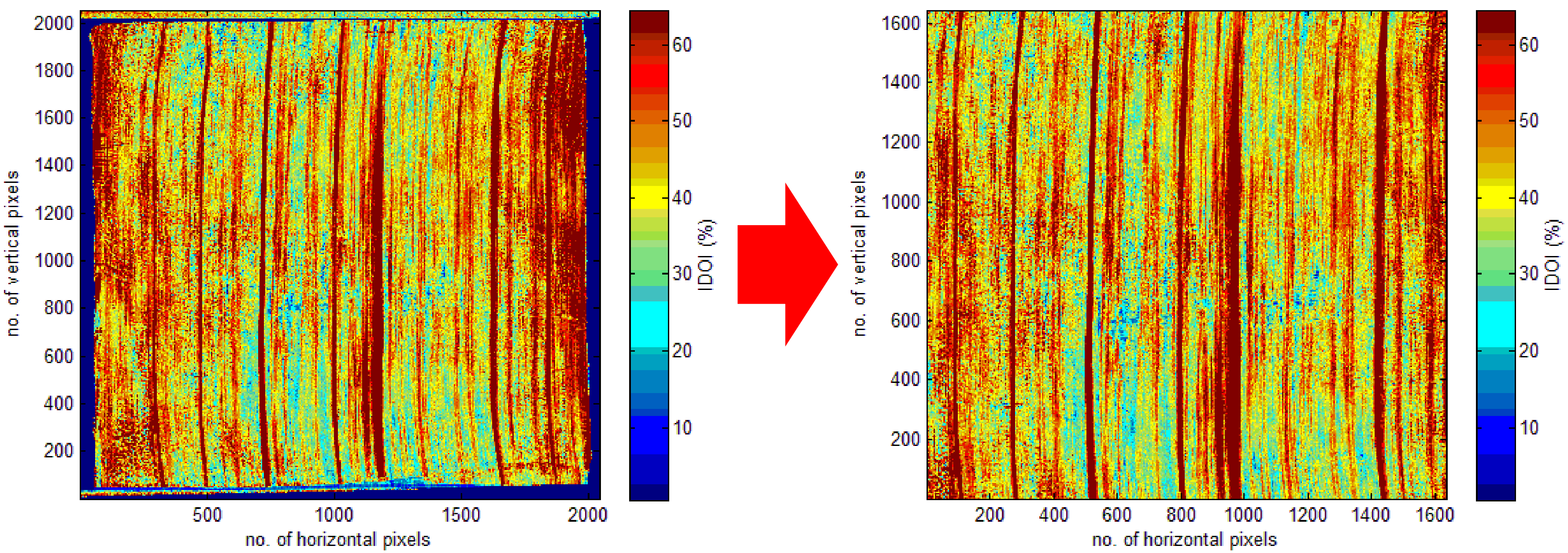
Specimen cutting

- Sections cut as you suggested
  - 5x 12.5 mm by 12.5 mm specimens



DOI maps

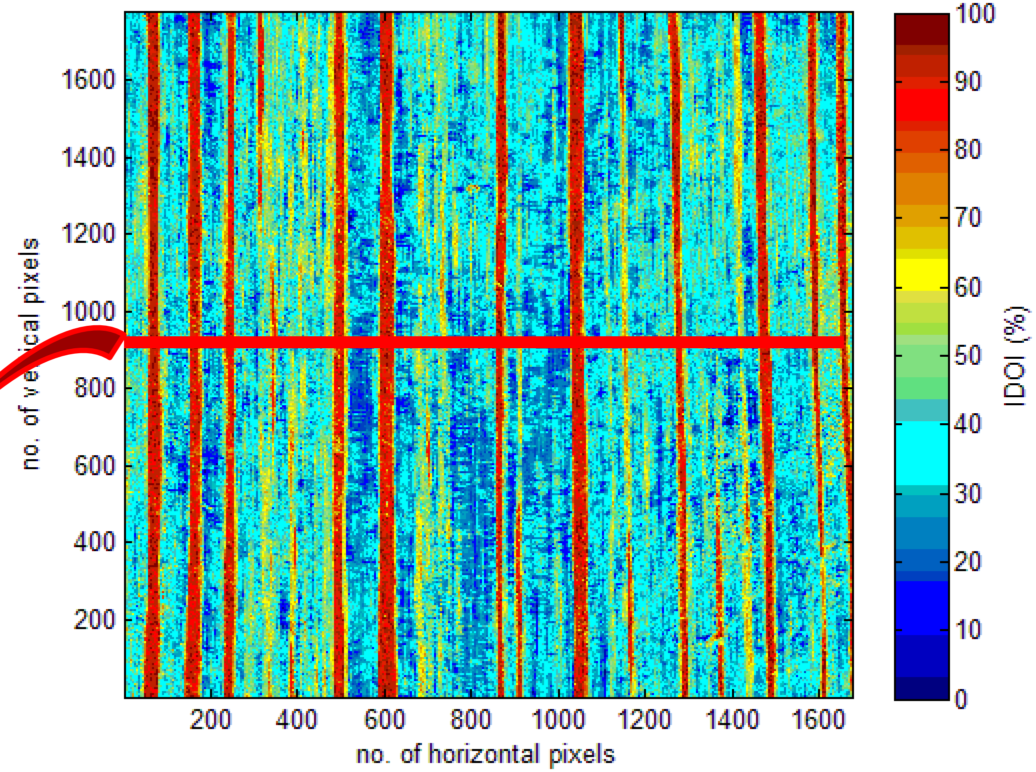
- Generate maps of DOI
- Each pixel represents DOI at that location
- Ignore 10% of pixels on edges to isolate ply from background and remove edge effects

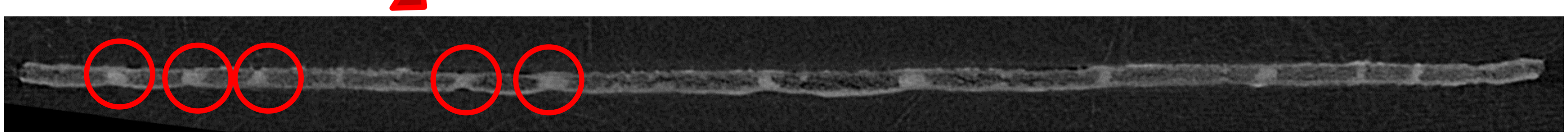


HLU

MicroCT Analysis from McGill University – Slide provided by Professor Hubert and student, Marc Palardy-Sim

- **Similar to last time, sections of high impregnation**





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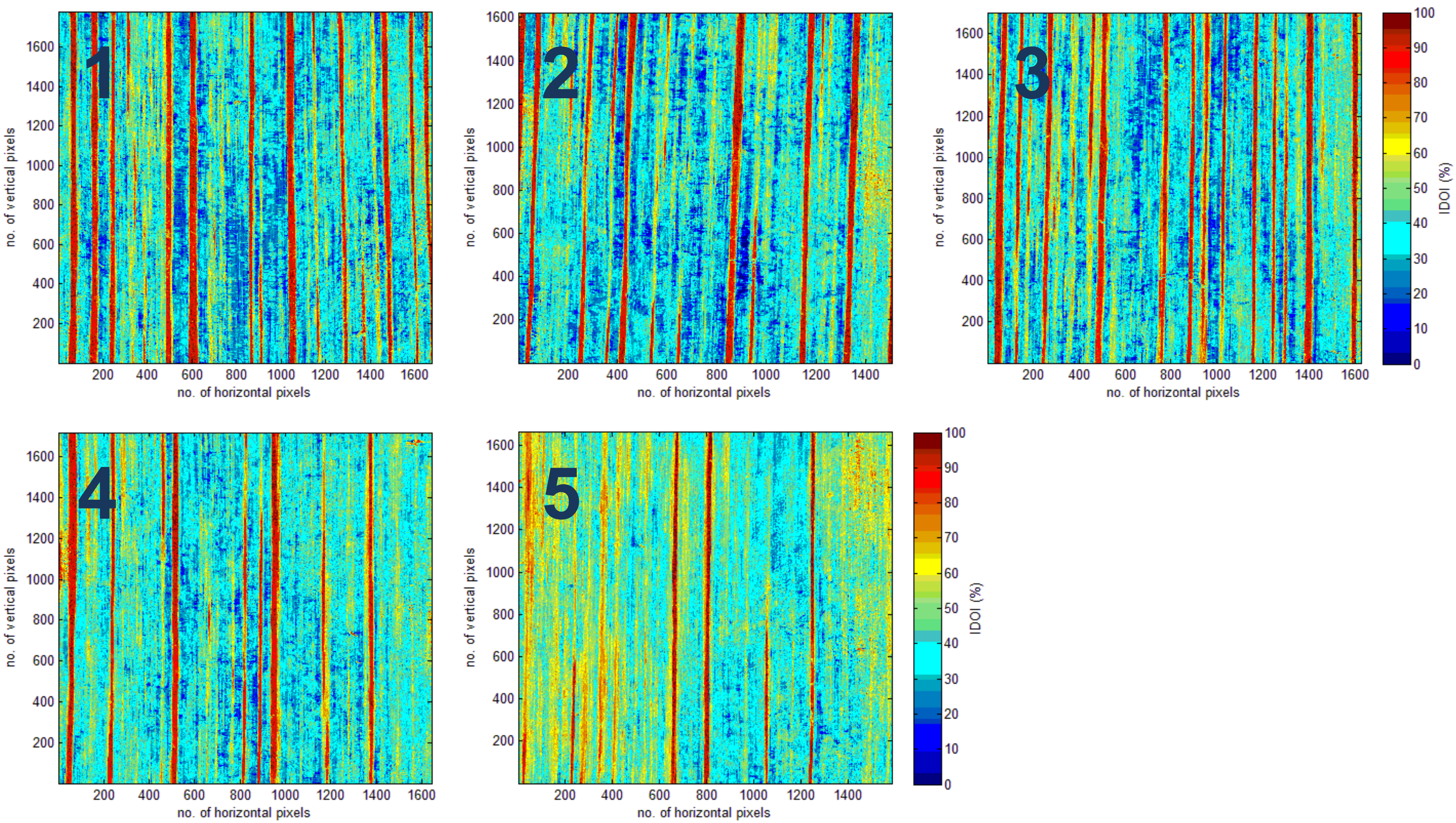
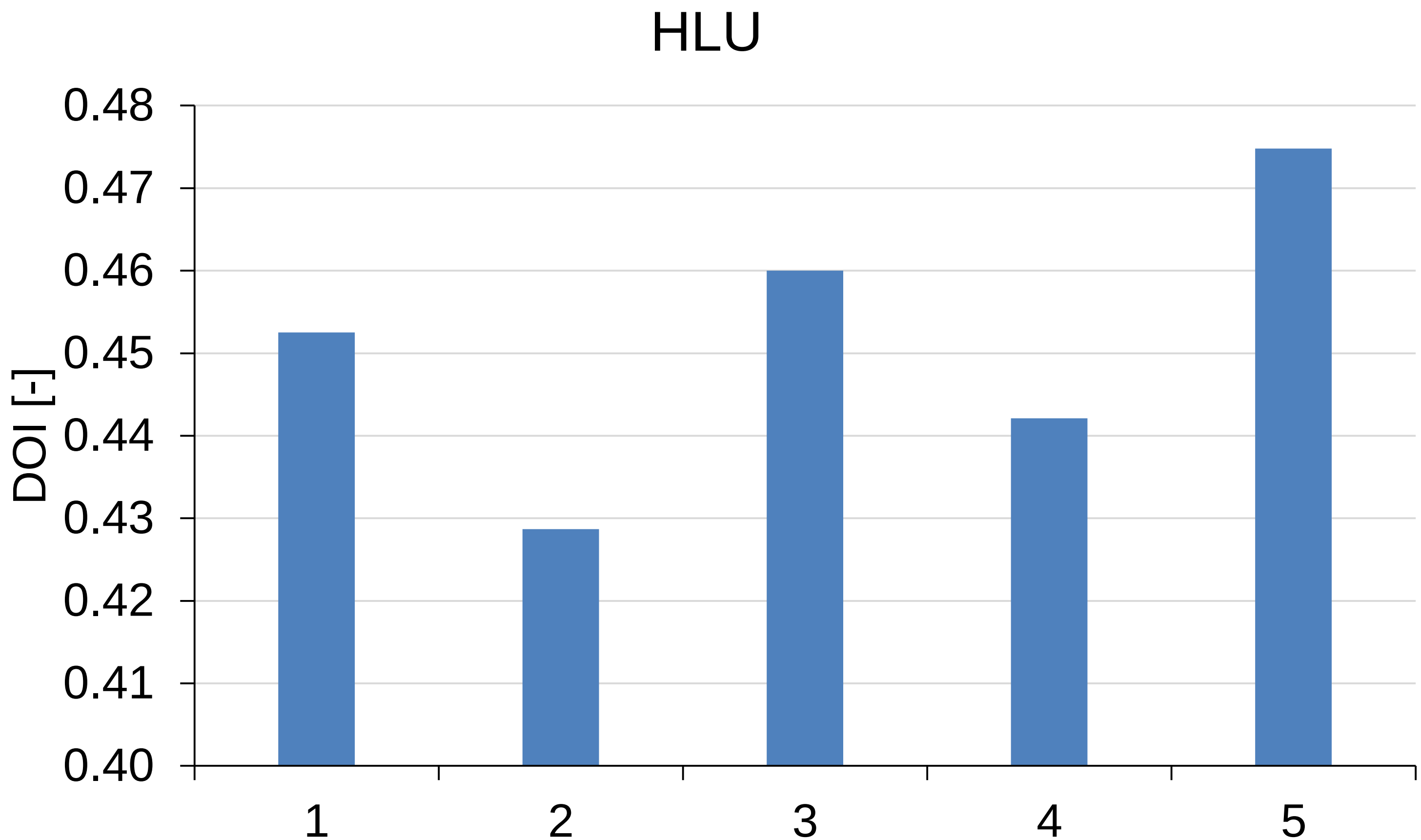
HLU

MicroCT Analysis from McGill University – Slide provided by Professor Hubert and student, Marc Palardy-Sim



HLU



Average	0.4525	0.4287	0.4600	0.4421	0.4748
St. dev.	0.2157	0.1958	0.2099	0.1760	0.1432

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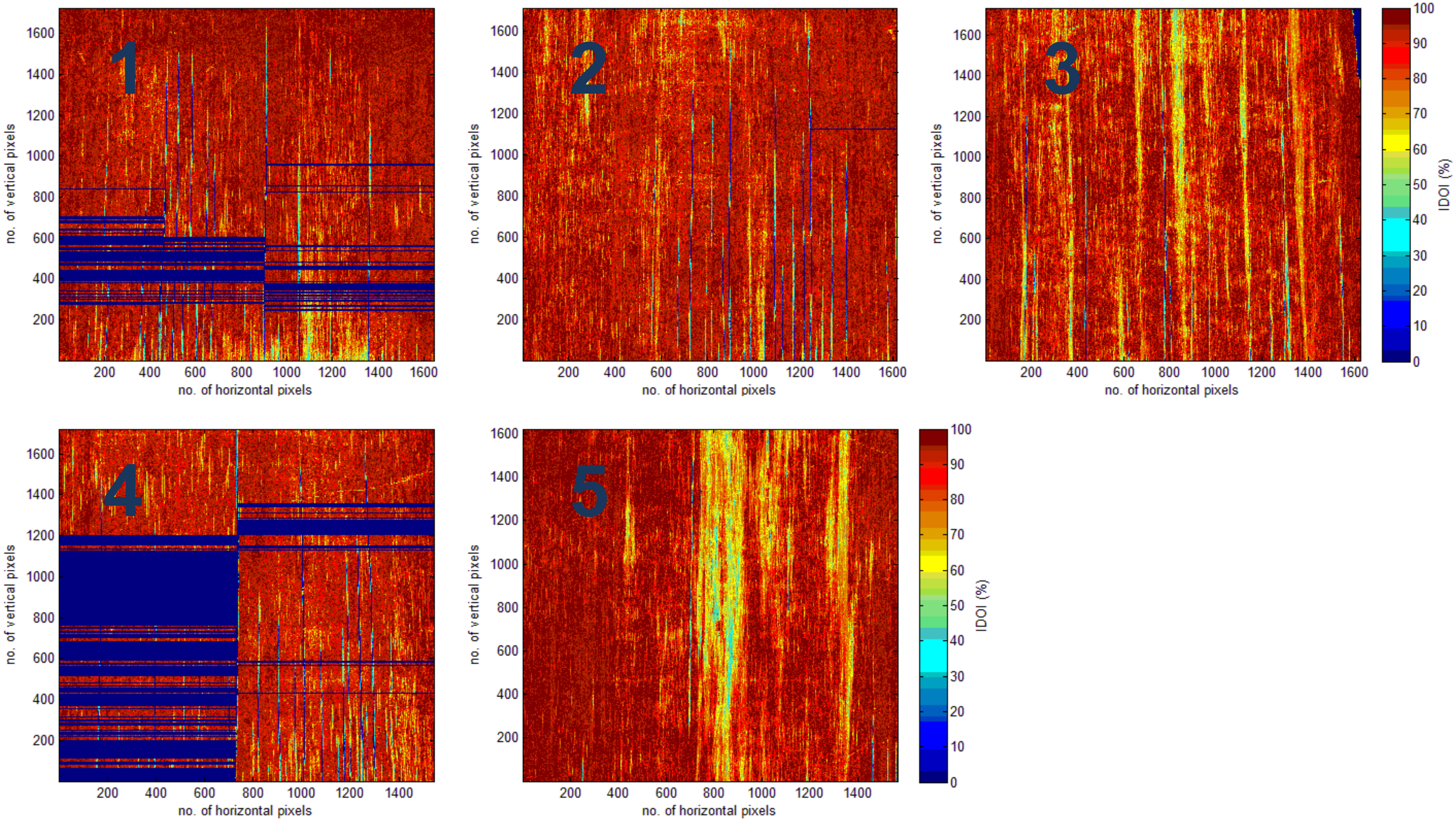
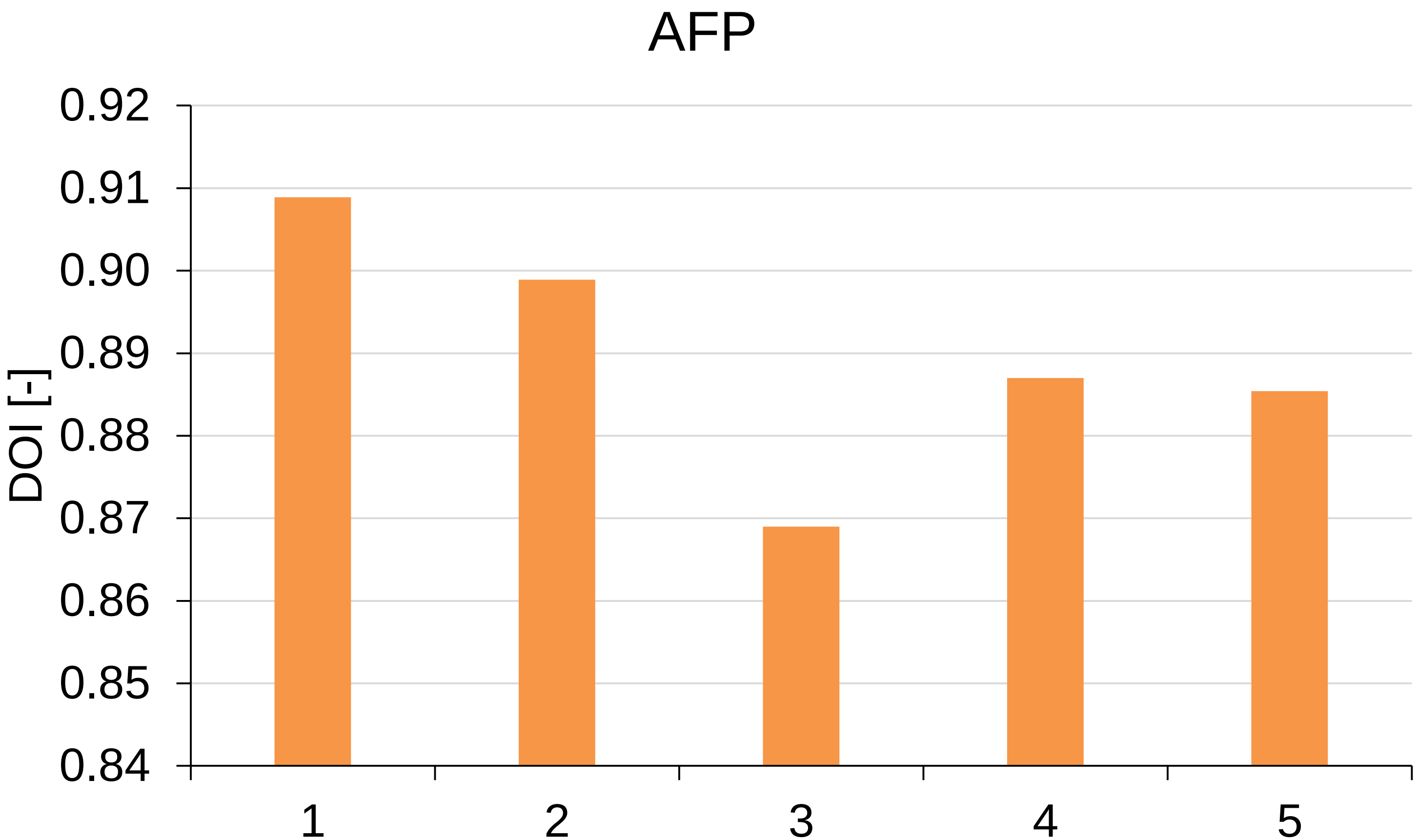
AFP

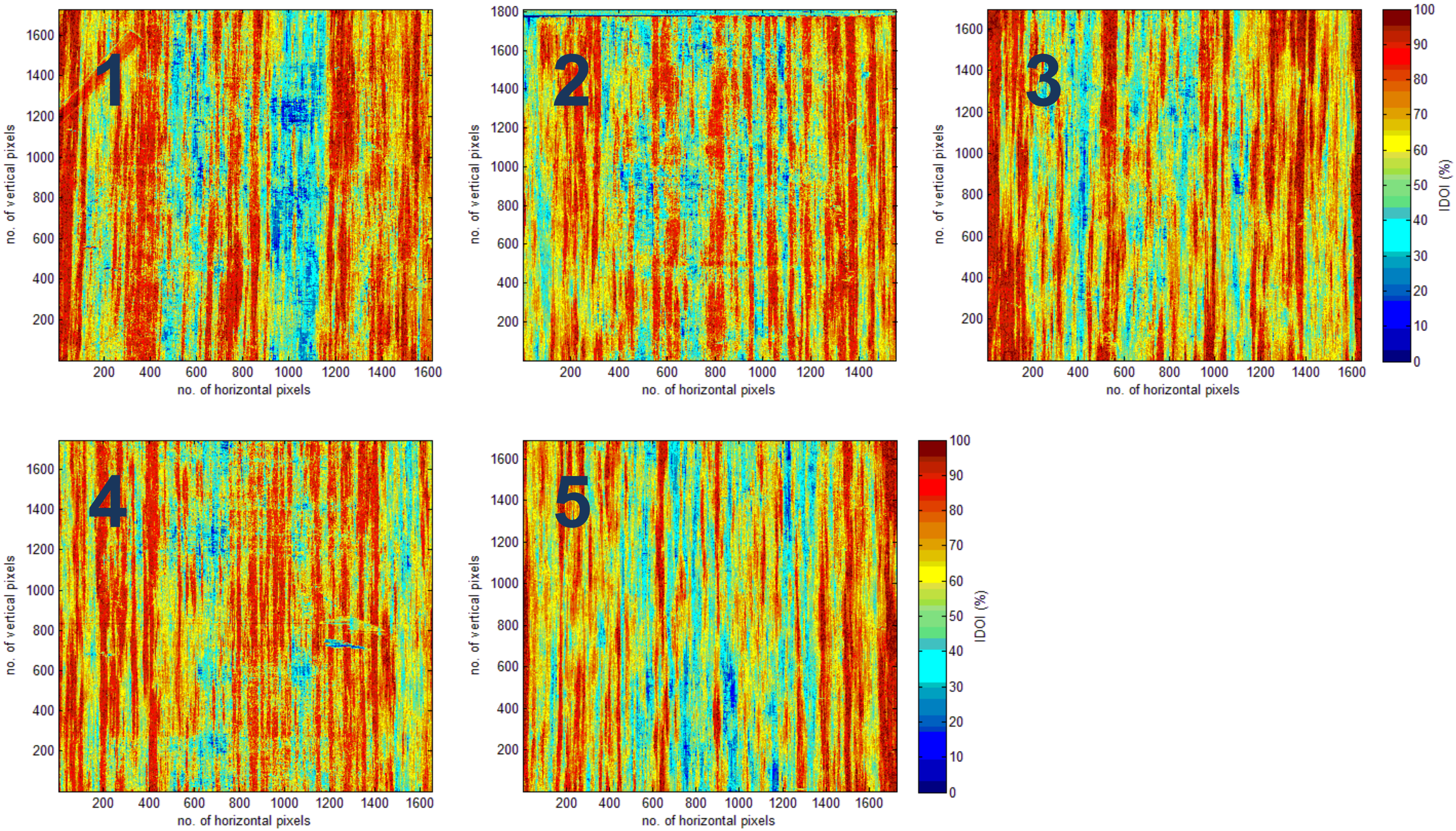
MicroCT Analysis from McGill University – Slide provided by Professor Hubert and student, Marc Palardy-Sim

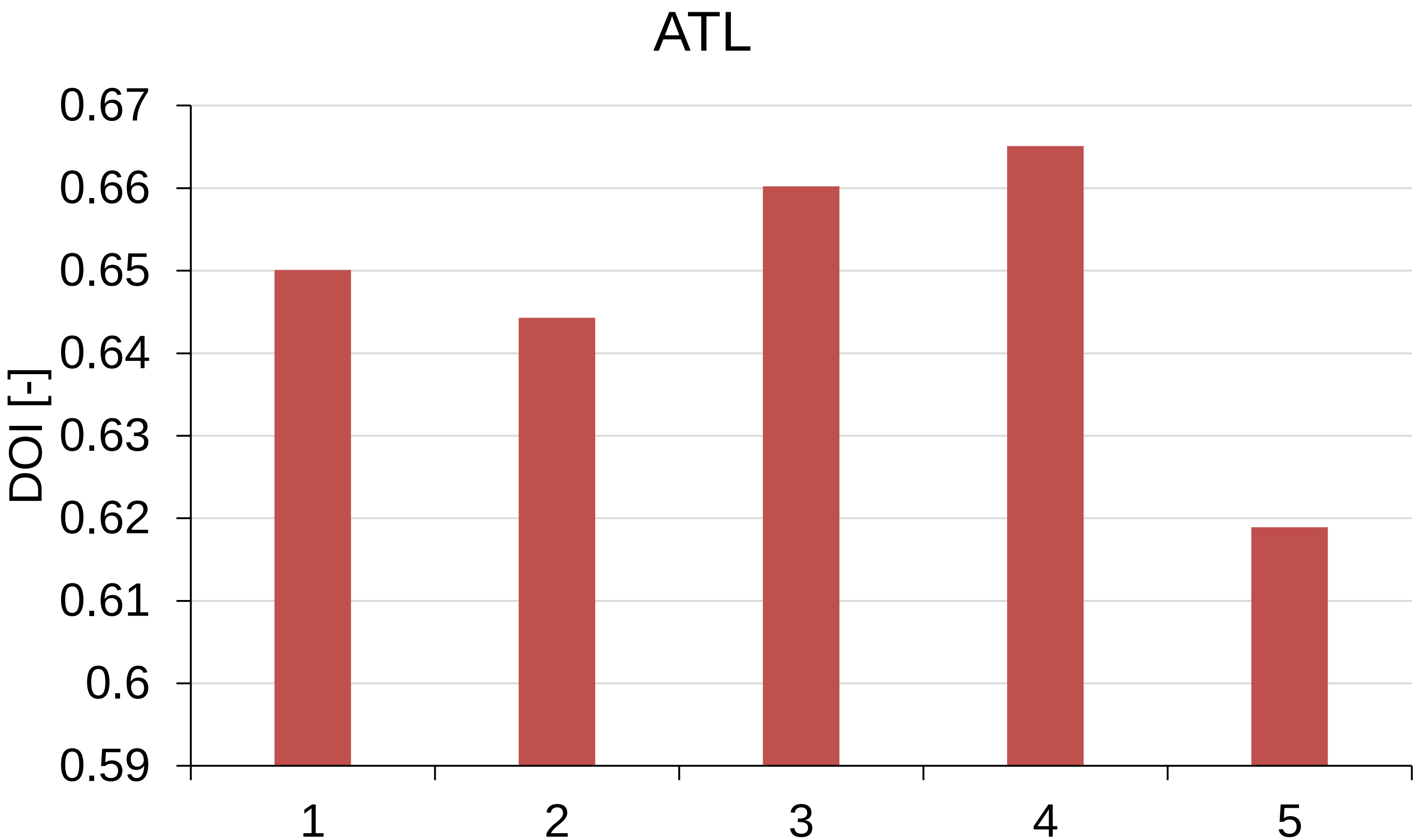




	1	2	3	4	5
Average	0.9089	0.8989	0.8690	0.8870	0.8854
St. dev.	0.1130	0.1135	0.1217	0.1254	0.1217

ATL





Average	0.6501	0.6443	0.6602	0.6651	0.6189
St. dev.	0.1978	0.1798	0.1797	0.1682	0.1801

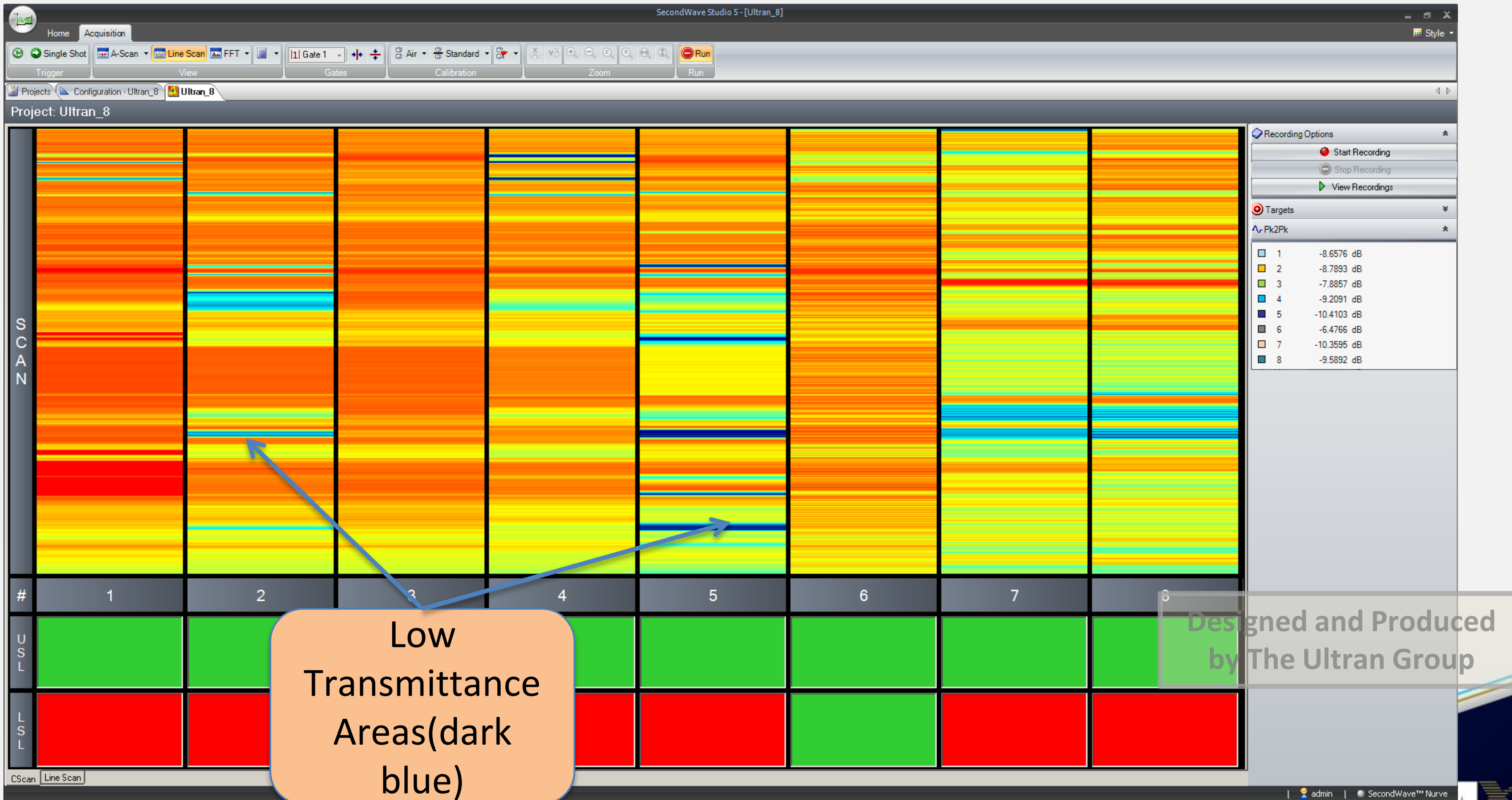
Output in line scan form is useful for statistical tracking and notification of process control

Line Scan during Continuous Inspection

High Variance

Rolling C-scan (2-D Image) can be useful for human inspection and assessment

Rolling C-scan during Continuous Inspection (8-channel system)



Appendix II

- Non-Contact Ultrasonic Measurement of Prepreg Level of Impregnation

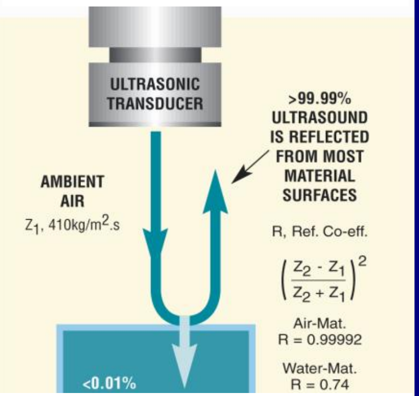
Non-contact ultrasound requires very high efficiency to capture any valuable transmission signals

1

Exorbitant Absorption by Air/ Gases -- *>100 dB @ 1 MHz for Air!*

2

Gross Z Mismatch Between Air/ Gases to Solids



Round Trip Loss to & from Material ~190 dB!

3

Inefficient Transmission from Piezoelectric to Air/Gases

PZT

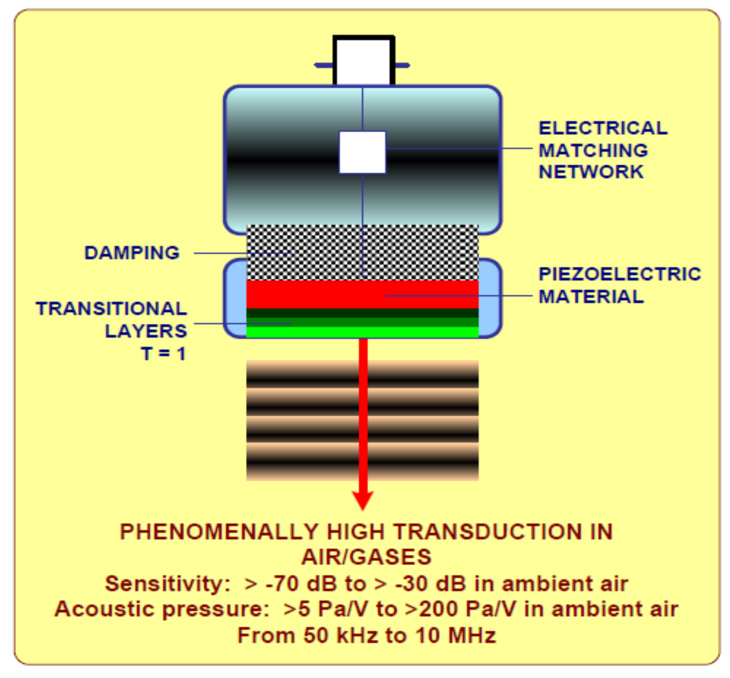
AIR

T = -97 dB!

1 and 2 are natural phenomena about which nothing can be done
#3 requires radical transducer concepts

High efficiency transducers for non-contact and low frequency ultrasound are driven by high acoustic matching and efficient piezoelectrics

Elements of Non-Contact Transducers*



High Performance from 30 kHz to 5 MHz

Features

- Transition layer and matching layers provide efficient transmission through air
- NCU transducers optimized for frequencies between 30 kHz and 5 MHz
- Gas matrix piezoelectric (GMP)* composite allows for enhanced performance at frequencies between 30 kHz and 500 kHz
- High quality results achieved with many composite materials

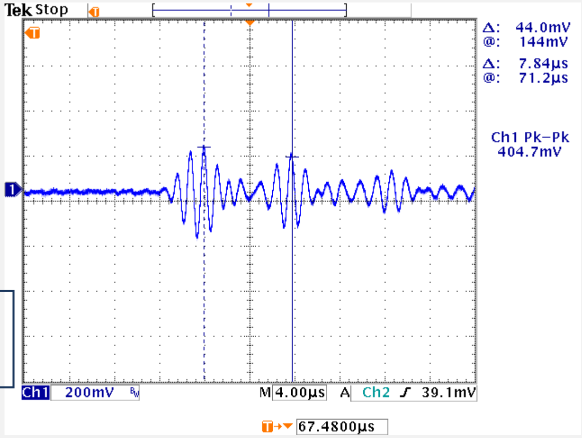
*US and International Patents

Ultran has developed transducers and systems to maximize efficiency

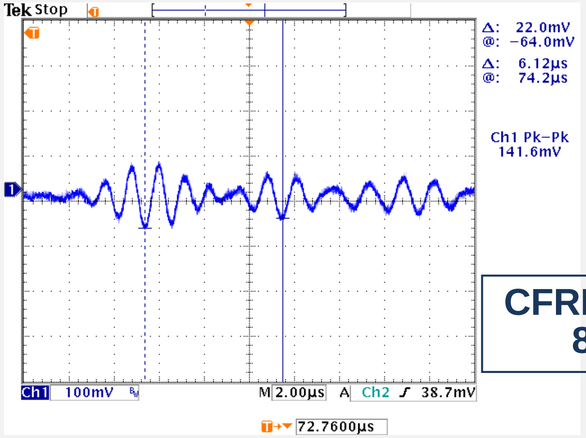
High Efficiency Evidence*

Applications Oriented Examples

1 MHz Transducers



Silica Filled Rubber 7 mm Thick



CFRP Composite 8.9 mm Thick

Excitation: Only 32 Volts One Burst!
Amplification: 64 dB

**Purpose of this exercise is to exhibit the NCU transducers high efficiency. Practical purposes can allow for higher excitation voltage*

NCU transmission amplitude varies between prepreg type and locally within samples

NCU Transmission Amplitude (700 kHz) and Water Pickup Values for 3 Sample Types

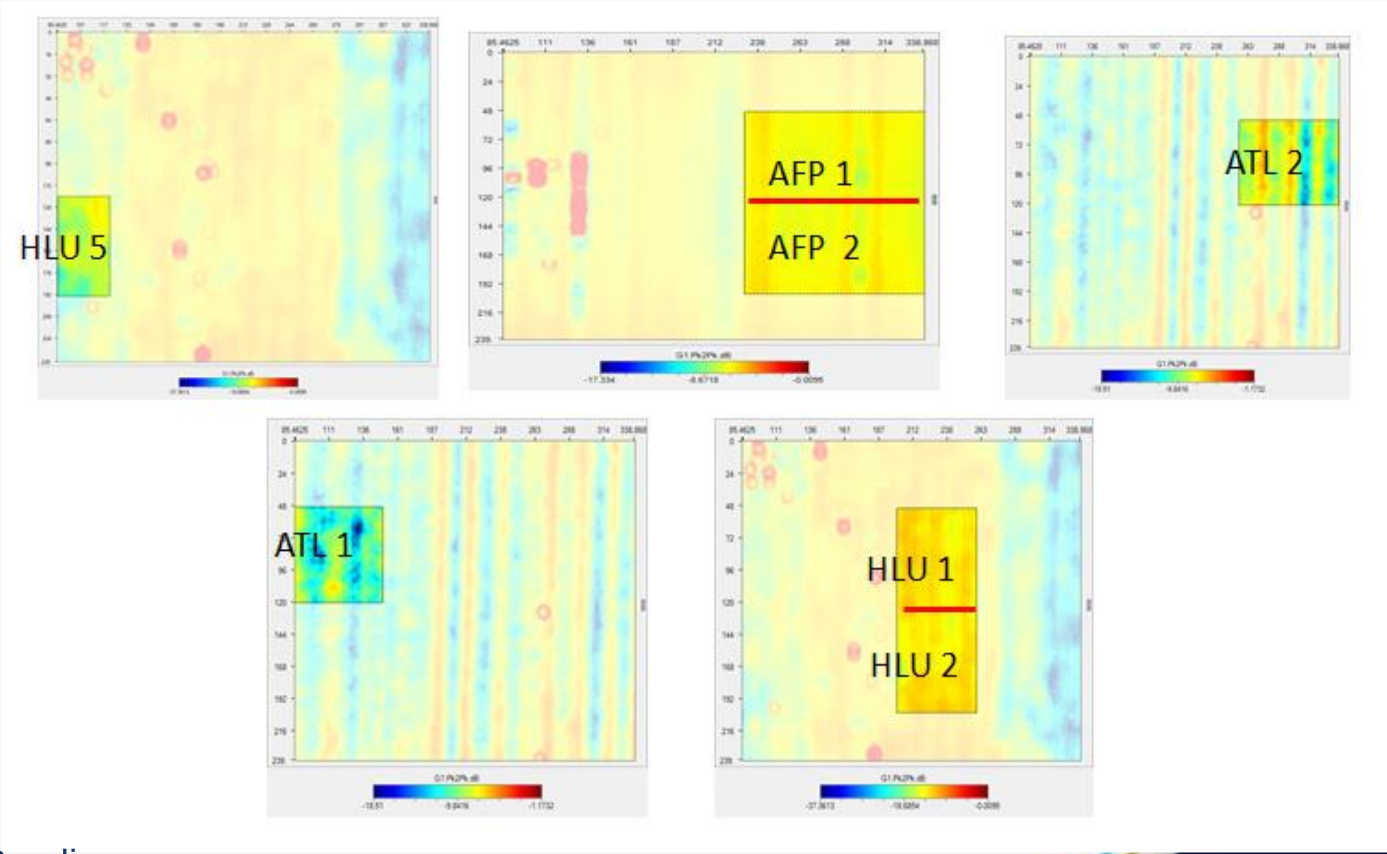
Sample	NCU Average Amplitude (dB)	Controlled Impregnation Level	W1 (g)	W2 (g)	WPU (%)
AFP-2	-5.51	High	0.269	0.270	0.4%
ATL-2	-9.79	Medium	0.392	0.425	8.4%
HLU-2 (1)	-15.55	Low	0.391	0.486	24.3%

NCU Transmission Amplitude (700 kHz) and Water Pickup Values for 3 Sections of HLU Sample

Sample	NCU Average Amplitude (dB)	W1 (g)	W2 (g)	WPU (%)
HLU-2 (1)	-15.55	0.391	0.486	24.3%
HLU-2 (2)	-10.90	0.400	0.474	18.5%
HLU-2 (3)	-24.36	0.398	0.583	46.6%

Sections of high uniformity from each sample were specifically selected to perform a high accuracy correlation between NCU and LOI

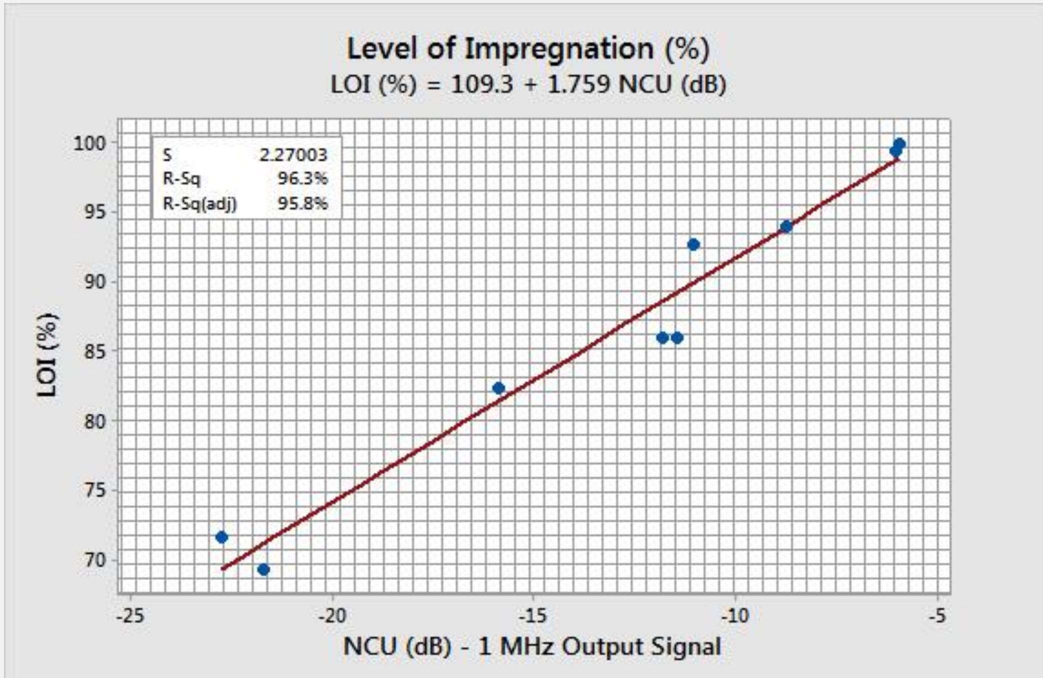
Pre-selected Regions for Guided Water Pickup Test to Perform Initial Correlation



*US Patent Pending

Using the guided water pickup test, the accuracy of measurement and correlation is significantly improved

Correlation Results between LOI measured from Guided Water Pickup Test and NCU Transmittance at 1 MHz*



Sample #	NCU T_X (dB)	WPU (%)	LOI (%) (1-WPU)
AFP 1	-6.01	0.6%	99.4%
AFP 2	-5.93	0.1%	99.9%
ATL 1	-11.04	7.3%	92.7%
ATL 2	-8.75	6.0%	94.0%
HLU 1	-11.45	14.1%	85.9%
HLU 2	-11.83	14.1%	85.9%
HLU 3	-21.73	30.7%	69.3%
HLU 4	-22.75	28.4%	71.6%
HLU 5	-15.86	17.7%	82.3%

*Results can be further improved by processing data and filtering out artifacts, such as pin-holes

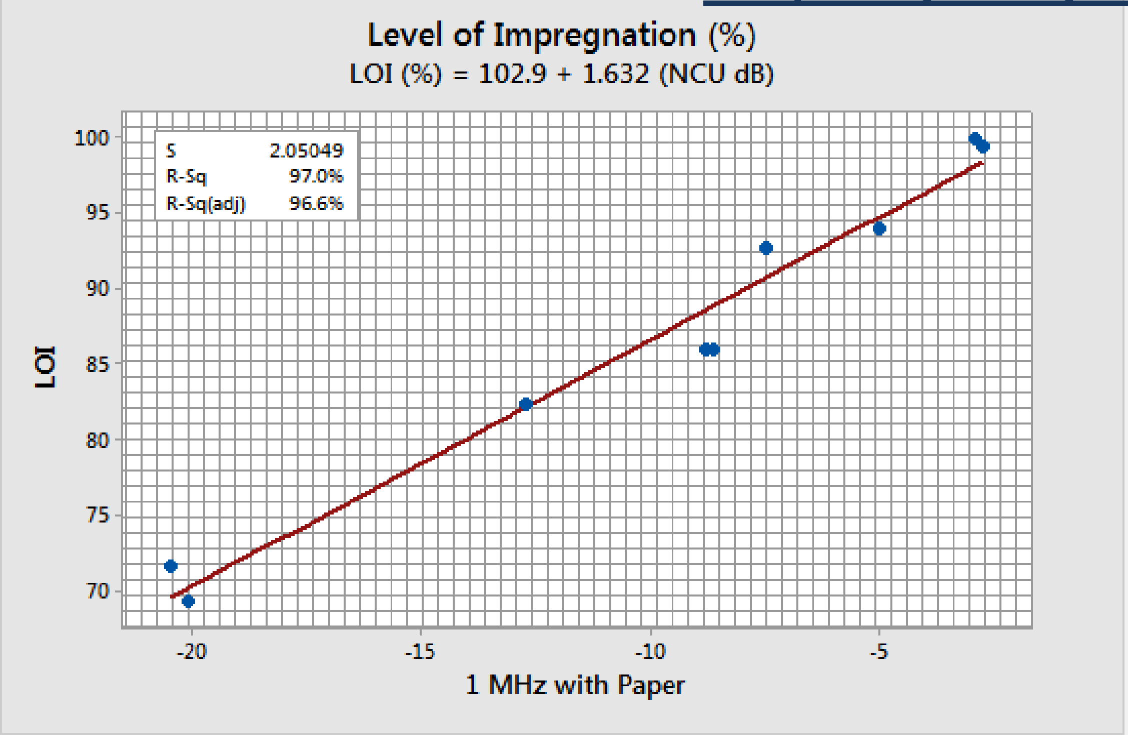
*US Patent Pending

R^2 = 96.3%

S= 2.27%

Analysis upon prepreg with backing paper may improve accuracy of measurement

Statistical Results with Paper Backing (1 MHz transmission) – From Initial Frequency Analysis



Sample	WPU %	LOI% (1-WPU)	NCU T_x w/o Paper (dB)	NCU T_x with Paper (dB)
AFP 1	0.6%	99.4 %	-6.01	-2.76
AFP 2	0.1%	99.9 %	-5.93	-2.95
ATL 1	7.3%	92.7 %	-11.04	-7.5
ATL 2	6.0%	94.0 %	-8.75	-5.02
HLU 1	14.1 %	85.9 %	-11.45	-8.64
HLU 2	14.1 %	85.9 %	-11.83	-8.79
HLU 3	30.7 %	69.3 %	-21.73	-20.09
HLU 4	28.4 %	71.6 %	-22.75	-20.47
HLU 5	17.7 %	82.3 %	-15.86	-12.72

R2 and S have improved compared to results without paper backing

R^2 = 97.0%

S= 2.05%