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PNNL-SA-126947

Frequency Domain Reflectometry Modeling for NDE of Nuclear Power Plant Cables

Light Water Reactor Sustainability

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January 2020

Light Water Reactor Sustainability R&D Program

Cable Research Collaboration

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LWRS

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- Robert Duckworth (ORNL)
- Thomas Rosseel (ORNL)

Non-LWRS

- Nicola Bowler (ISU) (NEUP)
- Ryan O'Hagan (AMS Corp.)
- Bill Berger (Fauske/ Westinghouse)
- Paolo Fantoni (Wirescan)

Goal: maximize impact with limited resources.

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Outline

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- Aging Concerns & Program Justification
- Electrical Cables in Nuclear Power Plants
- FDR Theory
- 2016 Systems Compared
- 2017 Modeling/Test
- Observations/Conclusions/Future Plans

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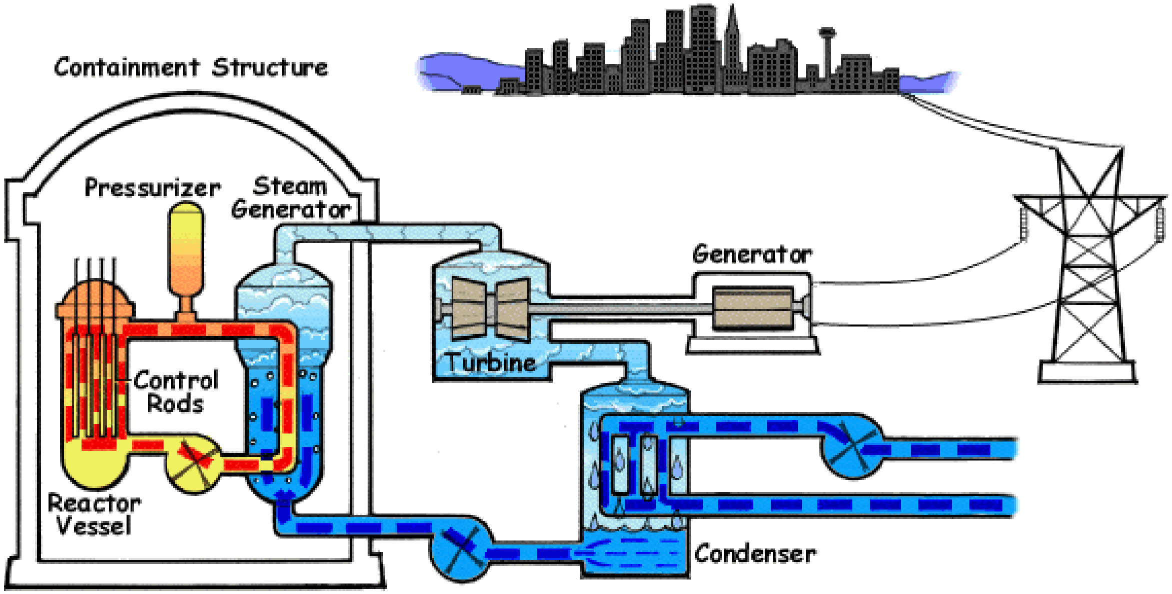
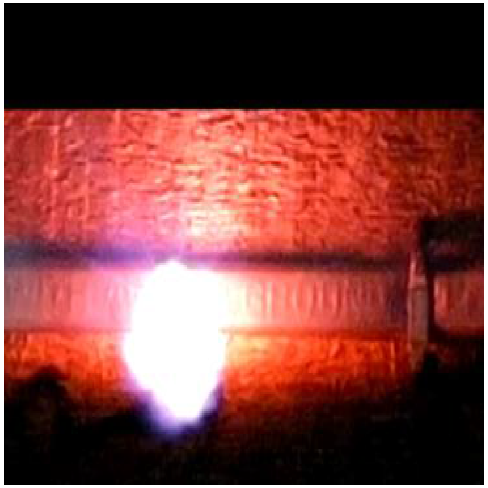
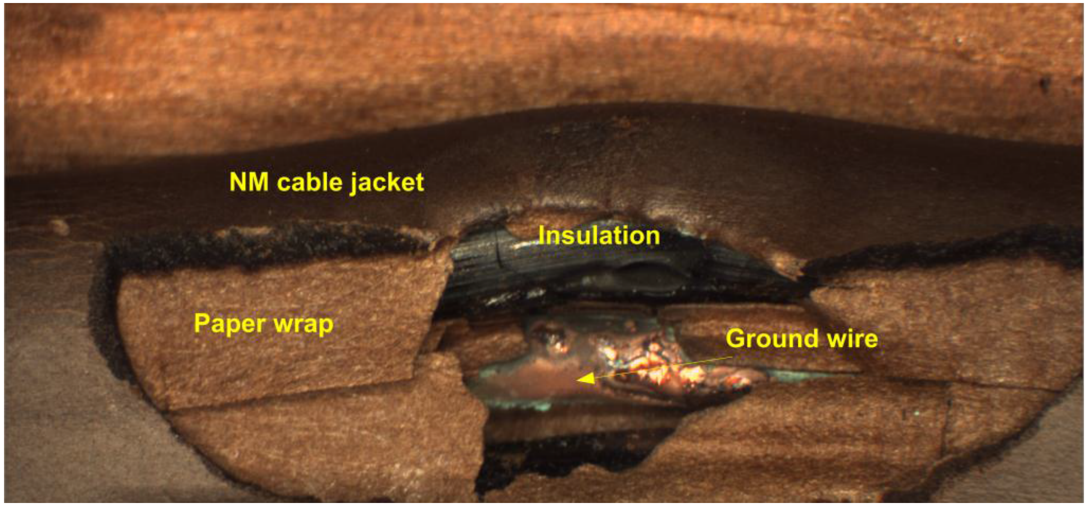
Nuclear Power Plants (NPPs)



- NPPs contain thousands of miles of electrical cable and wire of several hundred different types and sizes.
- Ramifications of cable failure can be significant, especially for cables connecting to: off-site power, emergency service water (ESW), emergency diesel generators (EDG).

Why the Concern for Aging?





Left – Arc Flash in 120 VAC house cable. Right – Damaged cable and insulation following Arc Flash. (Image courtesy of Underwriters Labs)

- Arc Flash failure can be dramatic and dangerous as an event.
- Following an Arc Flash, the cable load or sensor is no longer functional and this can further compromise plant integrity.

Cables in Nuclear Power Plants

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Application

- Power cables
- Control cables
- Instrument cables
- Thermocouple cables
- Specialty cables

Design

- Low-voltage (≤2 kV)
- Medium-voltage (2-46 kV)
- High-voltage (>46 kV)

Usage

- 61% Control
- 20% Instrumentation
- 13% AC power
- 5% Communication
- 1% DC power

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Electrical Cable Systems

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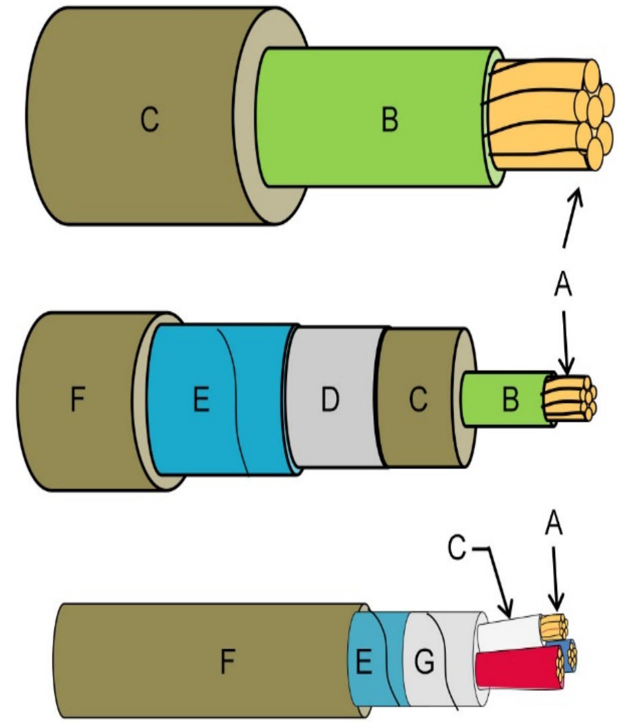
- Cables
  - Conductor
  - Insulation
  - Jacket
- Terminations
- Splices

A Uncoated copper conductor
B Semiconducting screen
C Insulation
D Insulation screen extruded semiconductor
E Shielding copper tape with/without drain wire
F Jacket
G Helically applied binder tape



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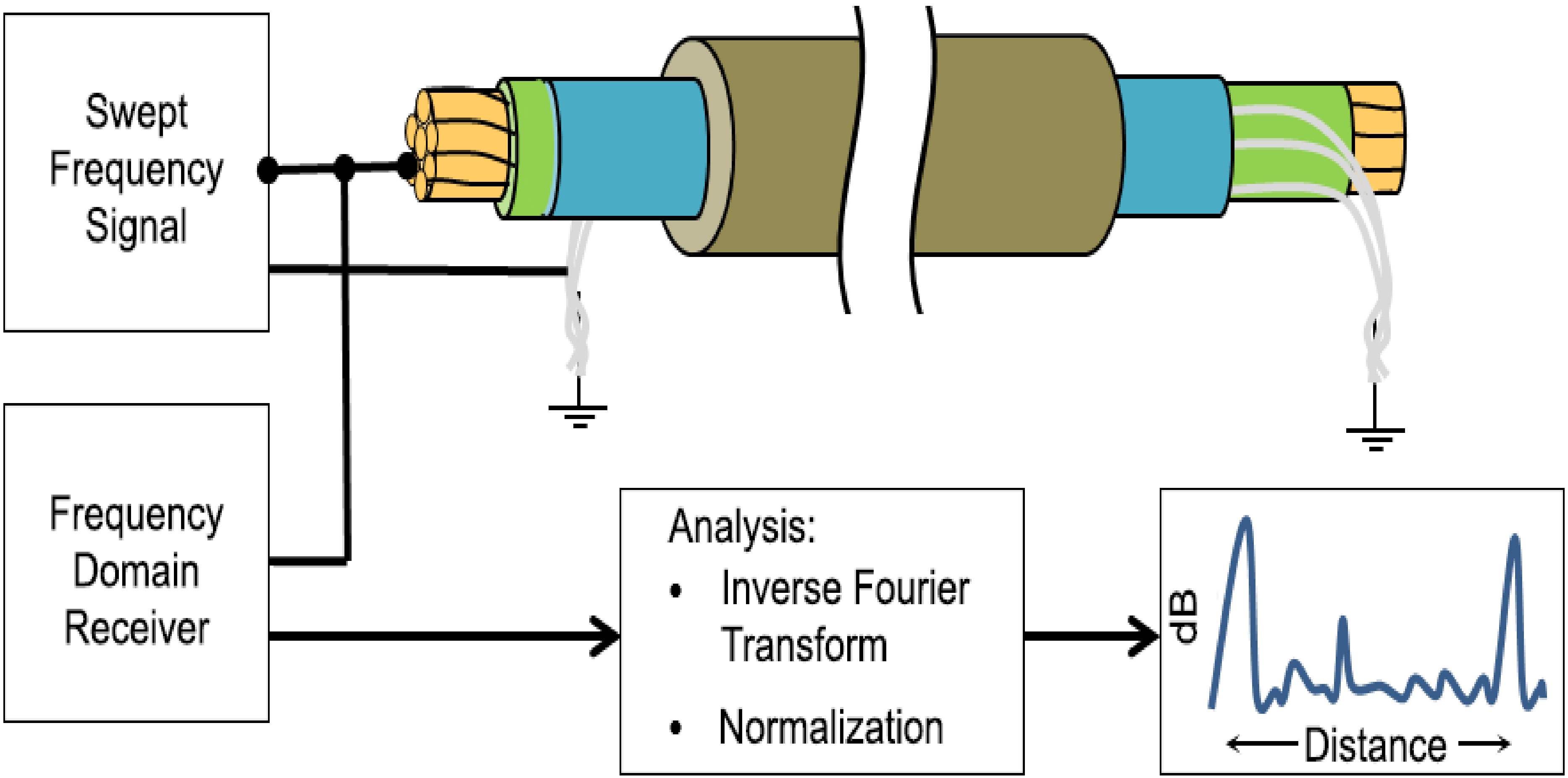
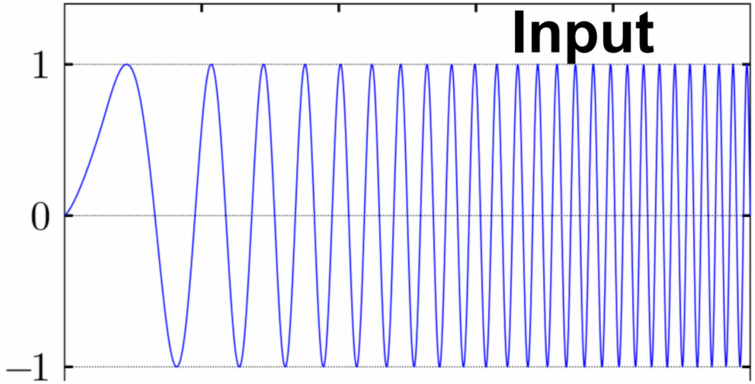
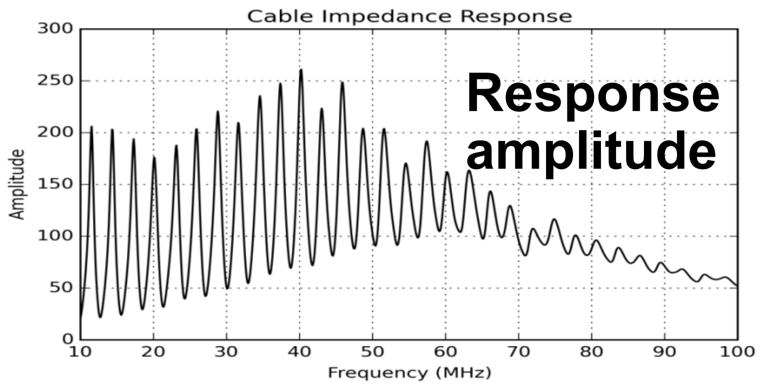
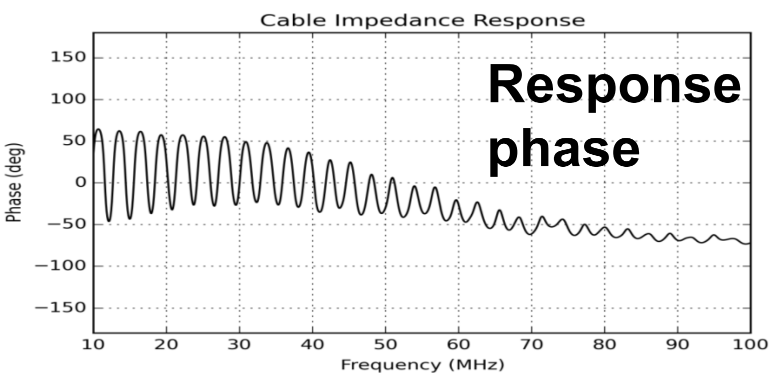
FDR Cable Test System Architecture

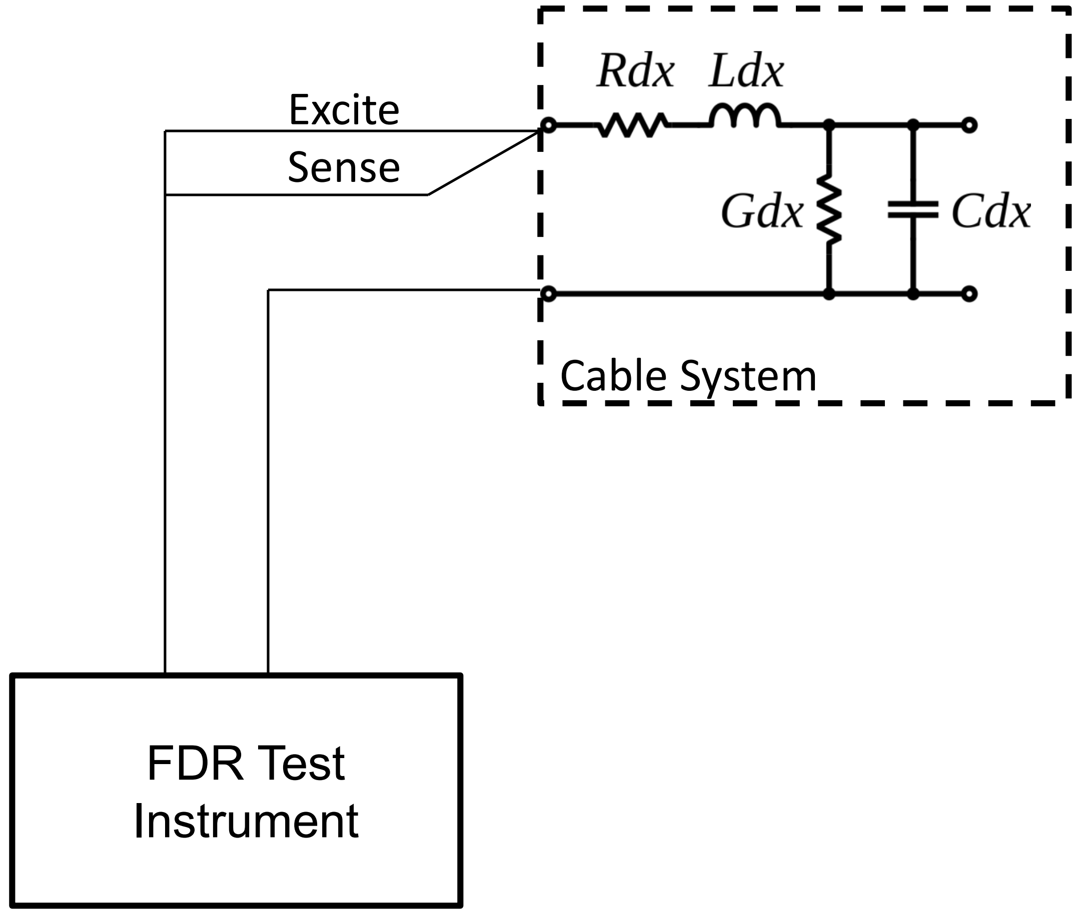


FDR Test Configuration









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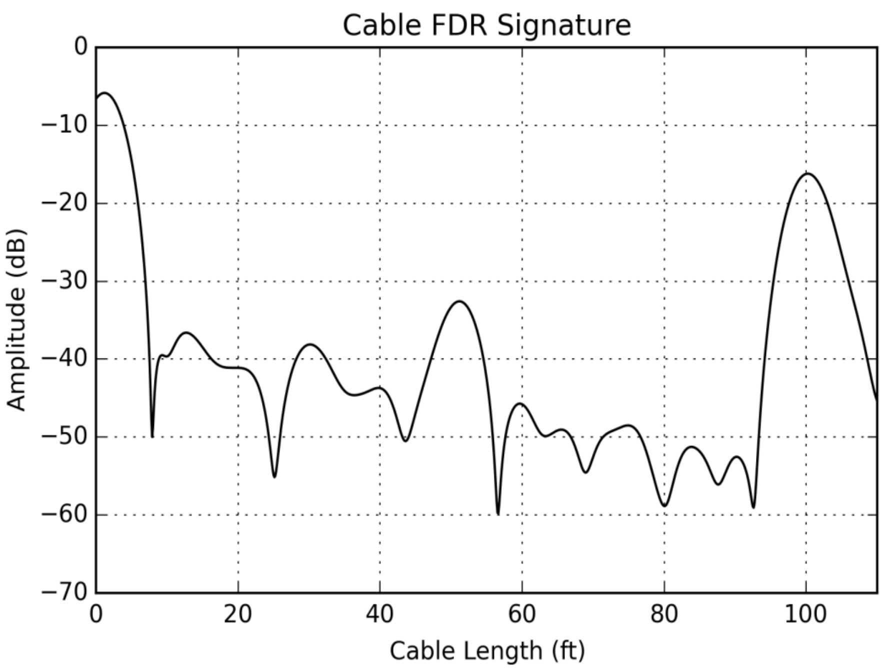
FDR Transformed to Time Domain can be Related to Distance by Wave Velocity



TR = IFT(FR)

DR = TR*V/2

where:

FR = Frequency response

IFT = Inverse Fourier Transform

V = propagation velocity

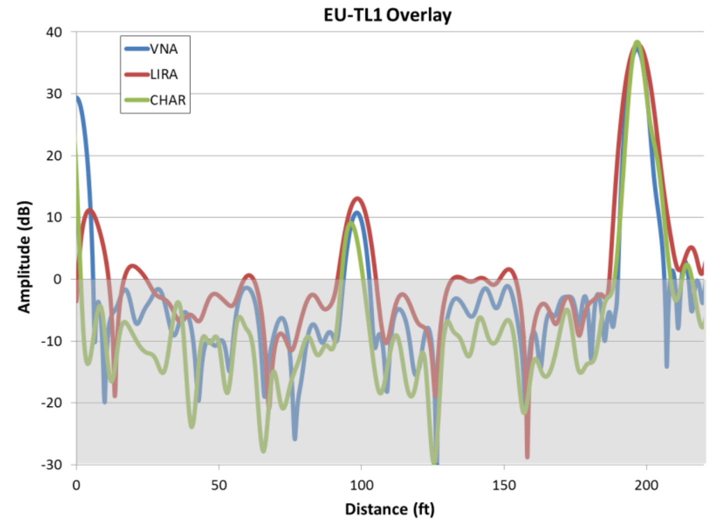
TR = Time response

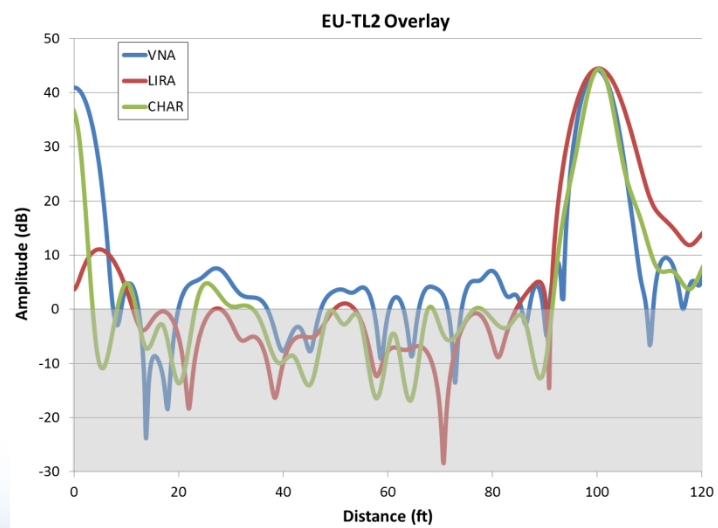
DR = Distance response

2 included because wave travels both to and from reflection points.

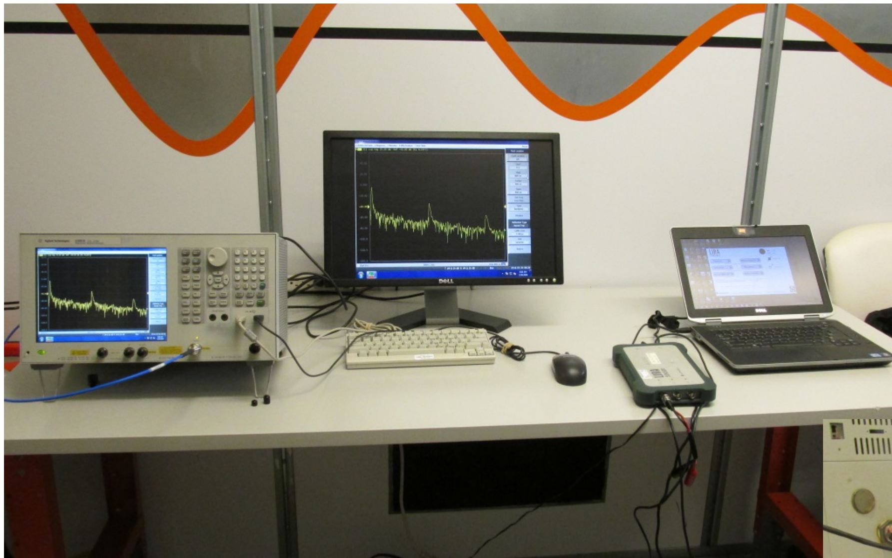
2016: Two different cable FDR comparisons among 3 instruments

- Responses are similar but not identical – particularly at low amplitude (grey)
- Significant peaks (above grey) are at same frequency and similar amplitude
- Trending should use the same instrument/ normalization approach

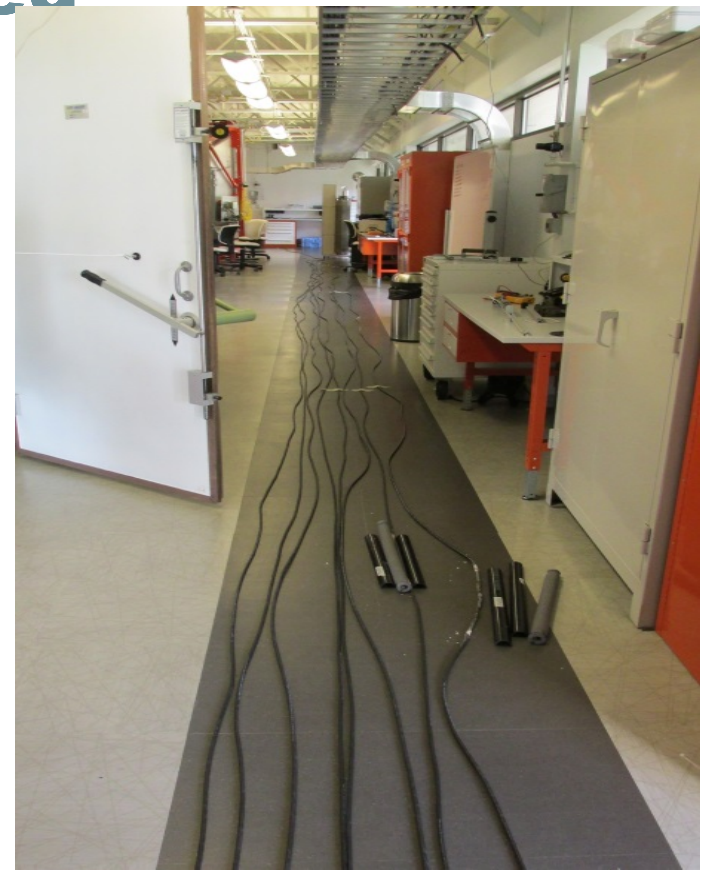




2016 Comparison of 3 FDR systems



2016 Cables were routed along floor and not moved while FDR systems were sequentially connected



2016 FDR Advantages/Disadvantages

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Advantages	Inspection of entire cable length from single-ended access
	Low voltage safe, non-destructive test
	Rapid inspection times (several minutes)
	Systems commercially available
	Sensitive detection and location of localized degradations
	In most cases, no need to de-terminate cable ends
Disadvantages	Global aging indicators still in development
	Baseline trend data helpful to assess cable condition
	Specialized training required for operation and analysis
	May not detect all degradations of concern

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2017 Co-axial and Triad Shielded Cable and FEM Models with Mechanical Damage

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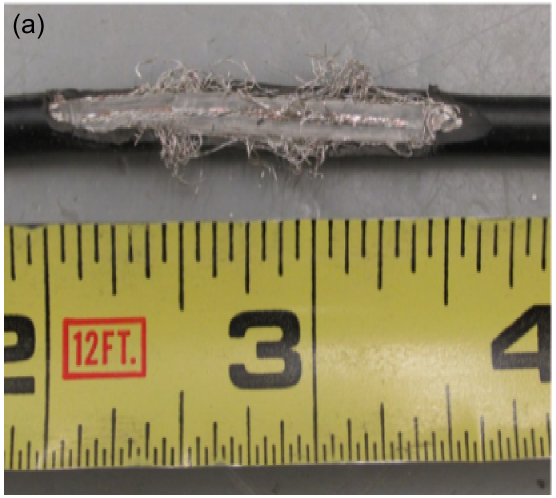

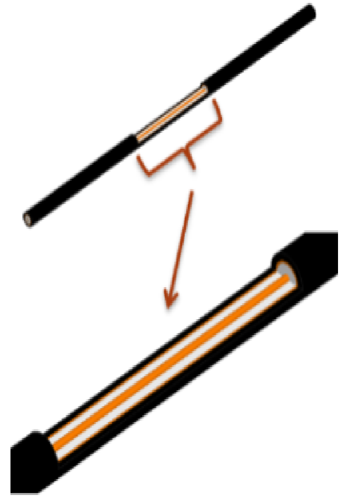

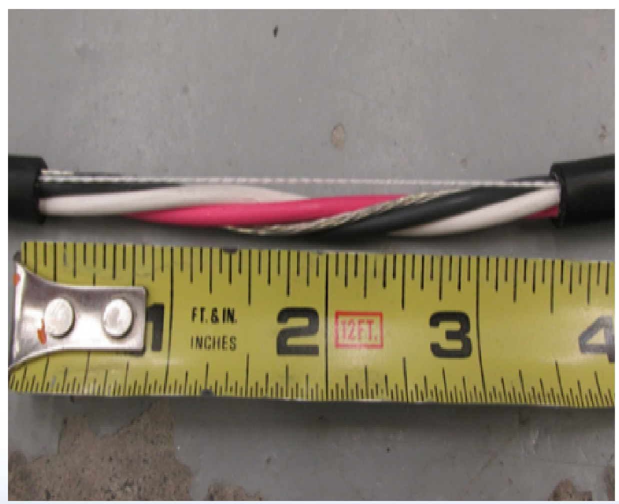

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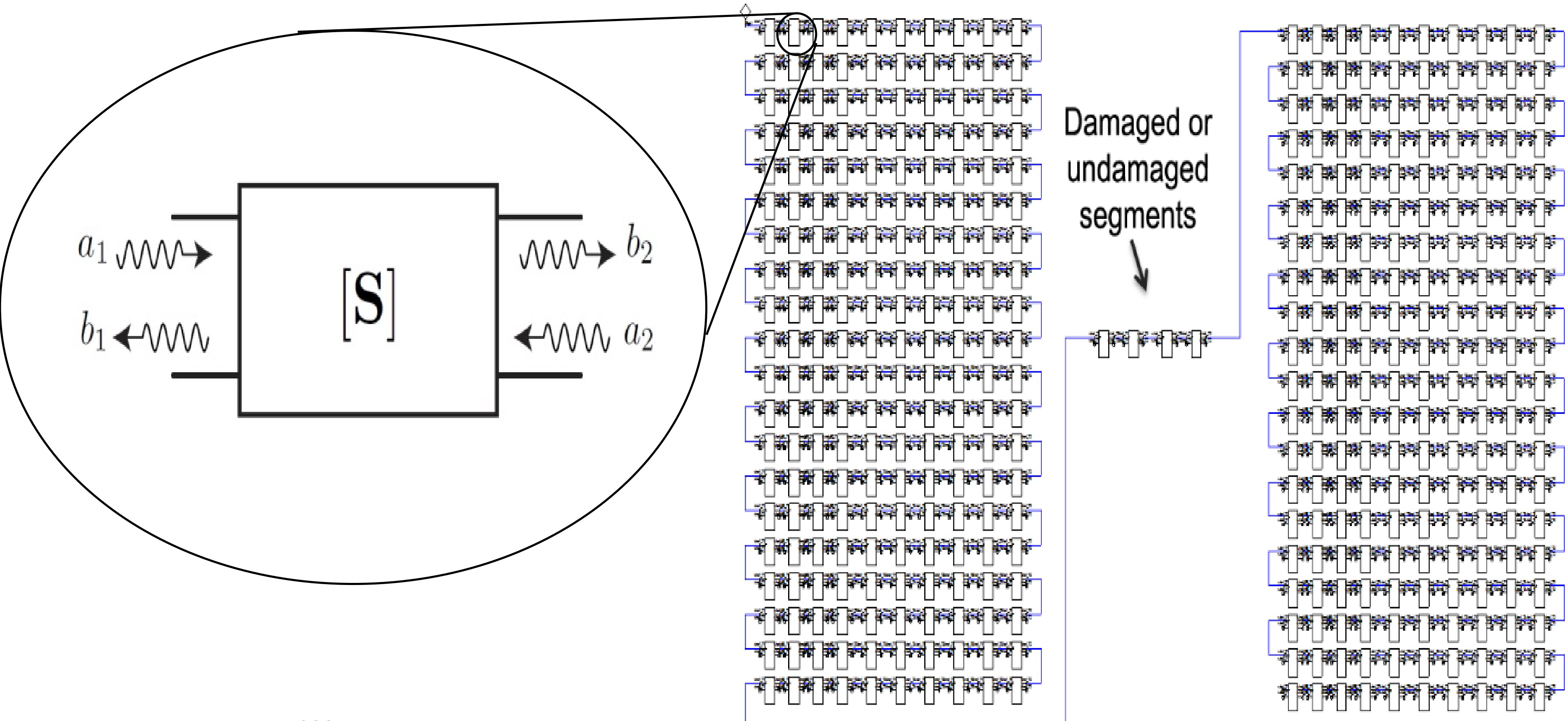
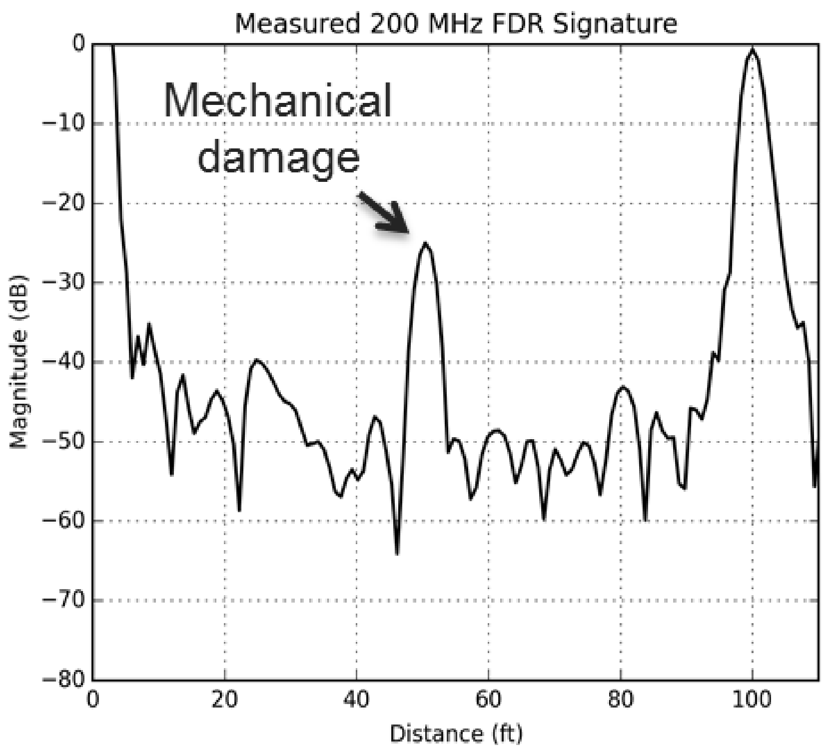
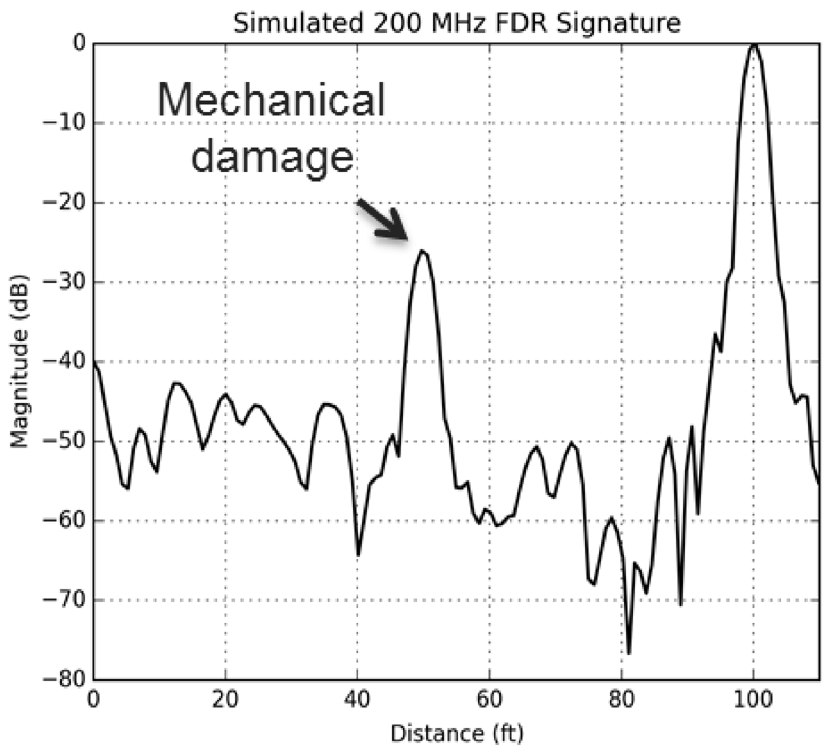
HFSS S-Parameter Circuit Model Used to Simulate FDR Responses



(L) Measurement and (R) ANSYS Simulation of 1.5 in. long Mechanical Damage of RG-58 Coaxial Cable

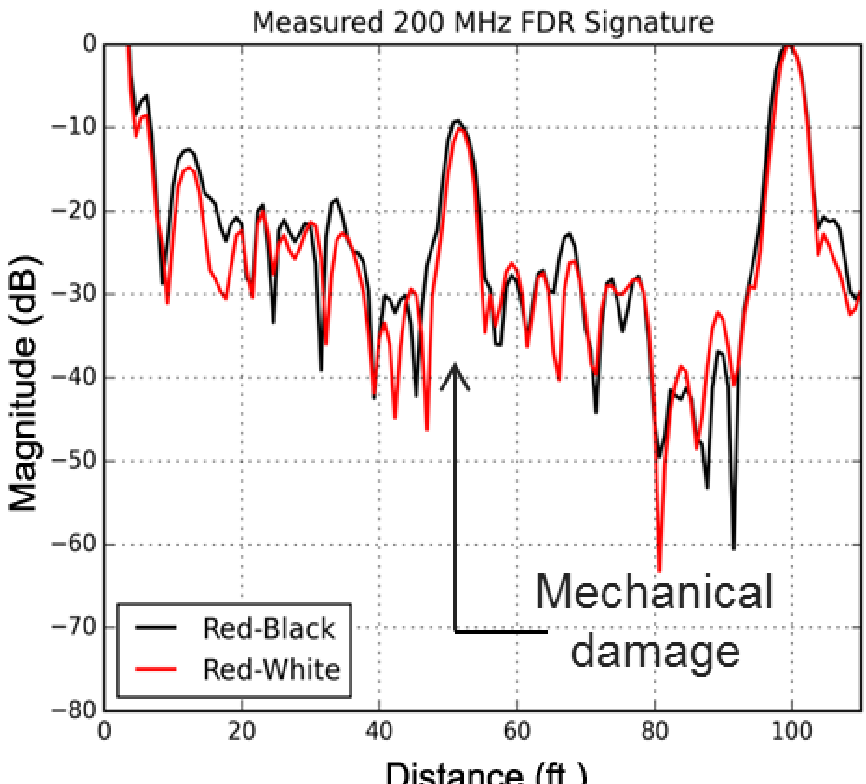


Measurement

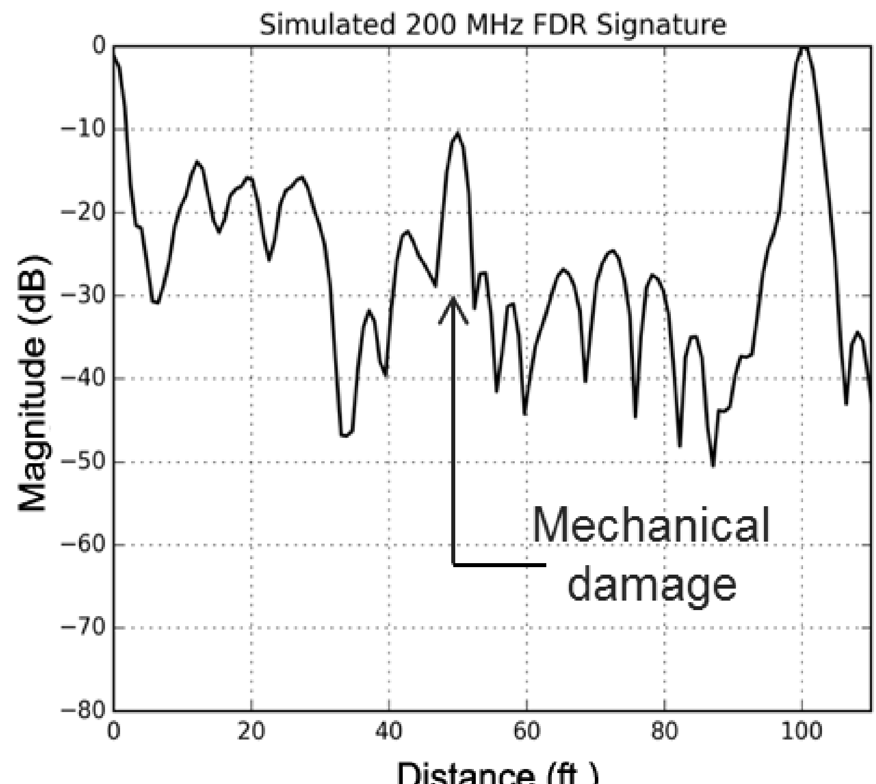


Simulation

(L) Measurement and (R) Simulation of 1.5 in. long Mechanical Damaged Section of Triad Shielded Cable



Measurement



Simulation

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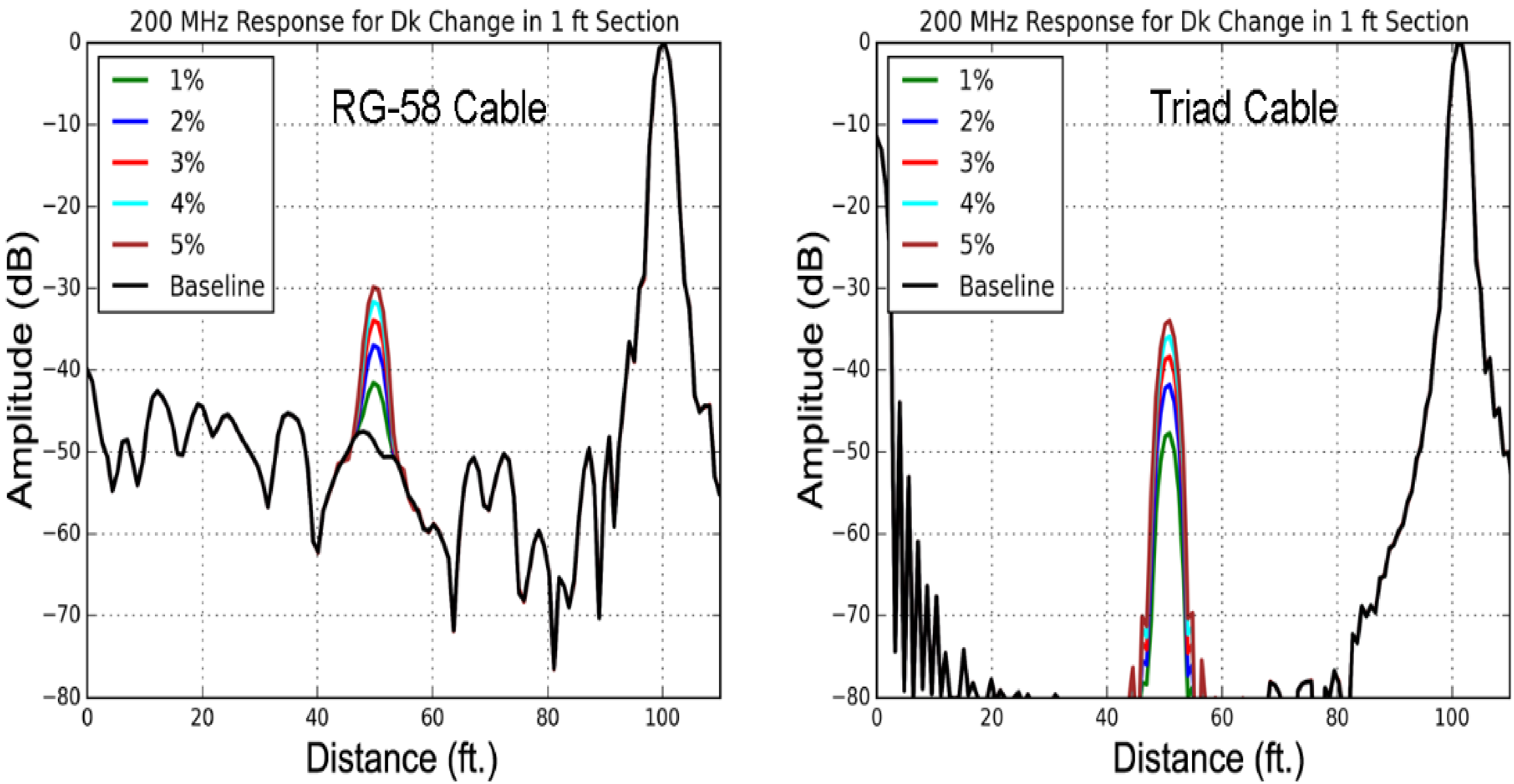
Simulated Insulation Dielectric Constant Influence on FDR



Simulated Defect Length (for 5% increase in Dielectric Constant in Shielded Triad Cable)

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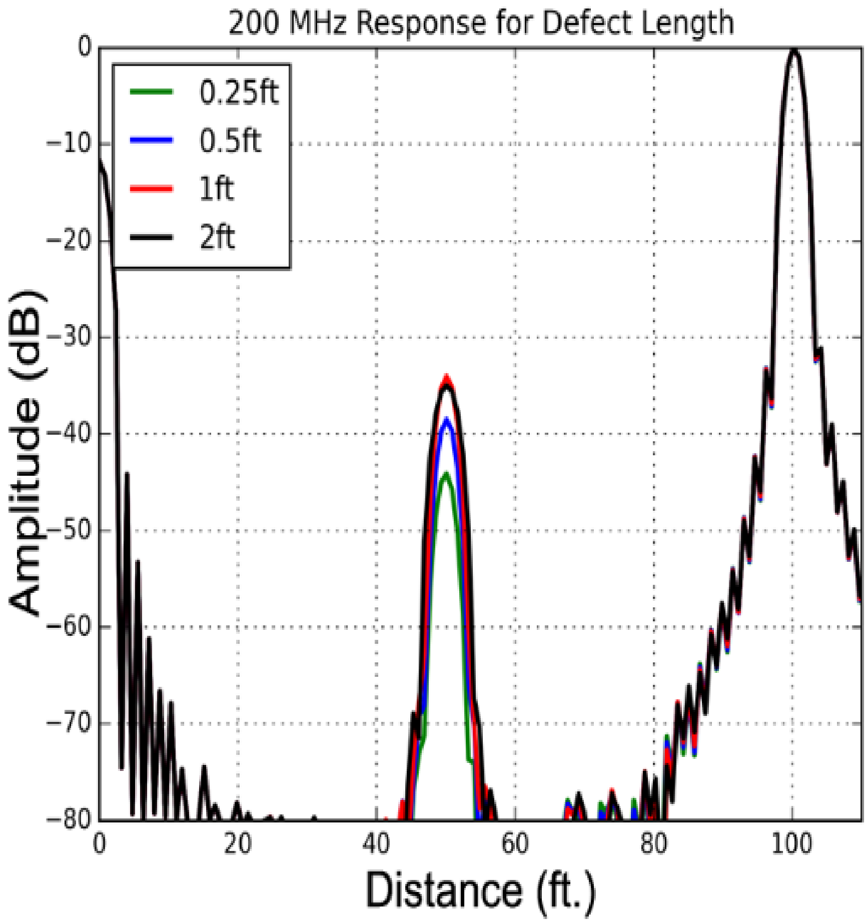

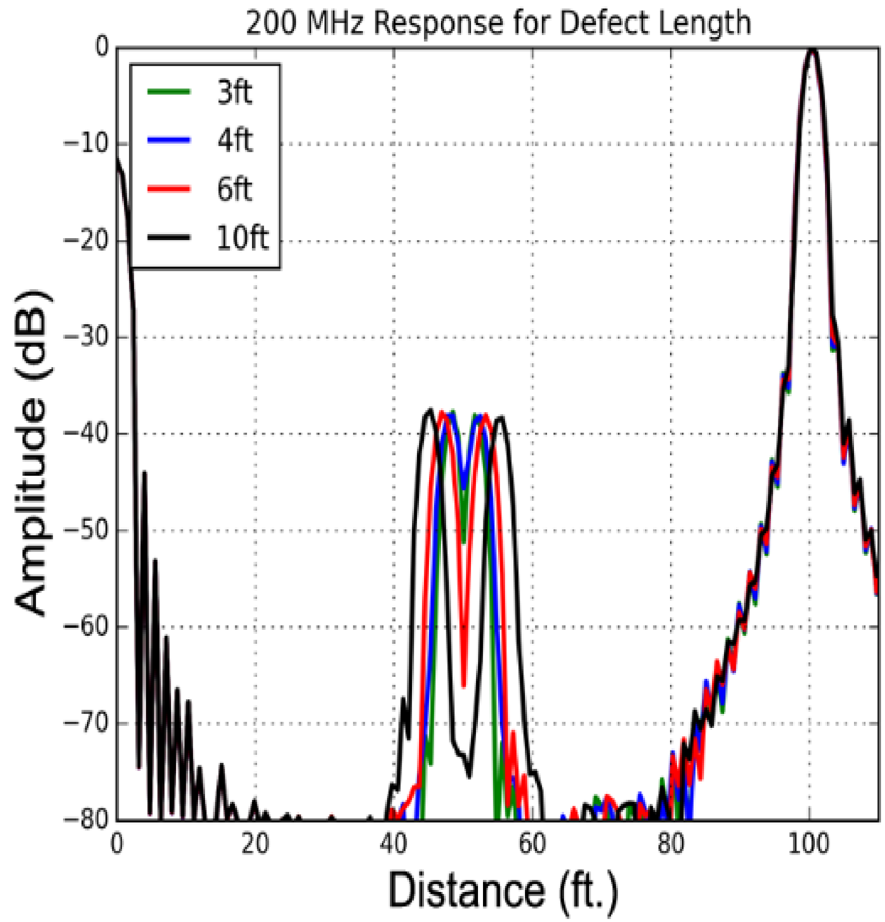

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Defect Length Influence Confirmation with Multiple Loop Artificially Aged Samples

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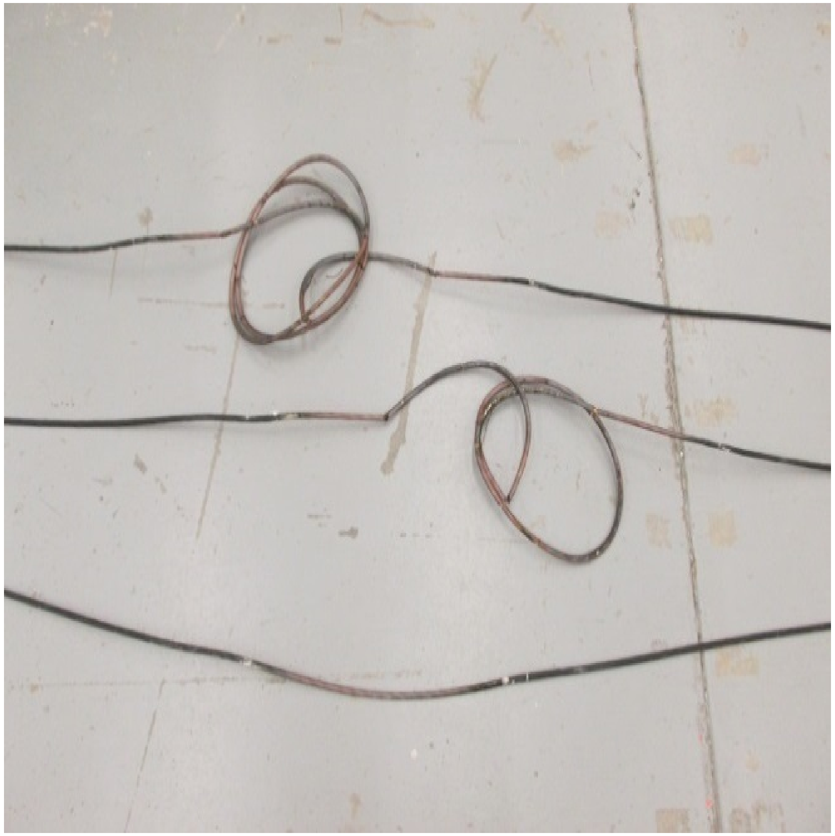

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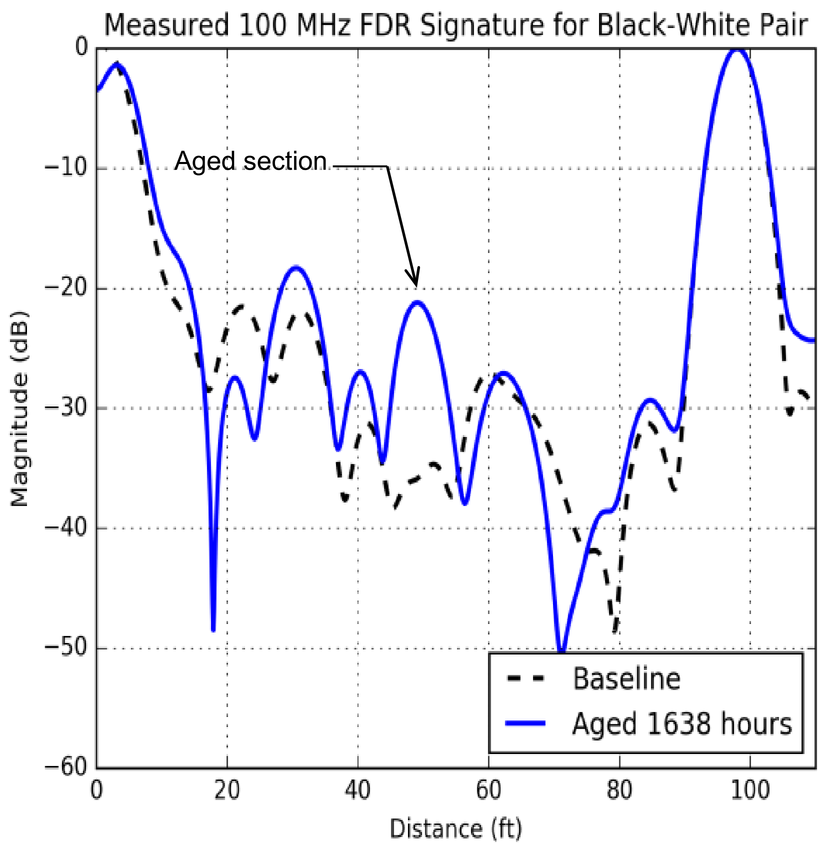
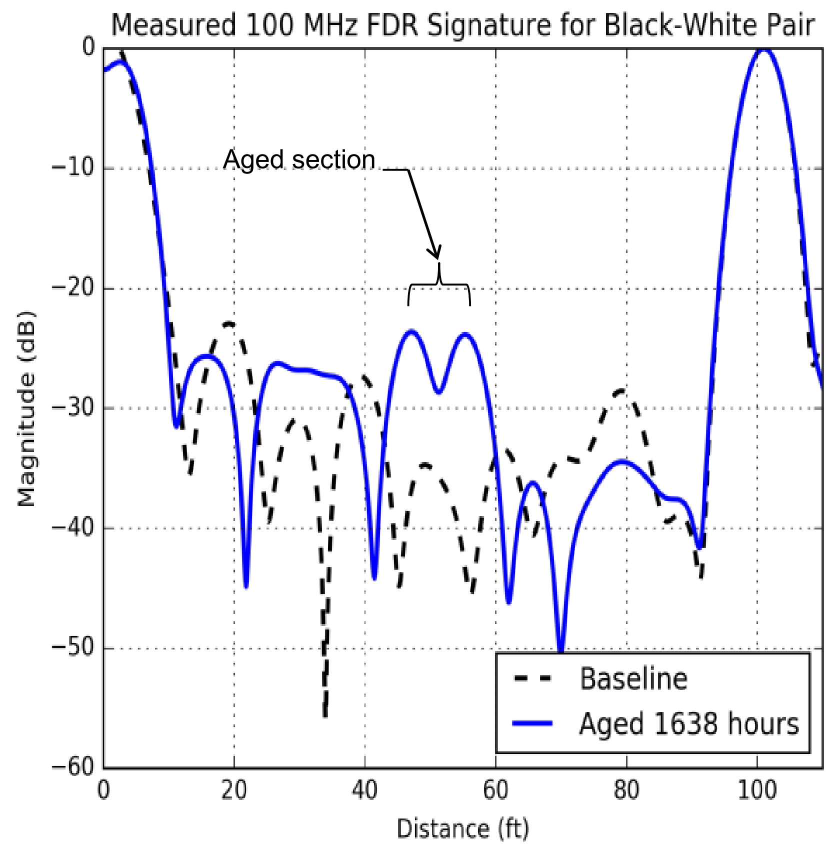
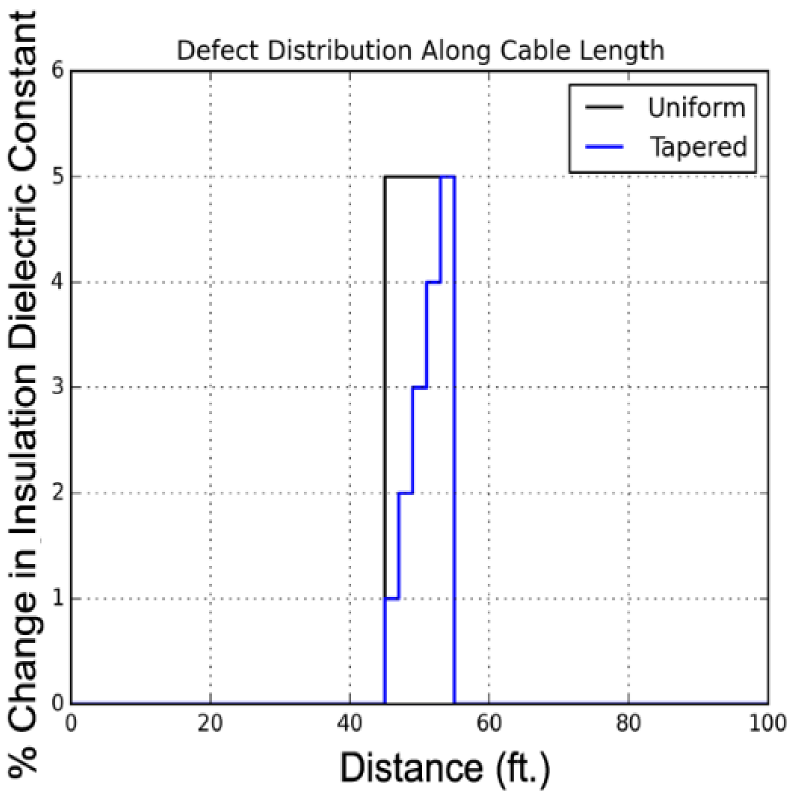
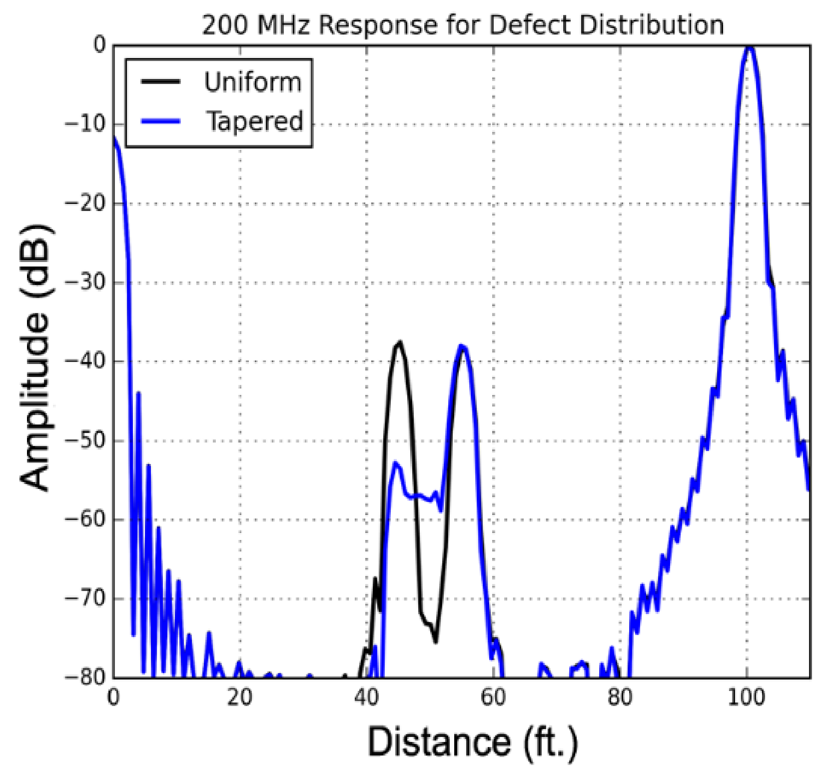
LIRA Measurements for a Uniformly Aged (left) 1.5 ft. and (right) 7.25 ft. Shielded Triad Cable



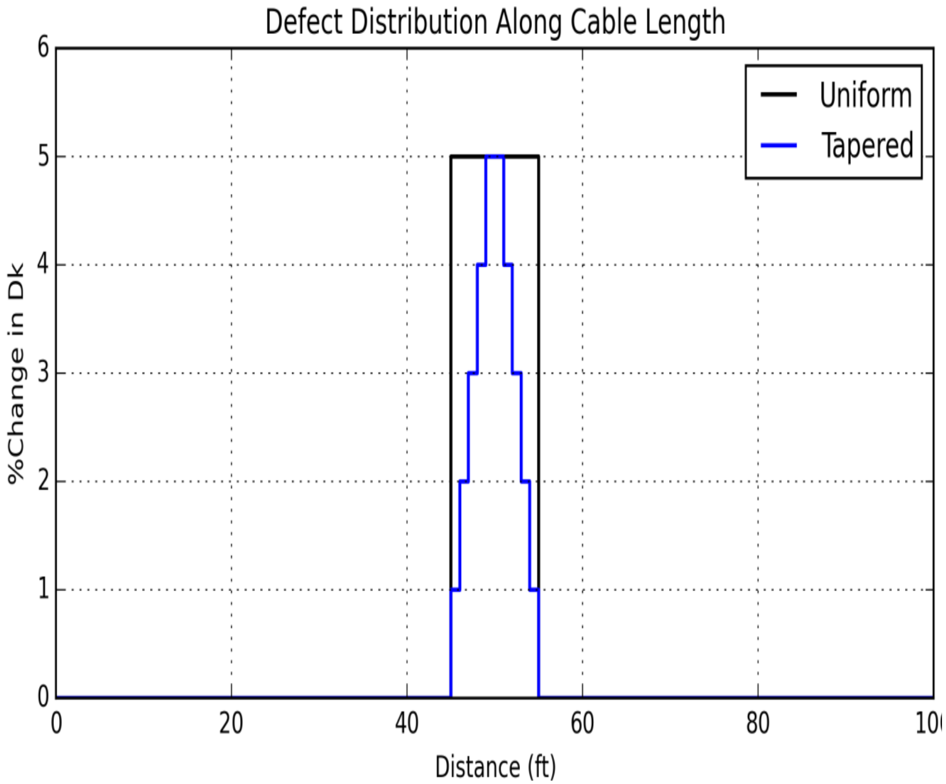


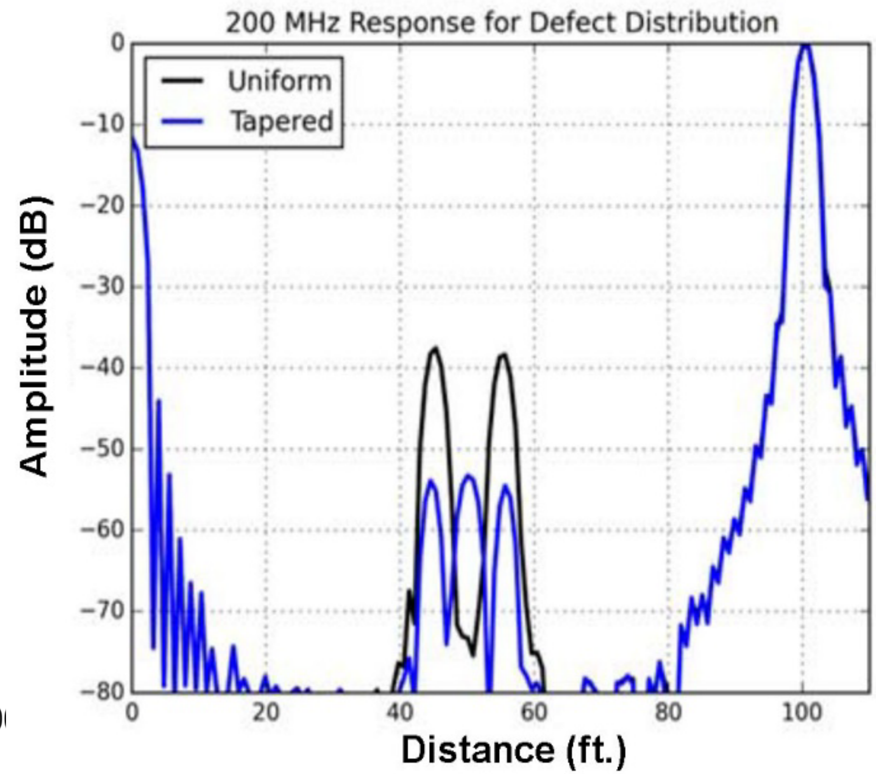
Simulated Single Sided Ramp Defect Profile Influence on FDR





Simulated Two-sided Ramped Capacitance Change Profile Influence on FDR





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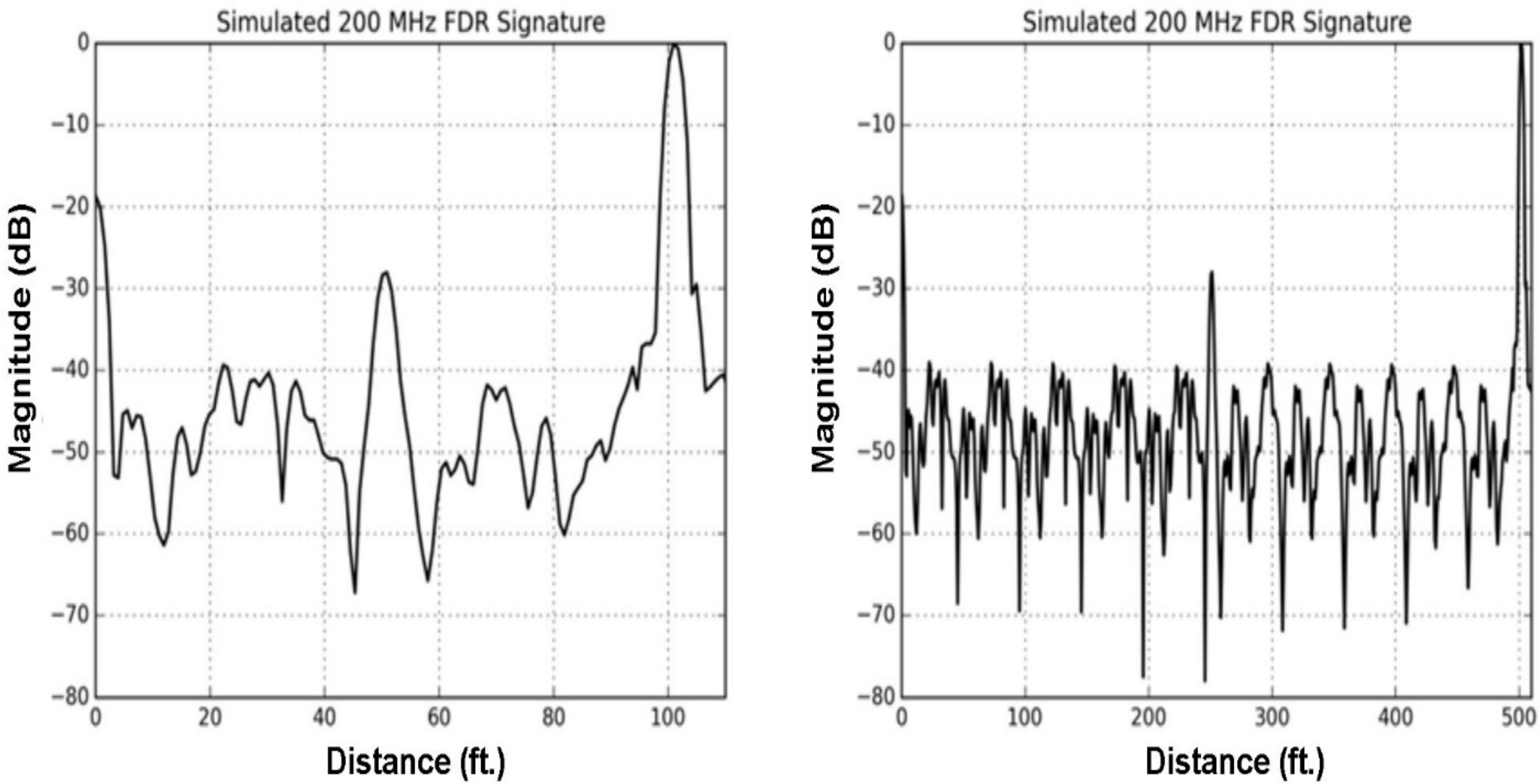
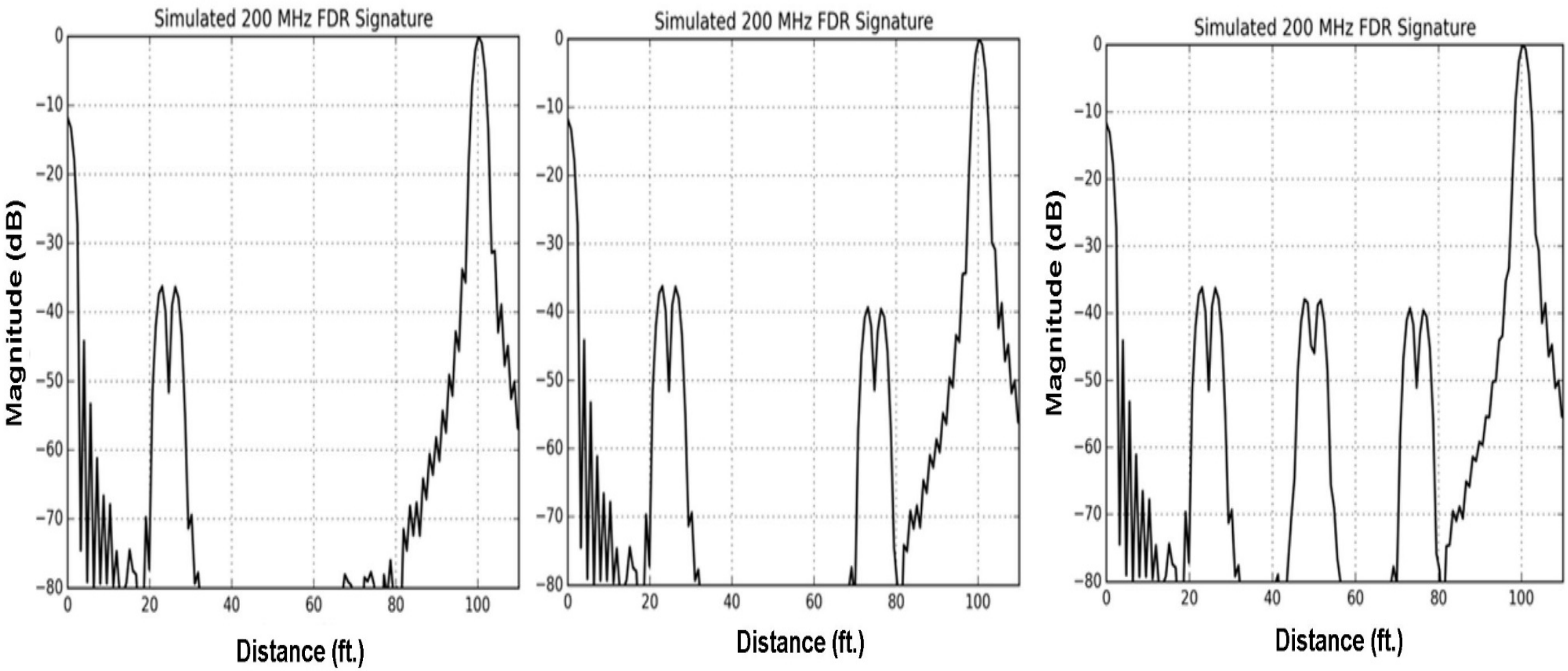
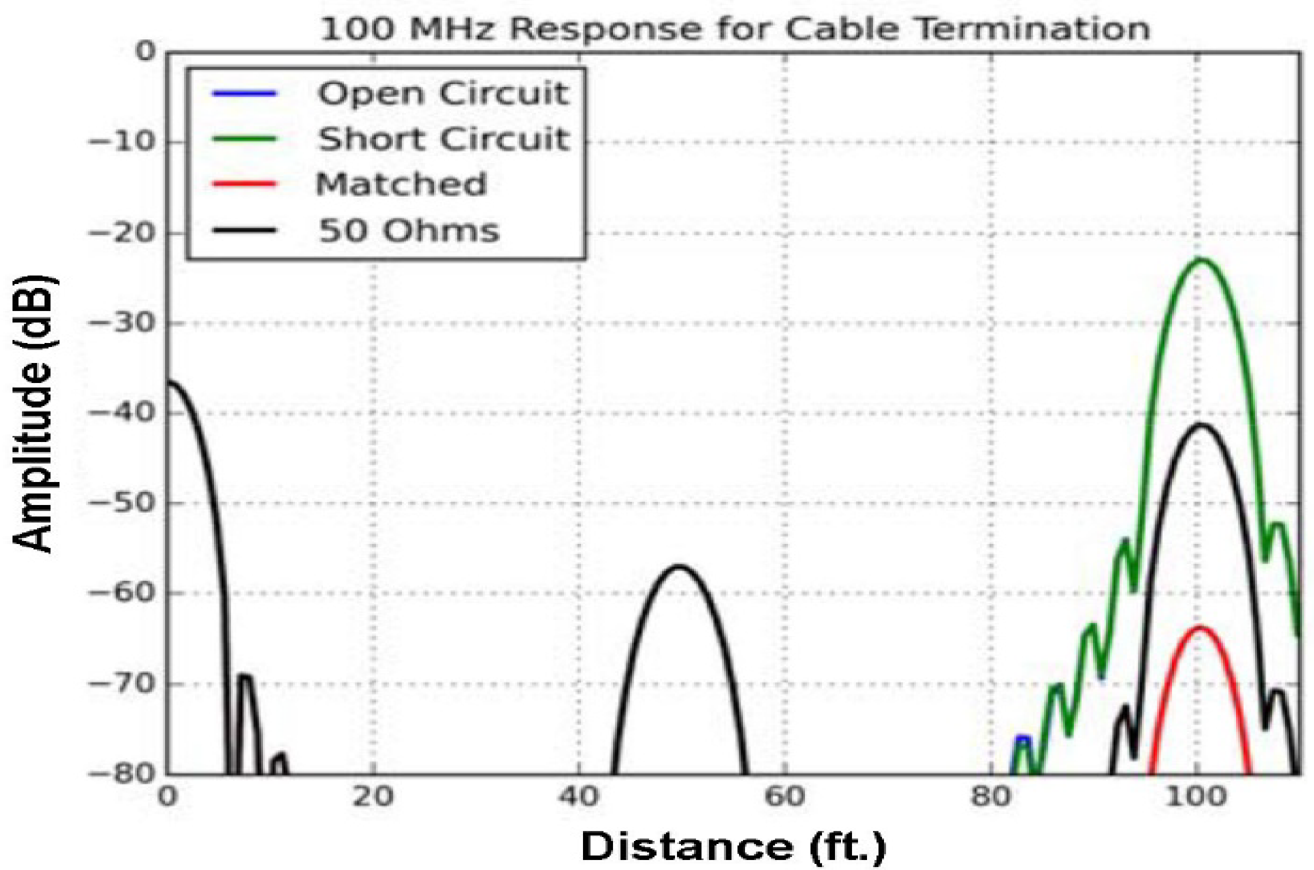
Simulated Influence of Cable Length on FDR Response



Number and Location of Defect Influence on FDR



Simulated Influence of Termination Load on Shielded Triad Cable with 3 ft. Defect @ 50 ft.



Conclusions

Physics-Based Model was developed and validated with other model and with test data.

FDRs were affected by:

- **Defect length**
- **Defect profile**
- **Environment around defect (air, water, conductor)**
- **Cable length/Frequency BW/ Loss/attenuation**

FDRs were not affected by:

- **Number of defects**
- **Location of defects**
- **Length of low-loss cable**
- **Distal end impedance (termination)**

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Questions?

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Backup

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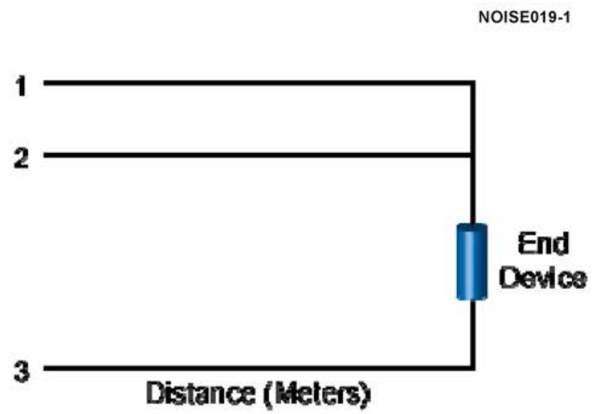
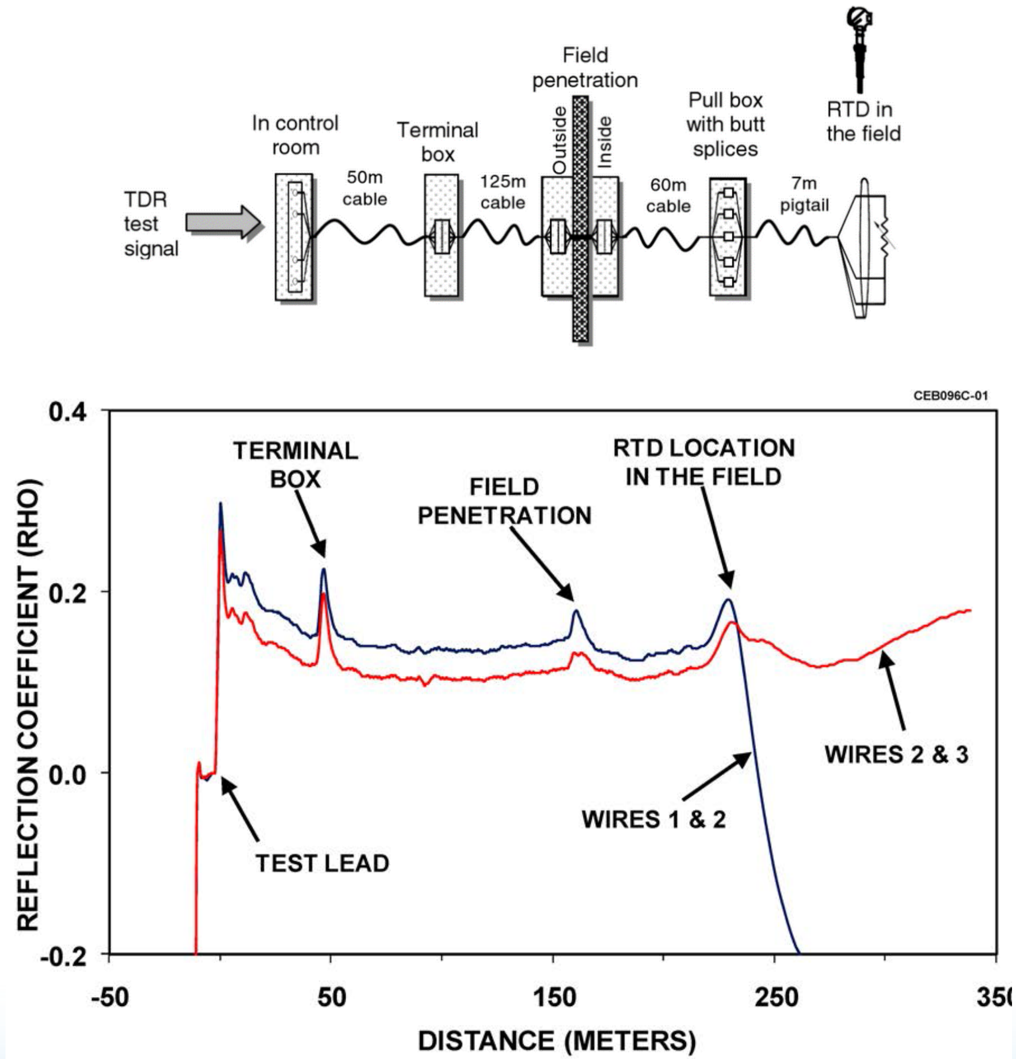
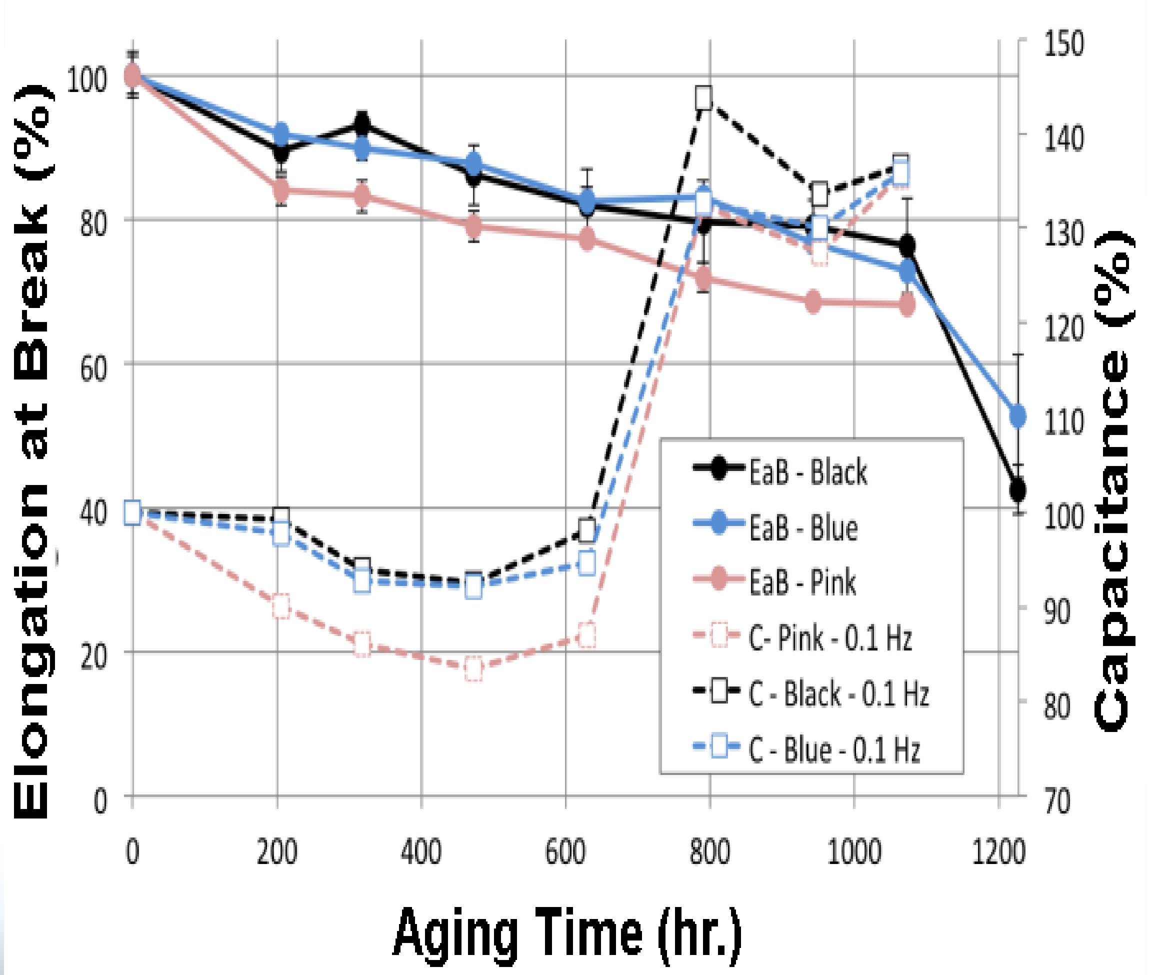
Time Domain Reflectometry

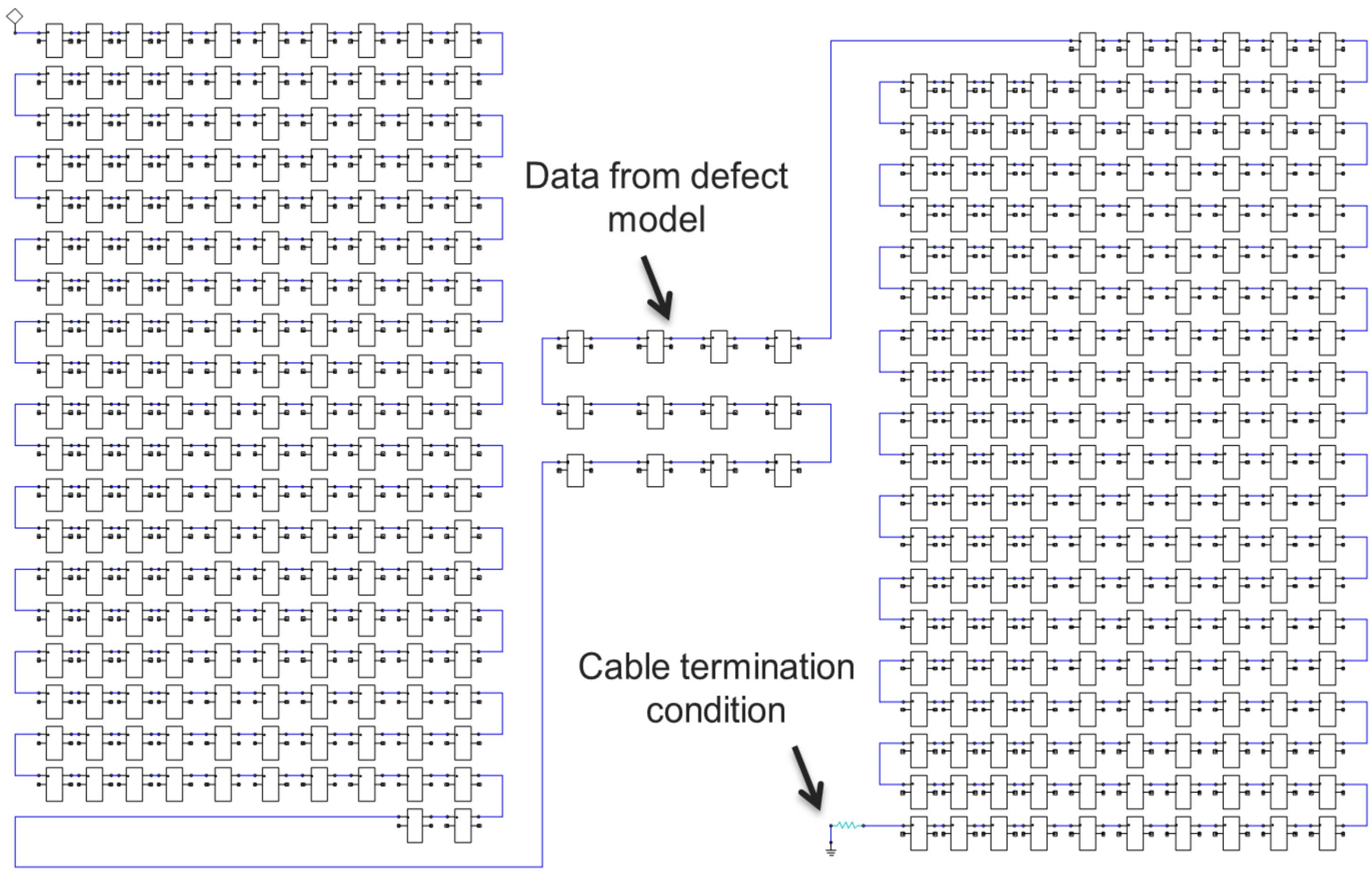




Comparison between EAB and specific capacitance C at 0.1 Hz. (The color indicates the color of the wire held at positive potential)



Courtesy of Iowa State University


Data from defect model
Cable termination condition