



Model-based Diagnostics for Wire Health Management

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National Aeronautics And Space Administration

14 Major Centers

19,000 Civil Service Employees

40,000 Contract Employees



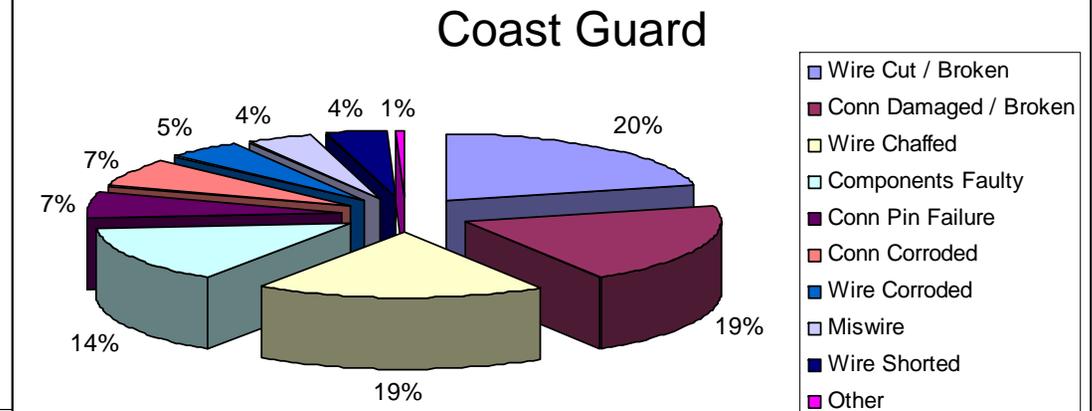
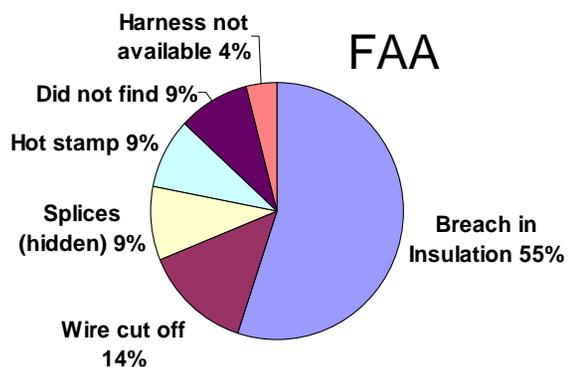
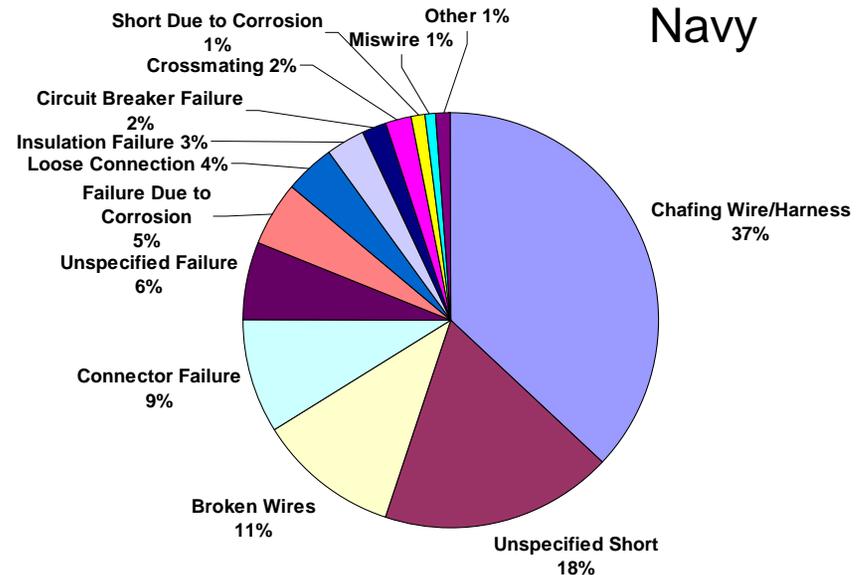


MOTIVATION: EWIS Agency Fault Summaries

- According to Captain Jim Shaw, manager of the in-flight fire project for the United States Air Line Pilots Association (ALPA), there are on average **three (3) fire and smoke events in jet transport aircraft each day in USA and Canada** alone, and the vast majority are electrical [ASW2000].

- According to Air Safety Week, "aircraft are making emergency landings, suffering **fire damage** to the point of being written off etc, at the rate of **more than one a month** based on the experience of the past few months" [ASW2001].

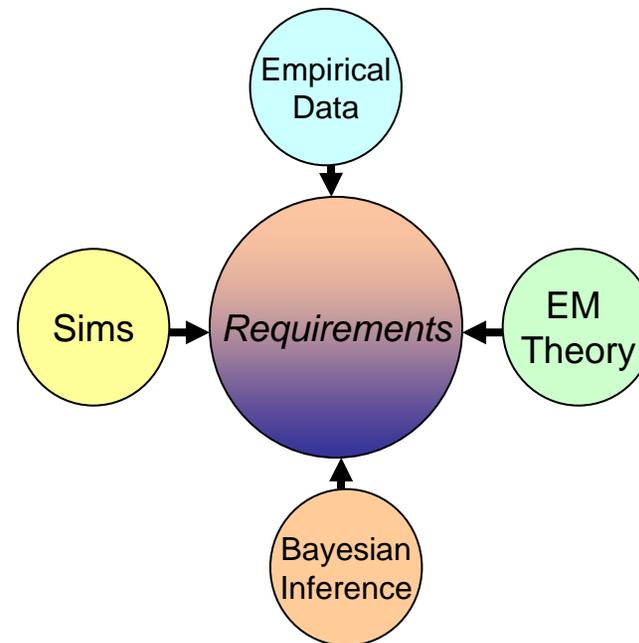
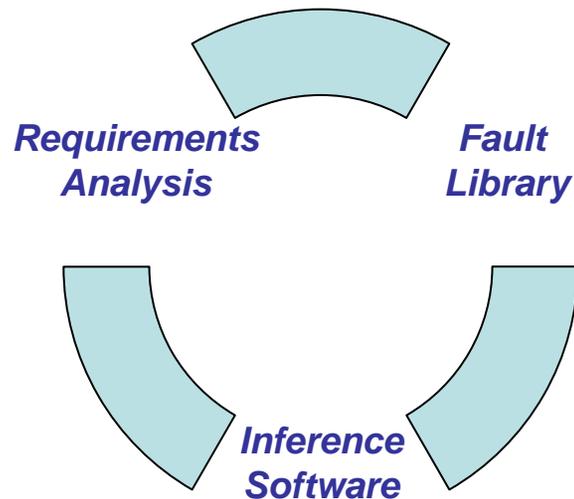
- Entire U2 fleet grounded in 2007 due to wire chafing evidence.





APPROACH: Wire Health Management Development

- **Fault library development** - Develop publicly accessible wire fault database containing electrical signatures of different faults and wire types.
- **Inversion algorithm development** - Develop inversion algorithms for retrieval of permittivity along length of each wire in harness.
- **Requirements analysis and definition** – Develop Questions we need to answer.



Philosophy:

Data driven - Recreate wire faults in lab and acquire reflectometry data

Simulation - Simulate faults in commercial simulator

Theory - Theoretical wave equation modeling

Bayesian inversion – Retrieving the model parameters over time.



Requirements Analysis & Definition

Fault progression analyses

- What are typical rates of chafe progression?
- How do signals change with worsening faults?
- What are the EWIS faults priorities and time-of-life requirements?

Identify sources of chafing

- Bulkheads
- Conduits
- Control cables
- Harness clamps
- Hydraulic lines
- Installation

Hardware specifications

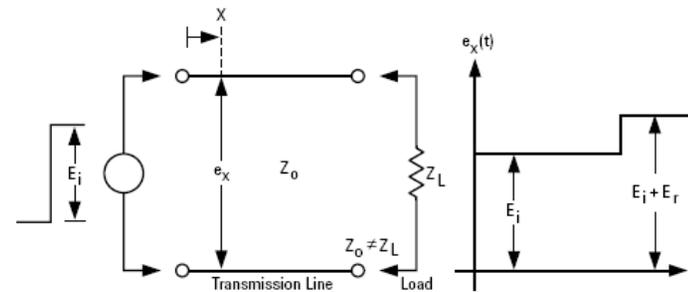
- What are the best signals to inject for different types of faults, wire types, and harness configurations?
- How often should data be collected?
- When should data be collected?

Harness specifications for health management

Should we run additional “Canary” lines (fiber optics)?
Should we sense for vibrations (piezo wire)?
Should we suggest harness configurations (ribbon)?
Junction box best practices for microwaves?

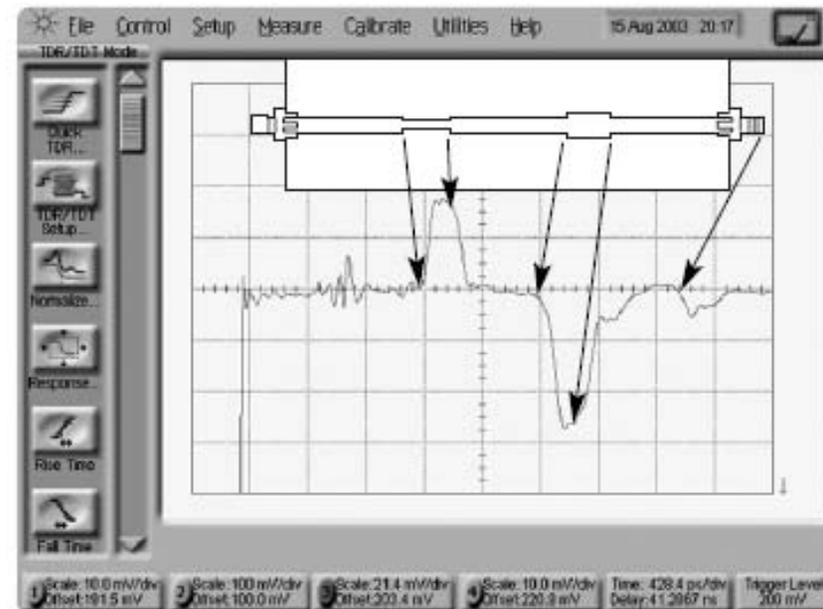


Time Domain Reflectometry A Primer



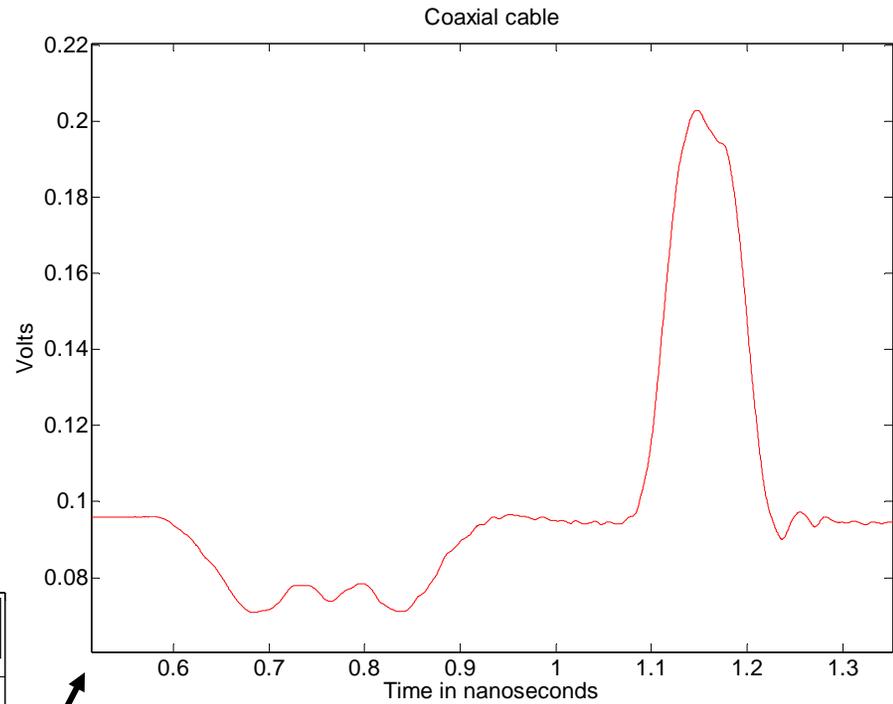
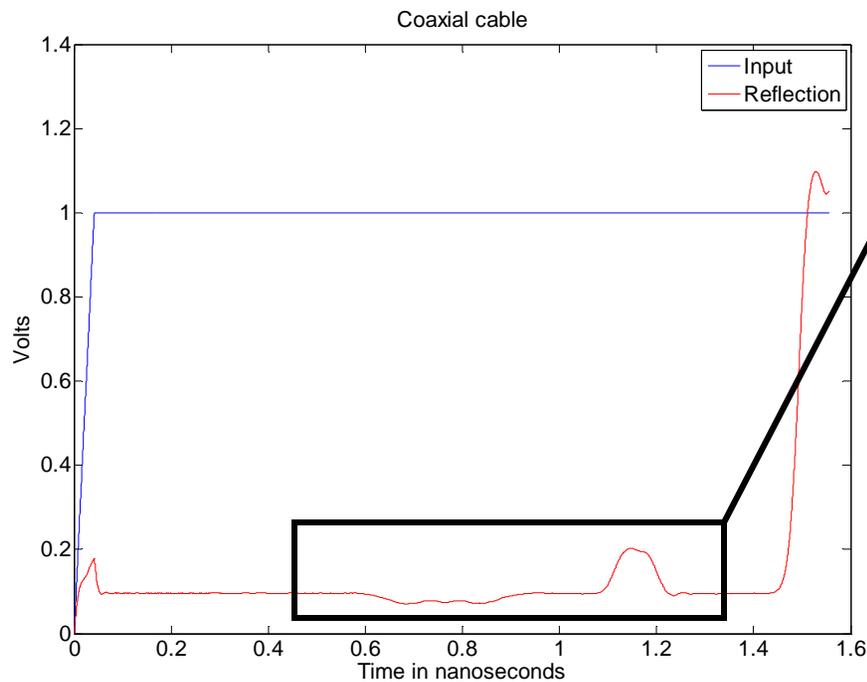
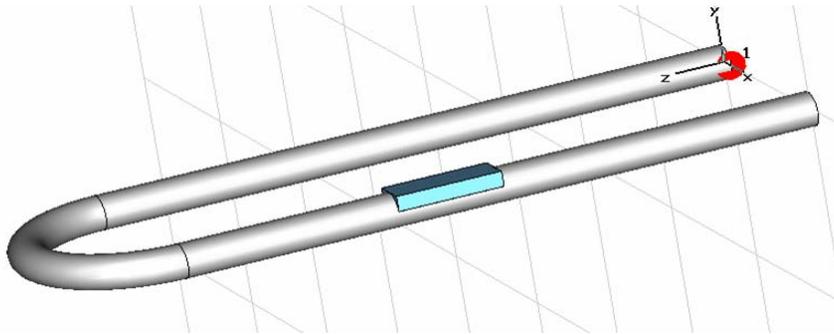
- A voltage step is applied to the circuit under test
- The reflected voltage (e_x) is measured at input: Reflections contain information about the health of the insulation.

Non-uniform transmission line
with two discontinuities





Effects of Geometry and Faults Coaxial Cable

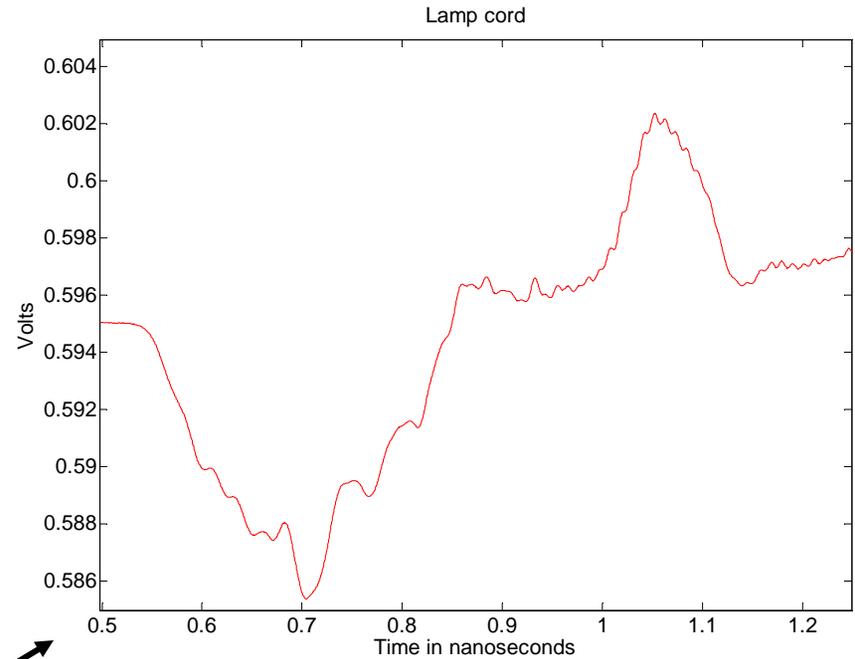
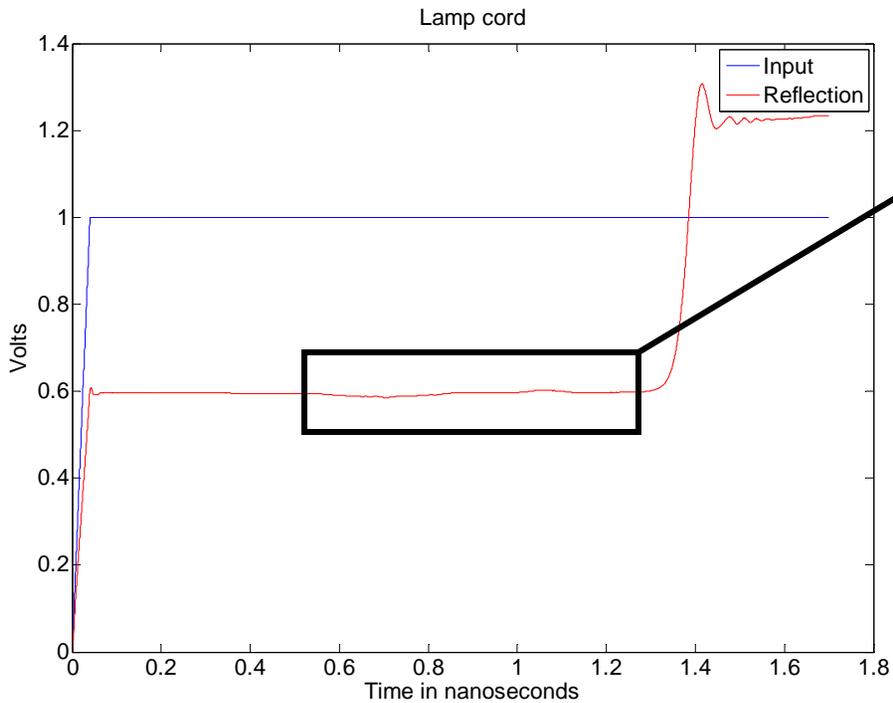
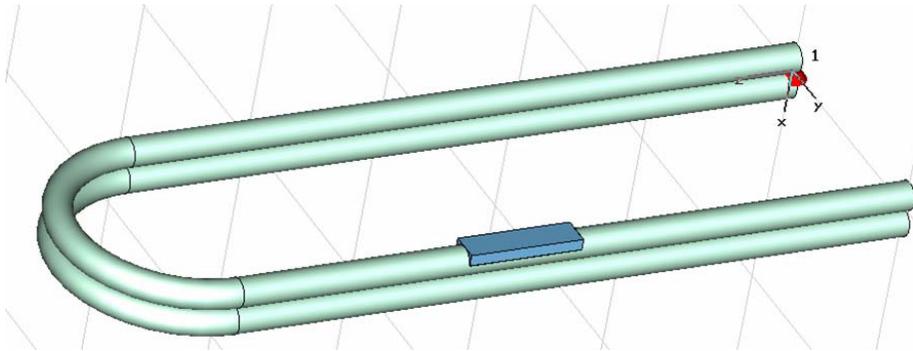


Magnitude of reflection due to bend: 26 mV
Magnitude of reflection due to fault: 109 mV

The straight section of wire is 60 mm long, and the bend radius is 10 mm. Each wire has a 0.25mm radius PEC core and 1.5mm radius dielectric with $\epsilon=2.08$.



Effects of Geometry and Faults Lamp Cord



Magnitude of reflection due to bend: 9.6 mV
Magnitude of reflection due to fault: 6.5 mV



Model-based Requirements

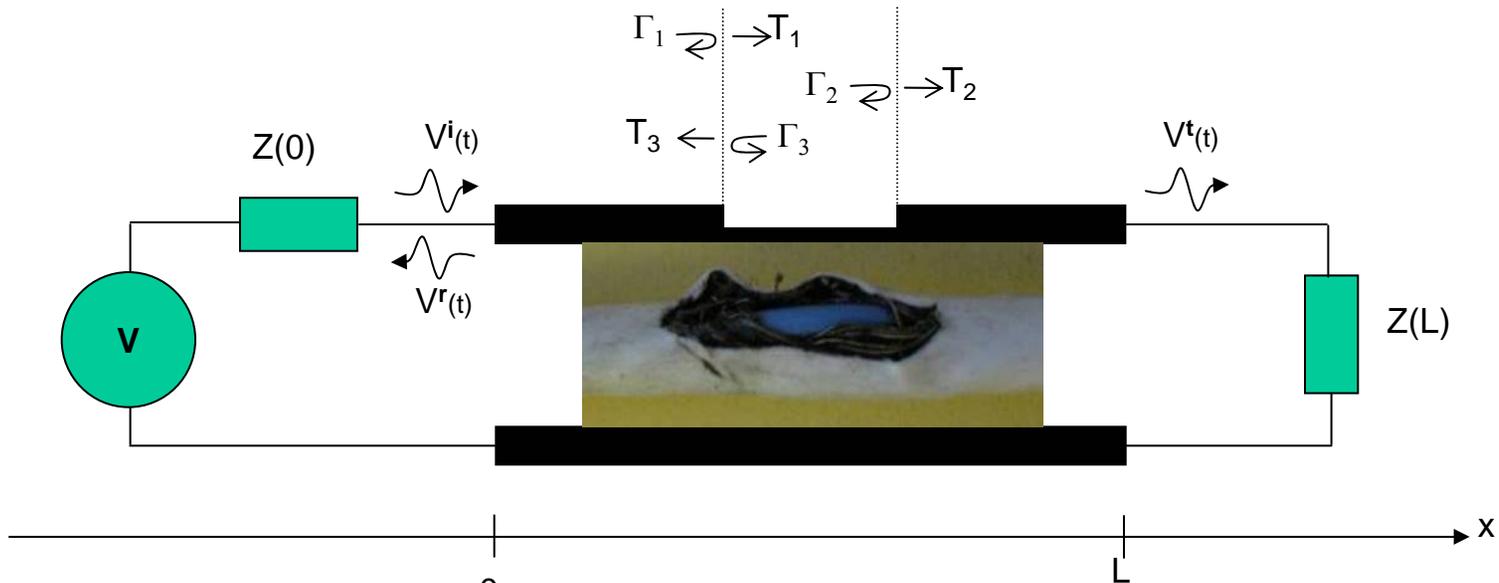
- How to answer these questions?
 - Laboratory experiments
 - Flight data
 - Simulations
 - ...

Central Thesis:

Moving beyond the “What is possible?” stage of investigation requires a model-based approach.



THEORY: Non-uniform Transmission Line Continuous Parameters



Voltage at any point can have a right going wave and a left going wave: $V(x,t) = V^+(x,t) + V^-(x,t)$

Split representation:
$$\begin{cases} V^+(x,t + \tau(0,x)) = a^+(x)V^t(t) + G^{c+}(x,t) * V^t(t) \\ V^-(x,t + \tau(0,x)) = a^-(x)V^t(t - 2\tau(x,l)) + G^{c-}(x,t) * V^t(t) \end{cases}$$

Incident waveform: $V^i(t) = a^+(0)V^t(t) + G^{c+}(0,t) * V^t(t)$

Reflected waveform: $V^r(t) = a^-(0)V^t(t - 2\tau(0,l)) + G^{c-}(0,t) * V^t(t)$

attenuation

propagation time

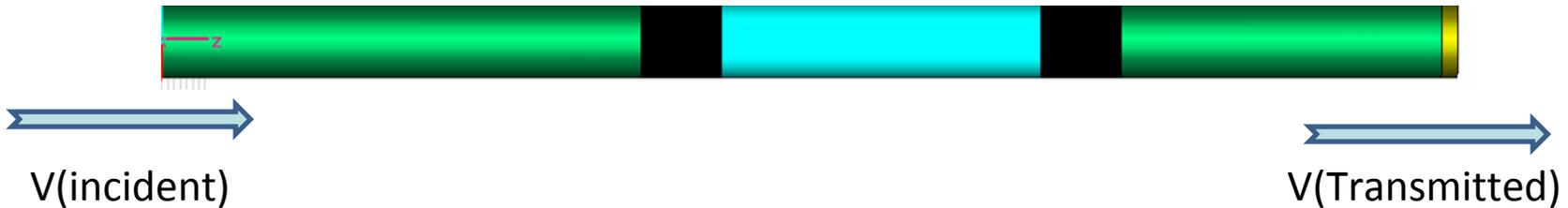
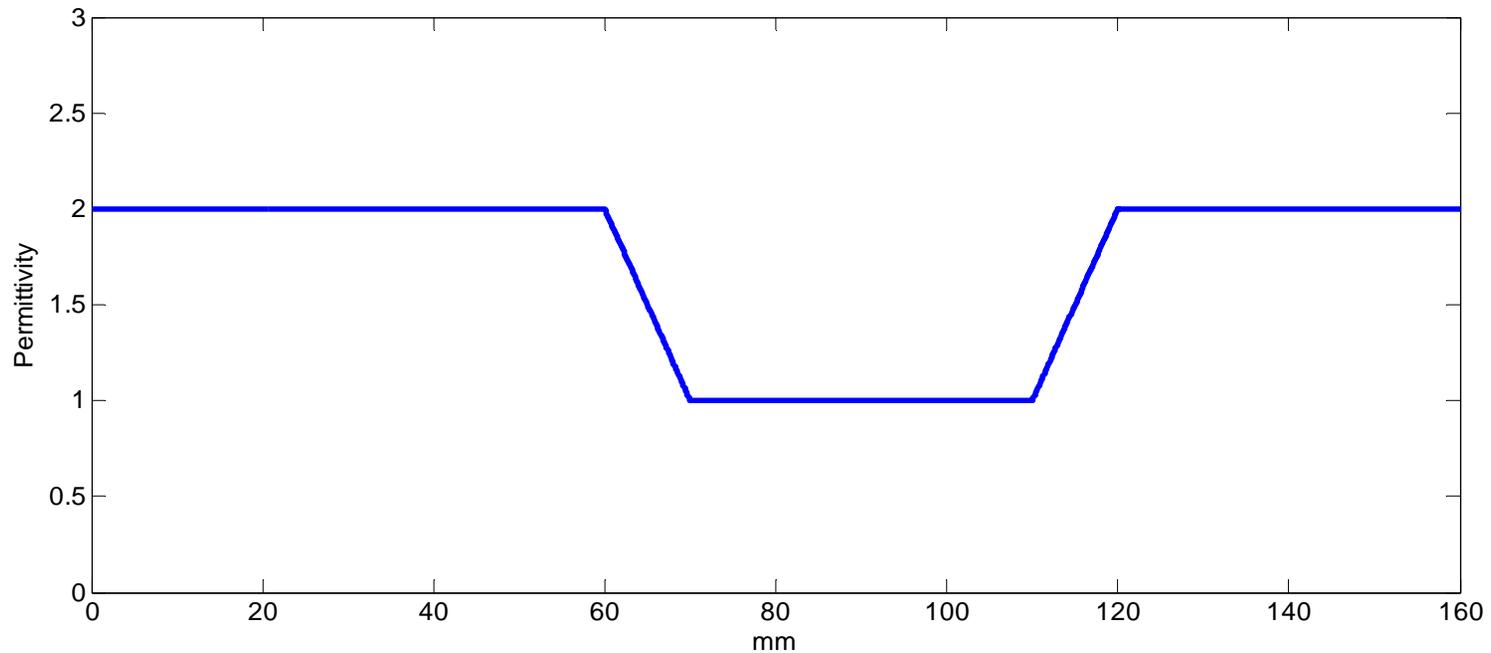
Compact Green's function

transmitted wave

boundary condition

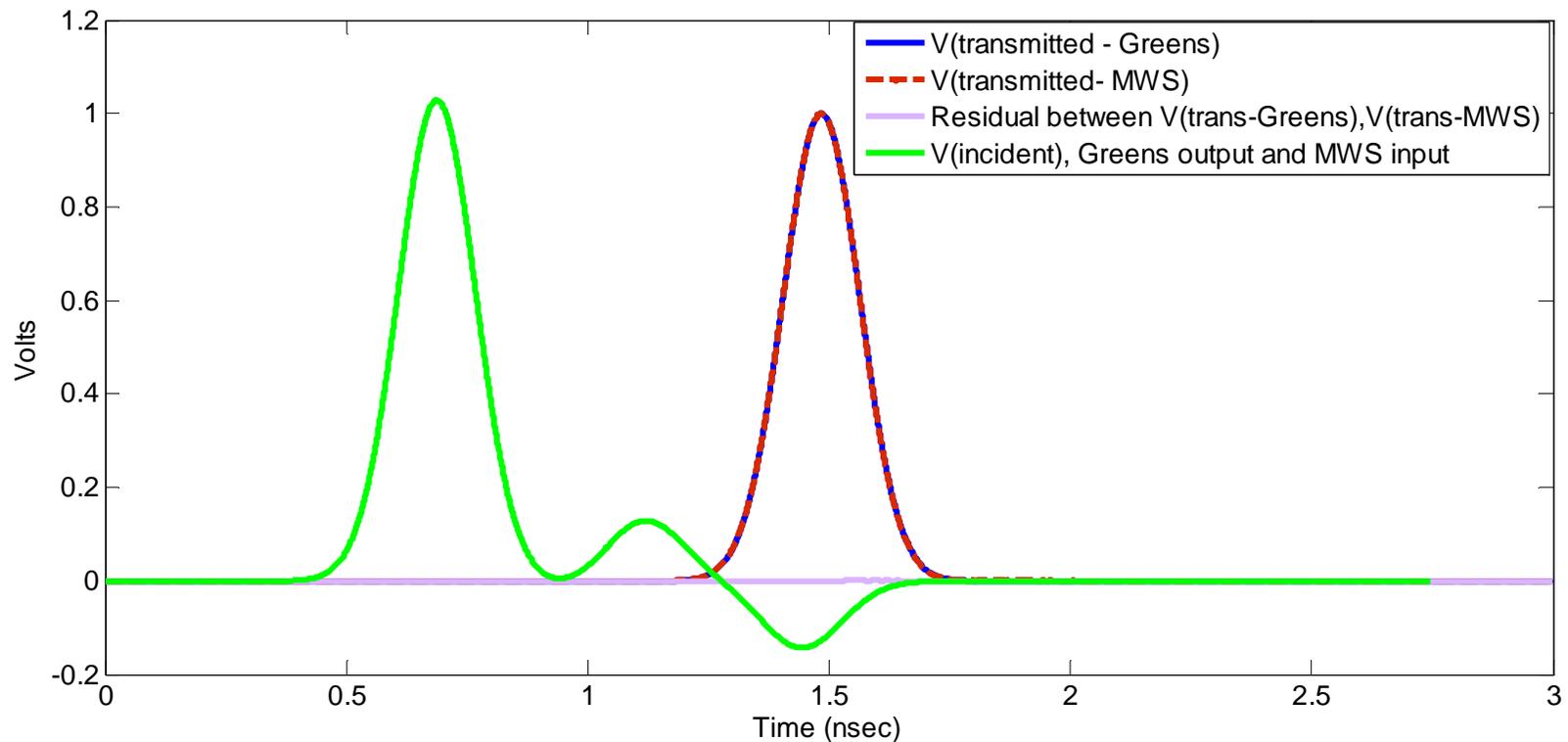
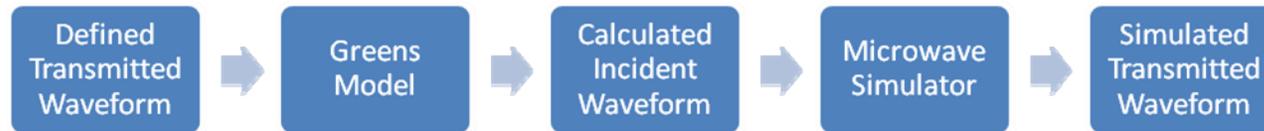


Non-uniform Permittivity Profile





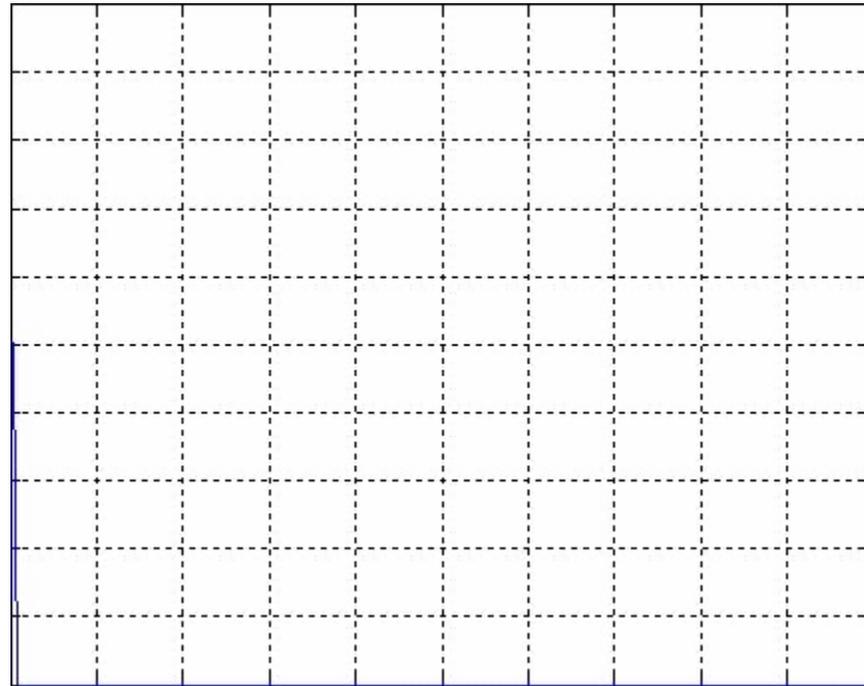
Validation of Theoretical and Microwave Simulation Models of a Heterogeneous Transmission Line





Movie of Compact Green's function step response

$V(x,t)$

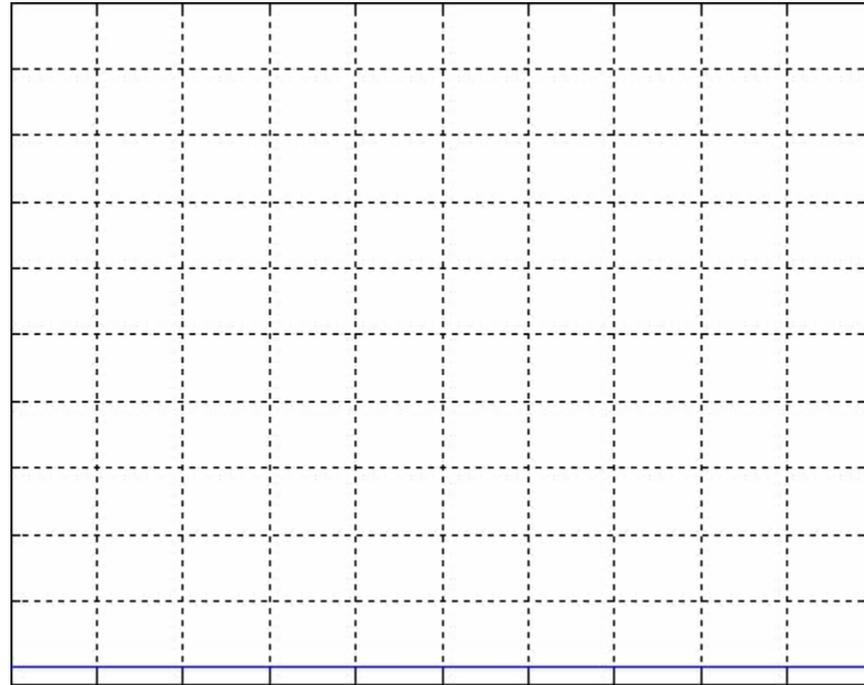


x



Movie of Compact Green's function Gauss response

$V(x,t)$



x



Non-uniform Transmission Line

Can form mapping between impedance parameters and our representation:

$$\{Z(x), c(x), R(x), G(x)\} \Leftrightarrow \{G^{c+}(x, t), G^{c-}(x, t), a^+(x), a^-(x)\}$$

where $Z(x) = \sqrt{\frac{L(x)}{C(x)}}$ and $c(x)$ is propagation velocity.

Can also form forwards and inverse mappings from observables to model parameters:

Forward model

$$\{G^{c+}(x, t), G^{c-}(x, t), a^+(x), a^-(x), c(x)\} \Leftrightarrow \{V^i(t), V^r(t), V^t(t)\}$$

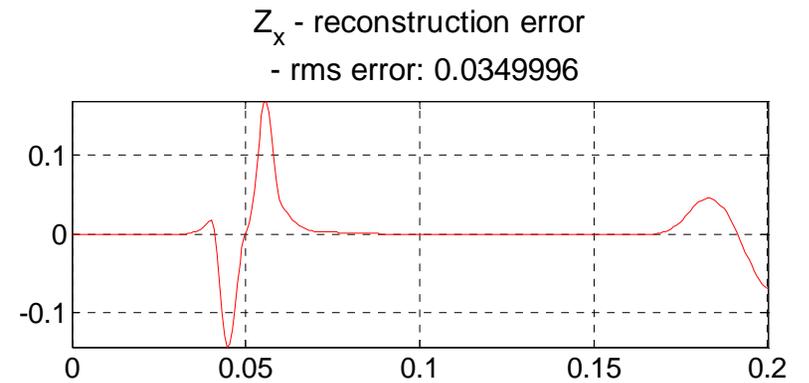
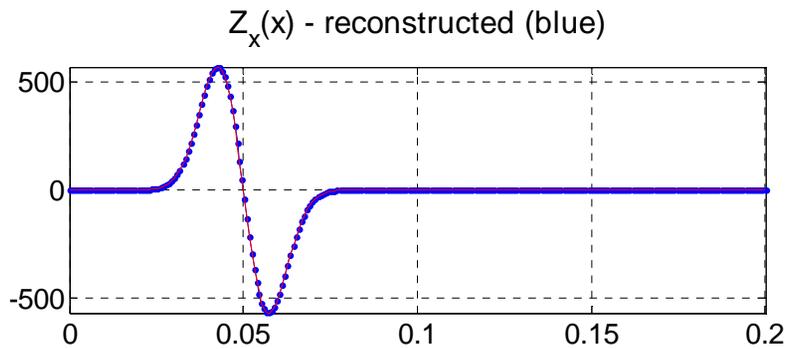
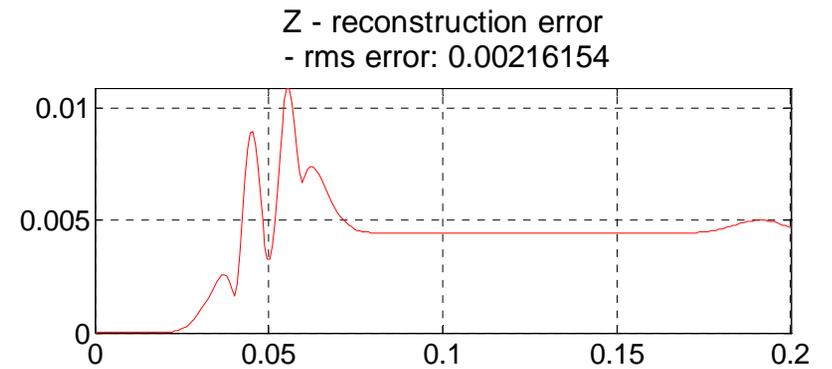
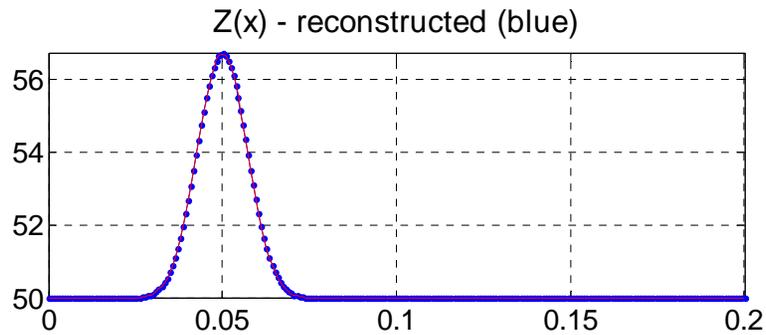
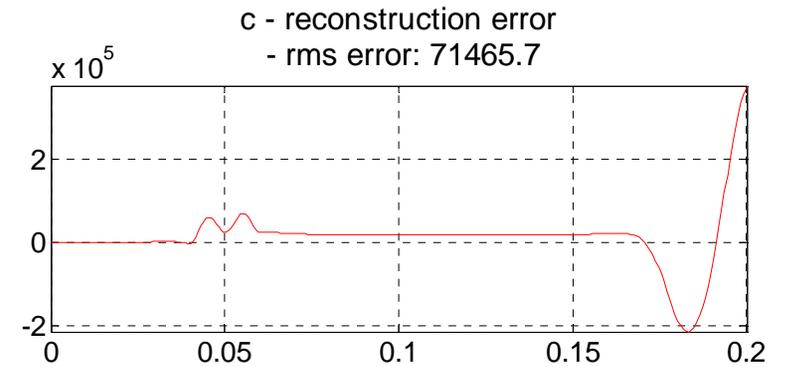
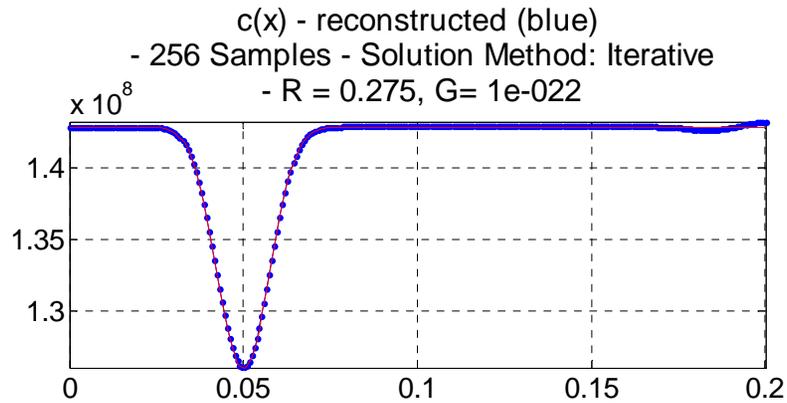
What we really want! \longrightarrow Inverse model (Bayesian inversion)

Random uncertainties make inversion **stochastic**:

- wire wiggles, insulation thickness varies
- instrumentation noise, wireless packet noise
- splices introduced
- cables move



Reconstruction





An Operational Concept

Op Concept:

- Collect data every time plane lands (V_i , V_r , V_t).
- Transfer data to ground station.
- Algorithm infers state of insulation continuously along critical harnesses (infer model parameters).
- Changes in state over days and weeks are used to detect chafing and to predict remaining useful life.

Unique Approach:

- Change interrogation signal based upon type of faults.
- Quantify uncertainties (there are no straight wires).
- Produce useful remaining life estimates.



Chafing Measurements

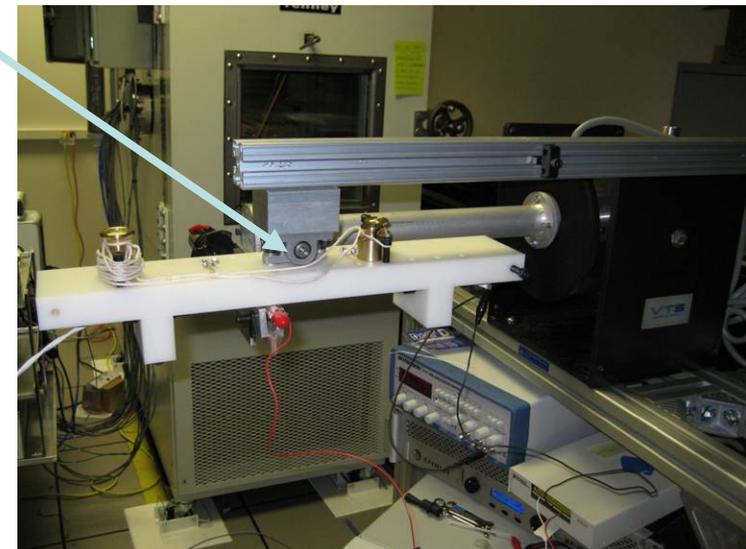
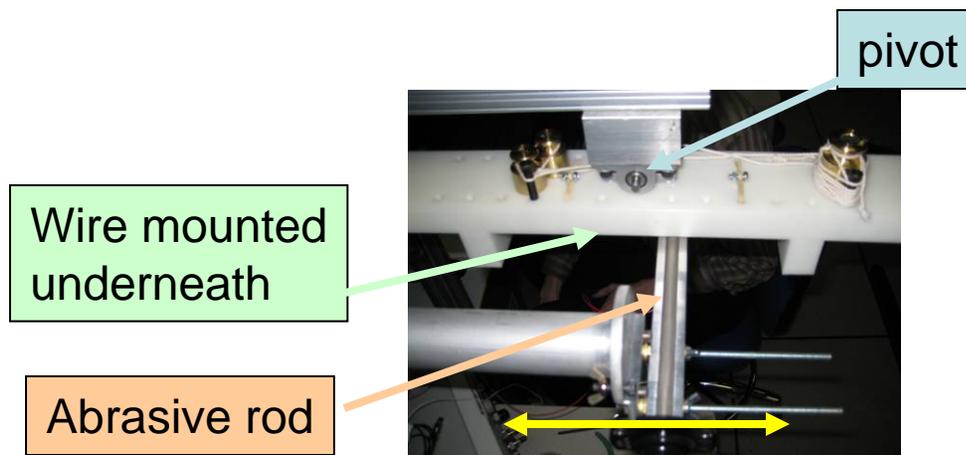
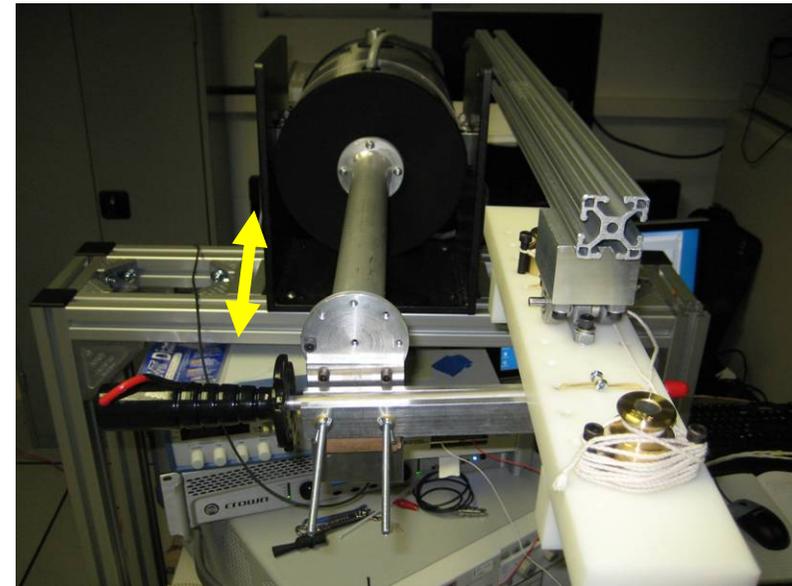
- Goal: Detect chafing while only the shielding is being damaged.
- Experiment Methodology
 - Measure shielded twisted pair without fault with TDR
 - Using abrasive apparatus, chafe wiring specified number of cycles after shield exposure
 - Measure with TDR.



Wire Chafing Methods

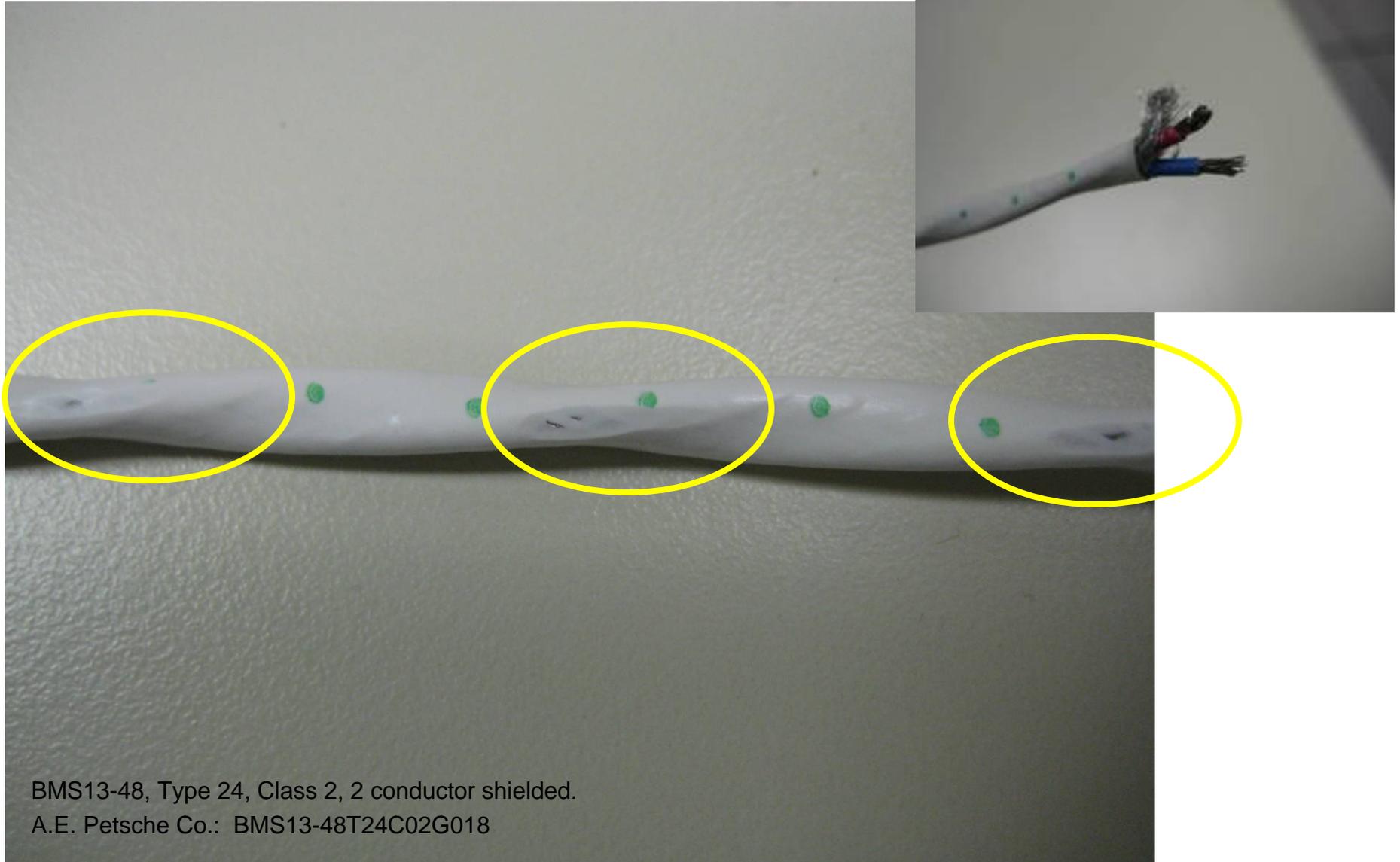
Goals:

- repeatable by other laboratories
- inexpensive setup
- allows for shooting TDR
- allows for micrometer access
- representative of real-world conditions
 - vibration based
 - conductive chafe





Chafed Shielding



BMS13-48, Type 24, Class 2, 2 conductor shielded.

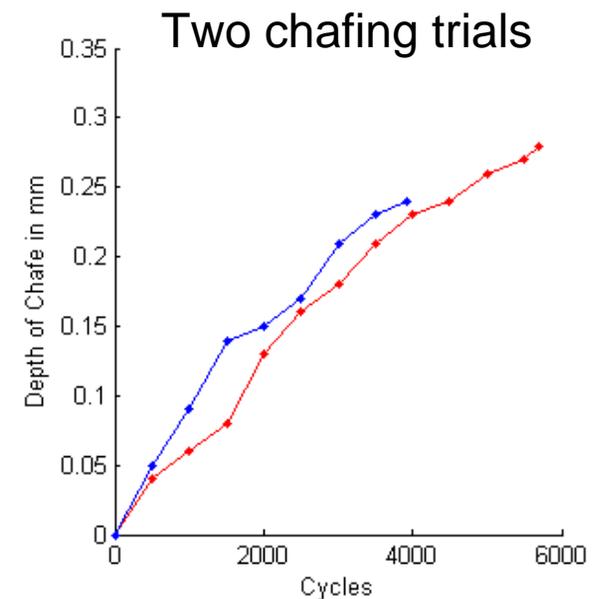
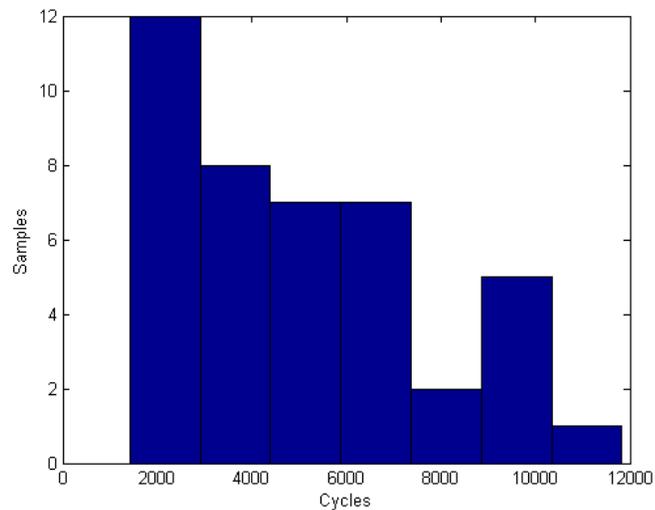
A.E. Petsche Co.: BMS13-48T24C02G018



Variability in Chafing to Shield

Experiment: Vibrated abrasive chafing mechanism at 10 Hz.
counted number of cycles until low voltage d.c. current flowed from abrasive rod to shielding.

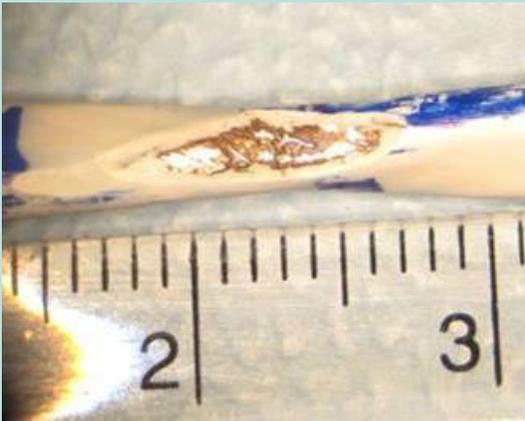
Since shielding is woven strands (not solid), some variability exists in chafing to shield.



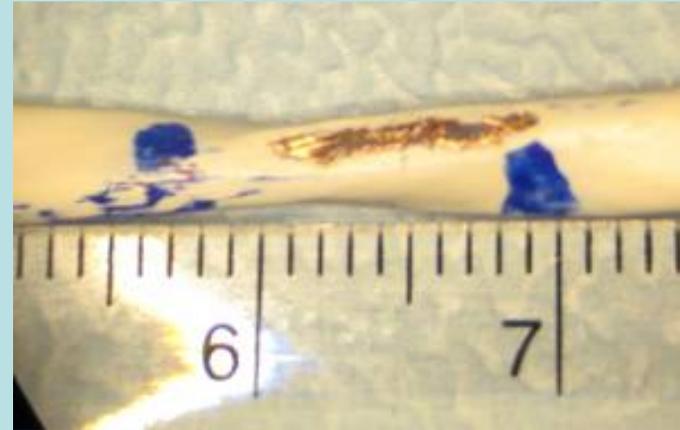


Progressive Chafing Examples

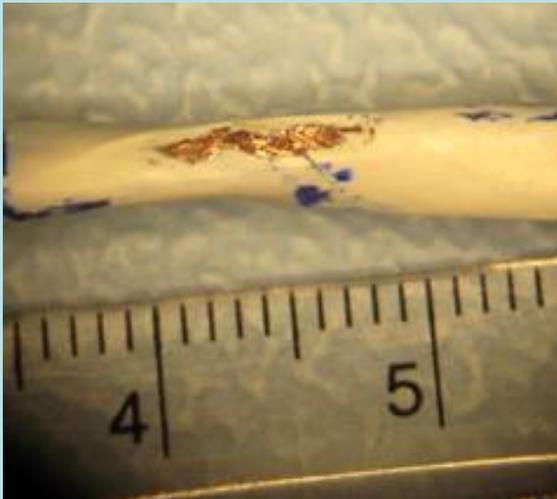
(approximately 1 cm stroke)



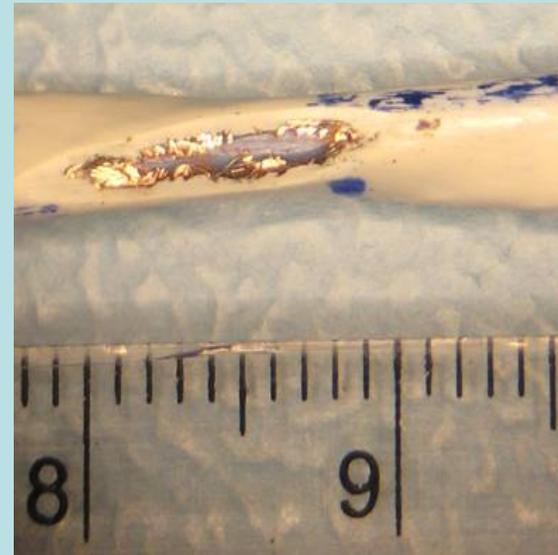
4K cycles beyond shield short.
Shield still relatively intact.



8K cycles beyond shield short.
Dielectric of inner conductors is exposed.



6K cycles beyond shield short.
Shield has holes.

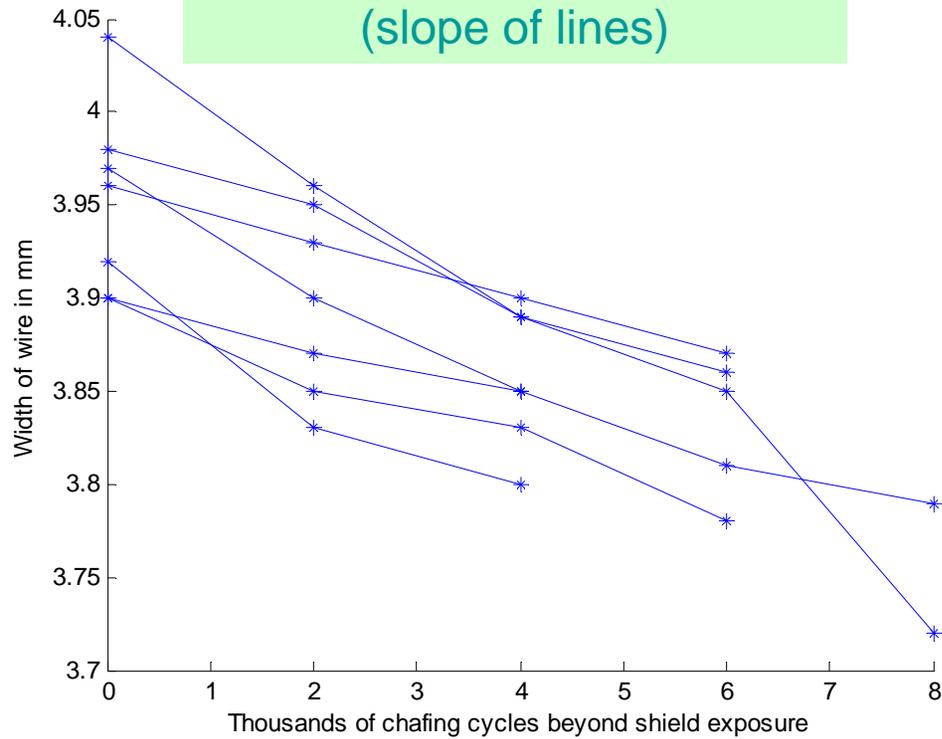


10K cycles beyond shield short.
Inner dielectric is scraped but intact.

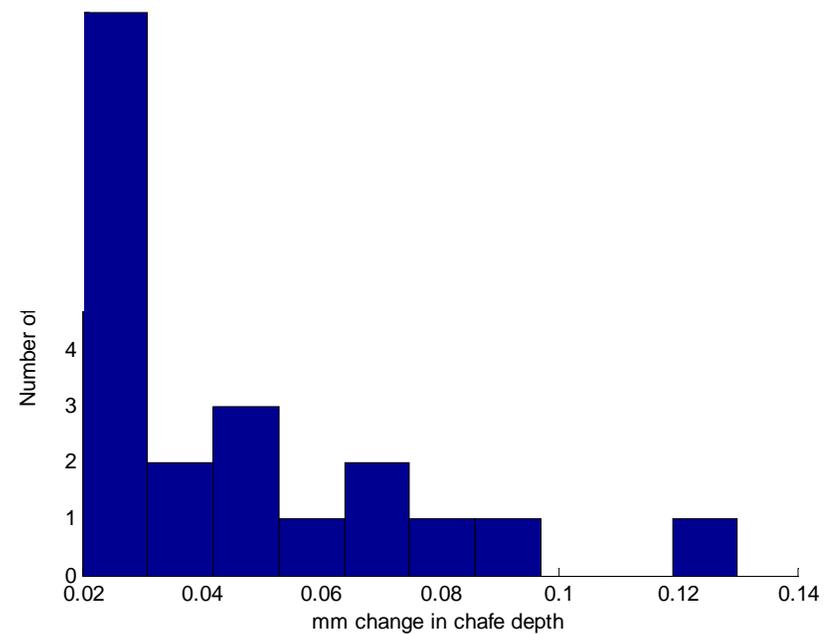


Rate of Chafing

Consistency in rate of chafing
(slope of lines)



Histogram of depth of chafe per
2,000 cycles

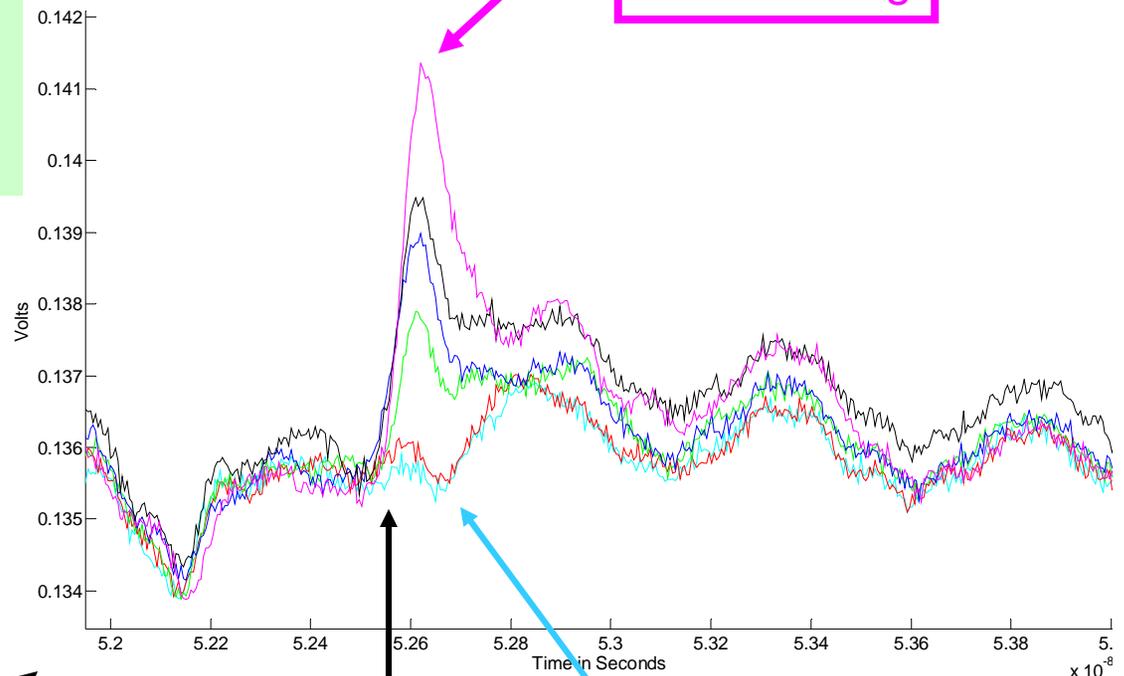
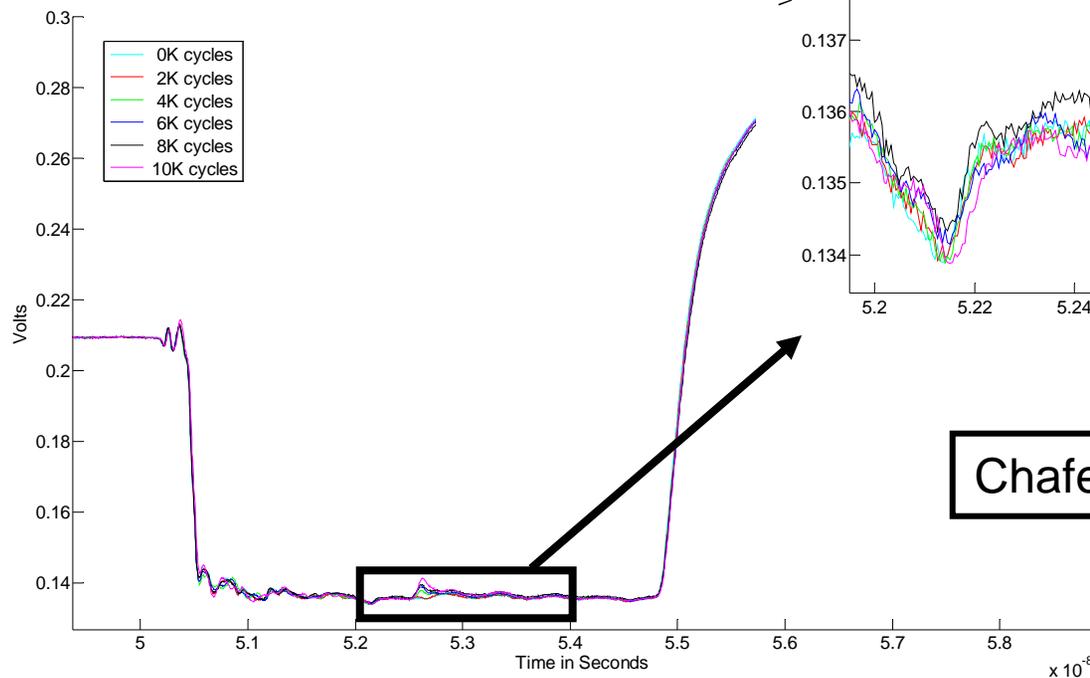




Progressive Chafing on single twisted pair

Started cycle count once shielding
was first exposed by chafing.

Important to note: Damage is
localized to shielding ONLY,
No inner conductors were exposed.

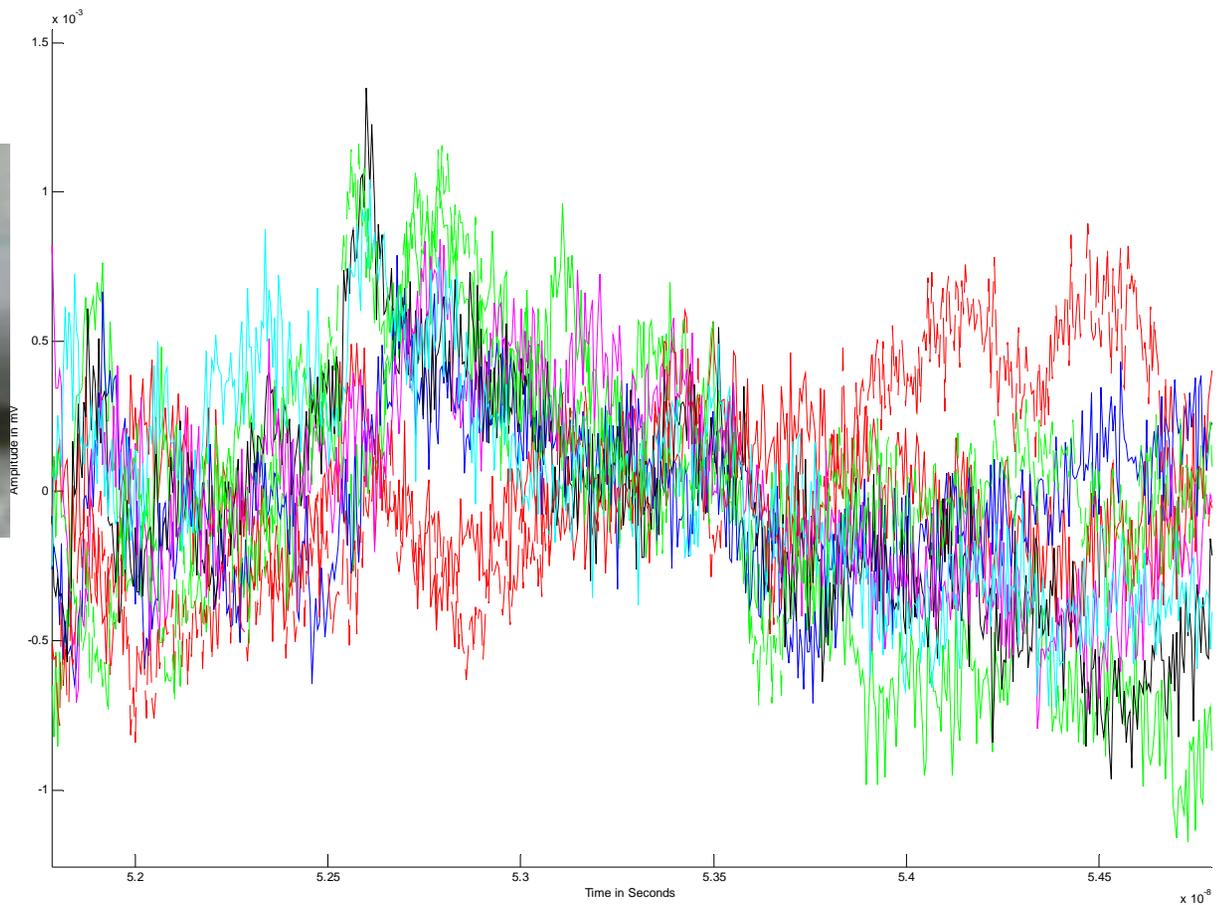




TDR Results

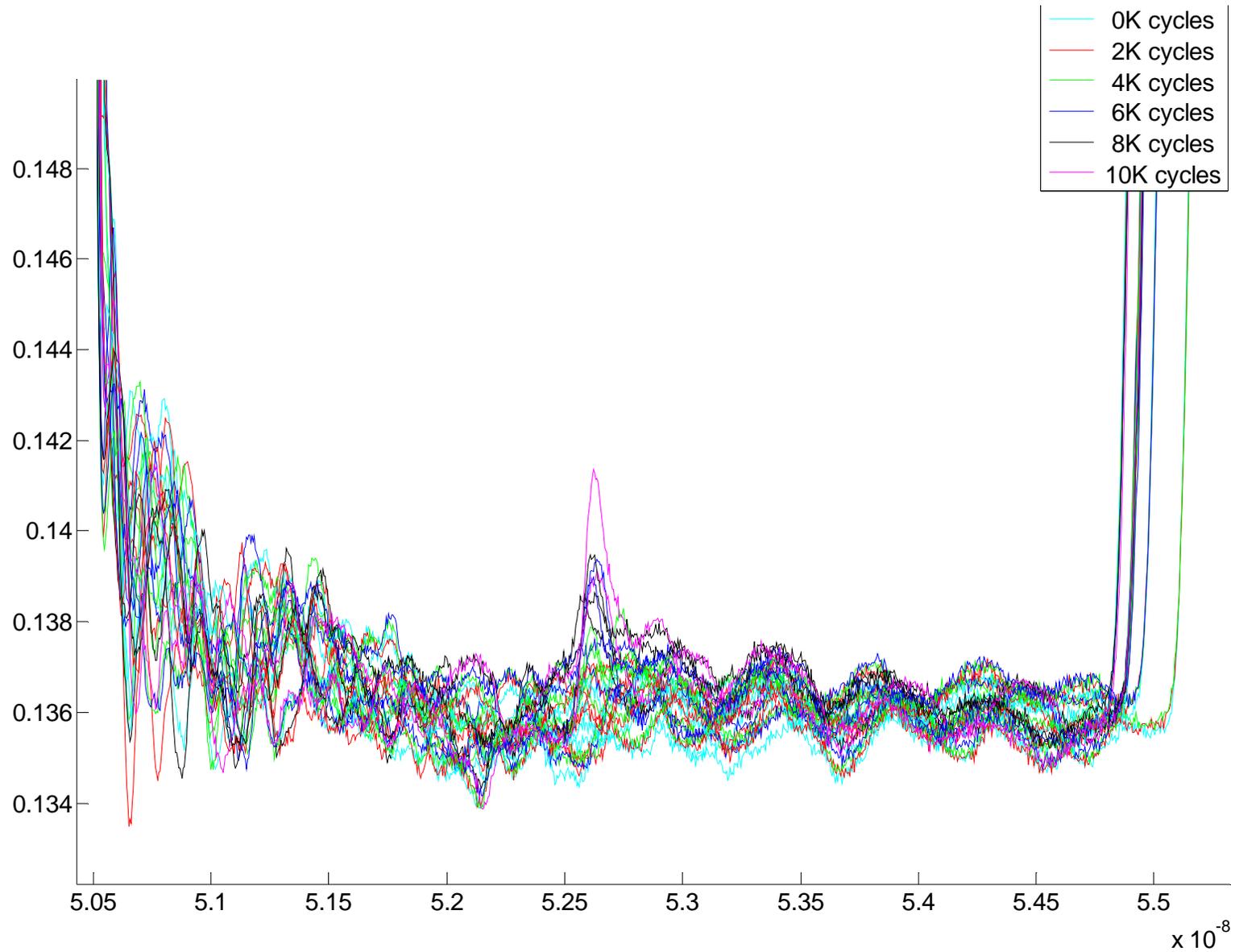
baseline – shielding exposed

Exposed shielding is not detectable from no fault case.





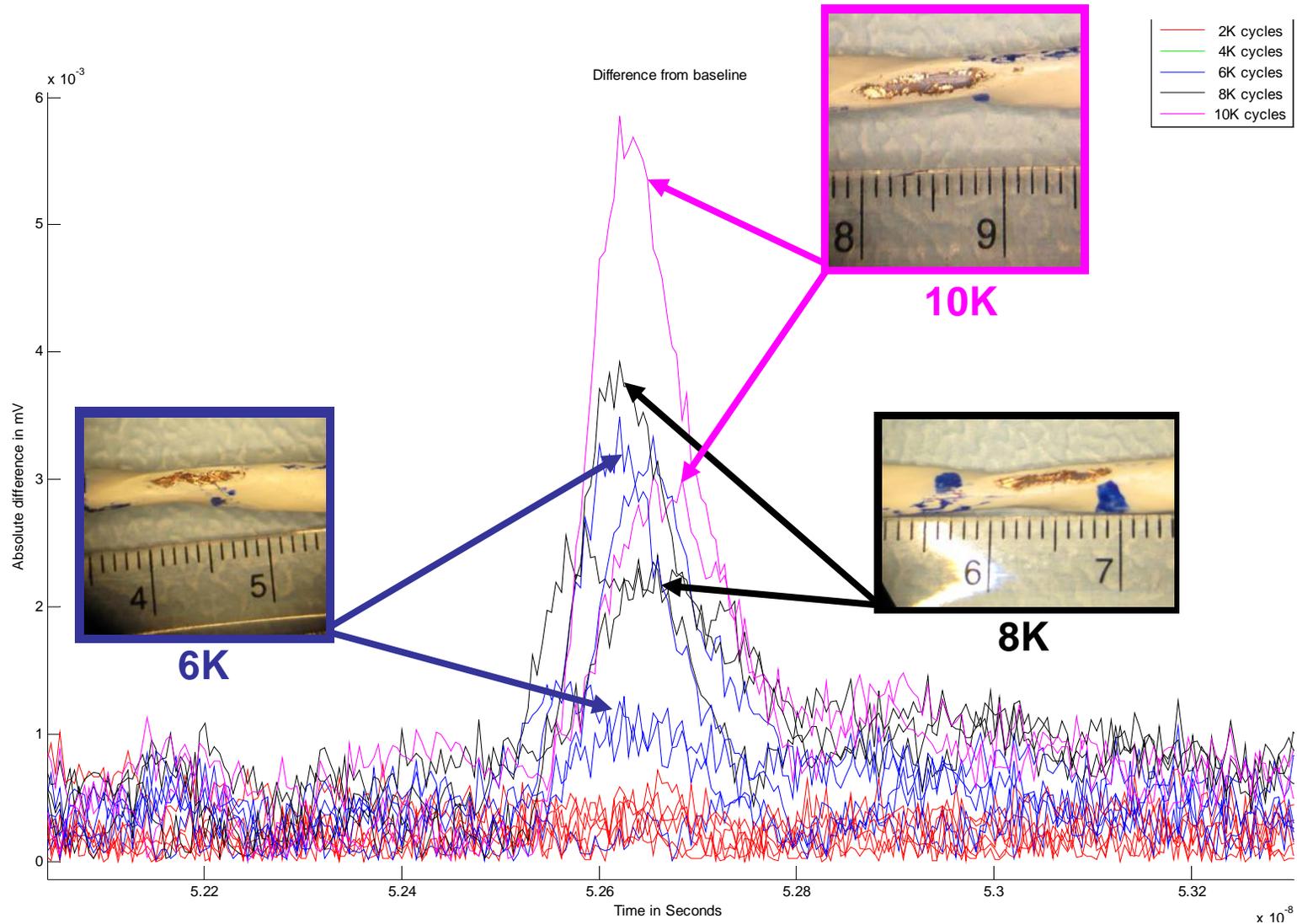
All TDR trials





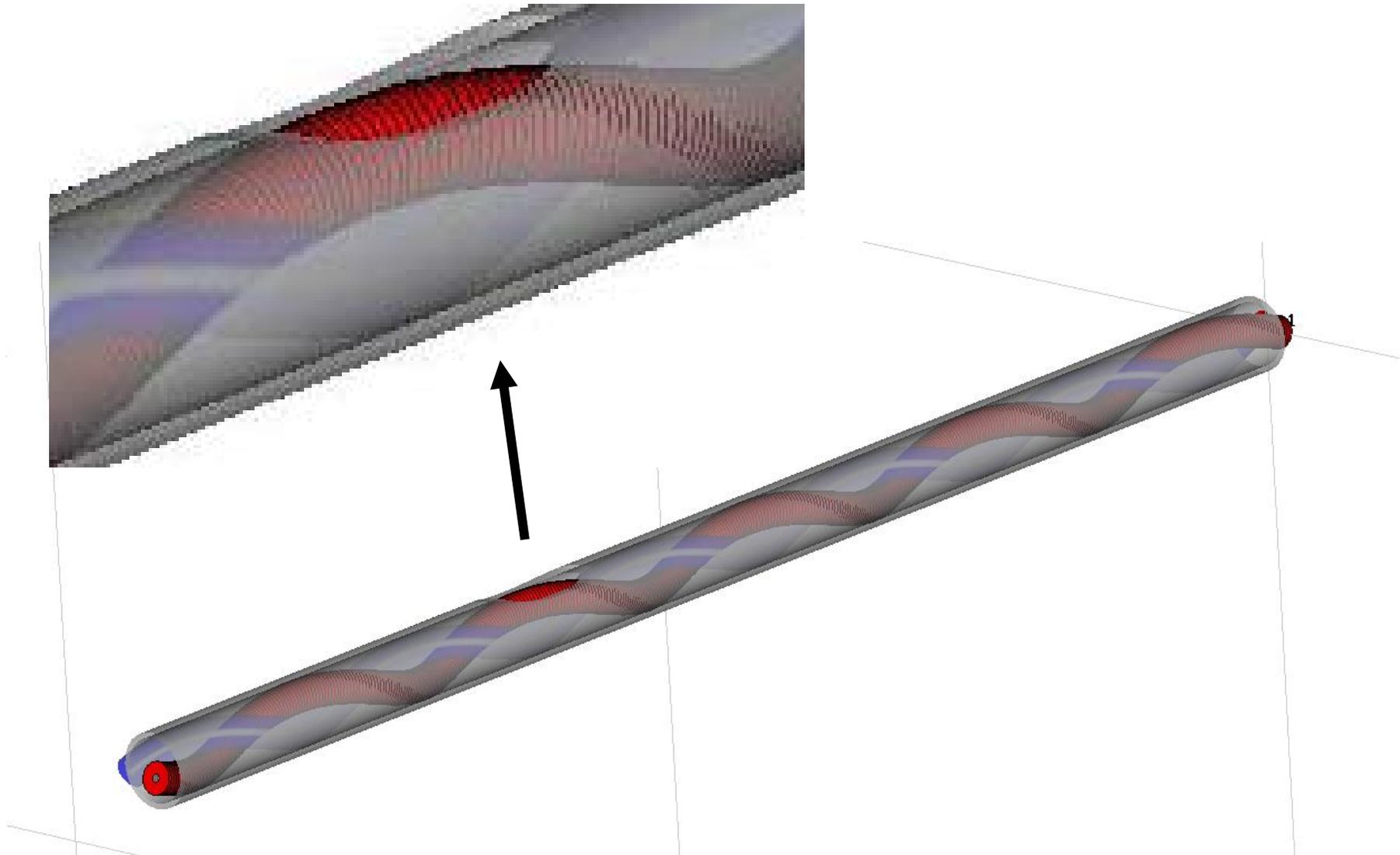
TDR Results

Progressive chafing – multiple wires difference from baseline



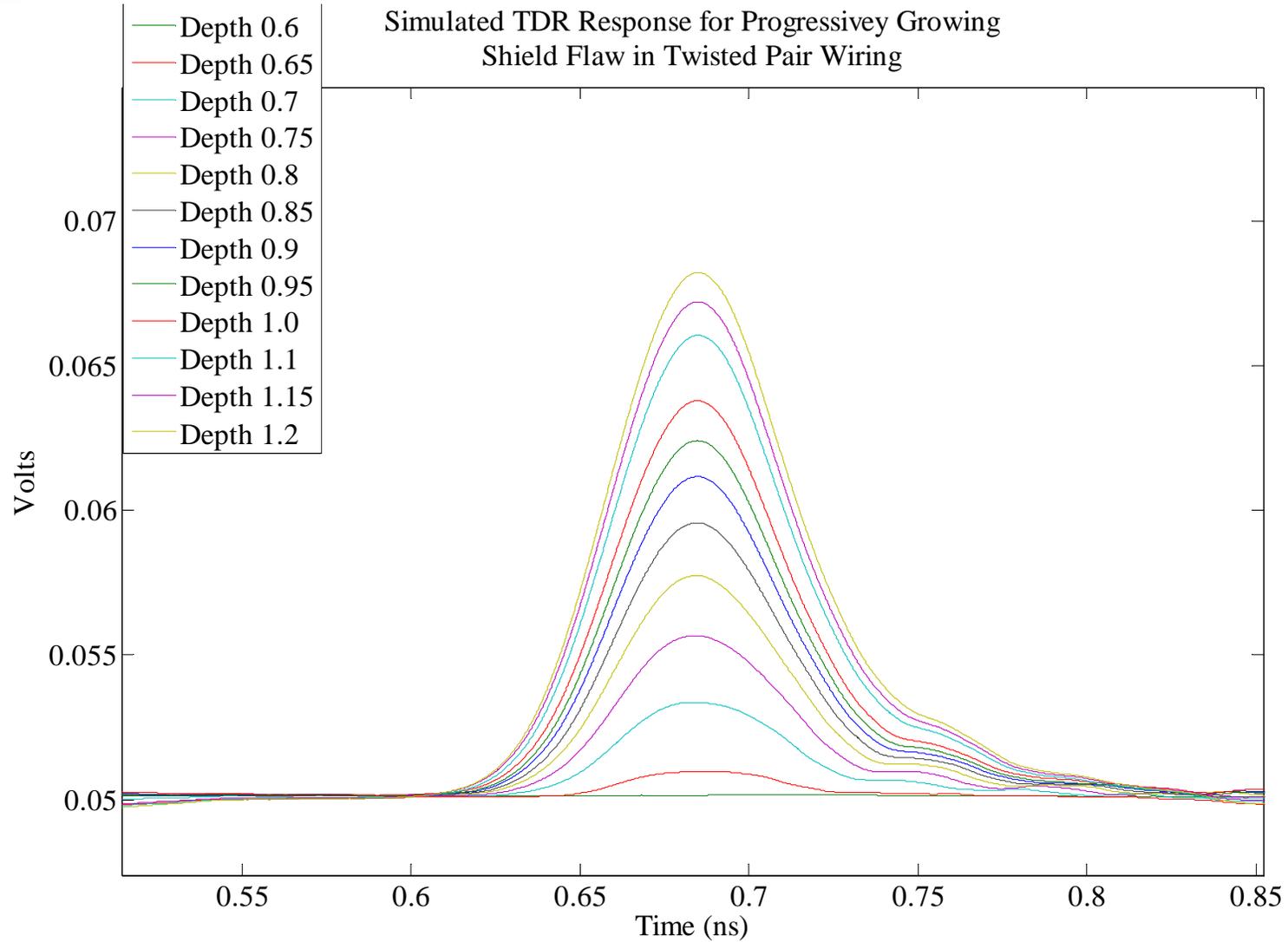


Twisted Pair Geometry



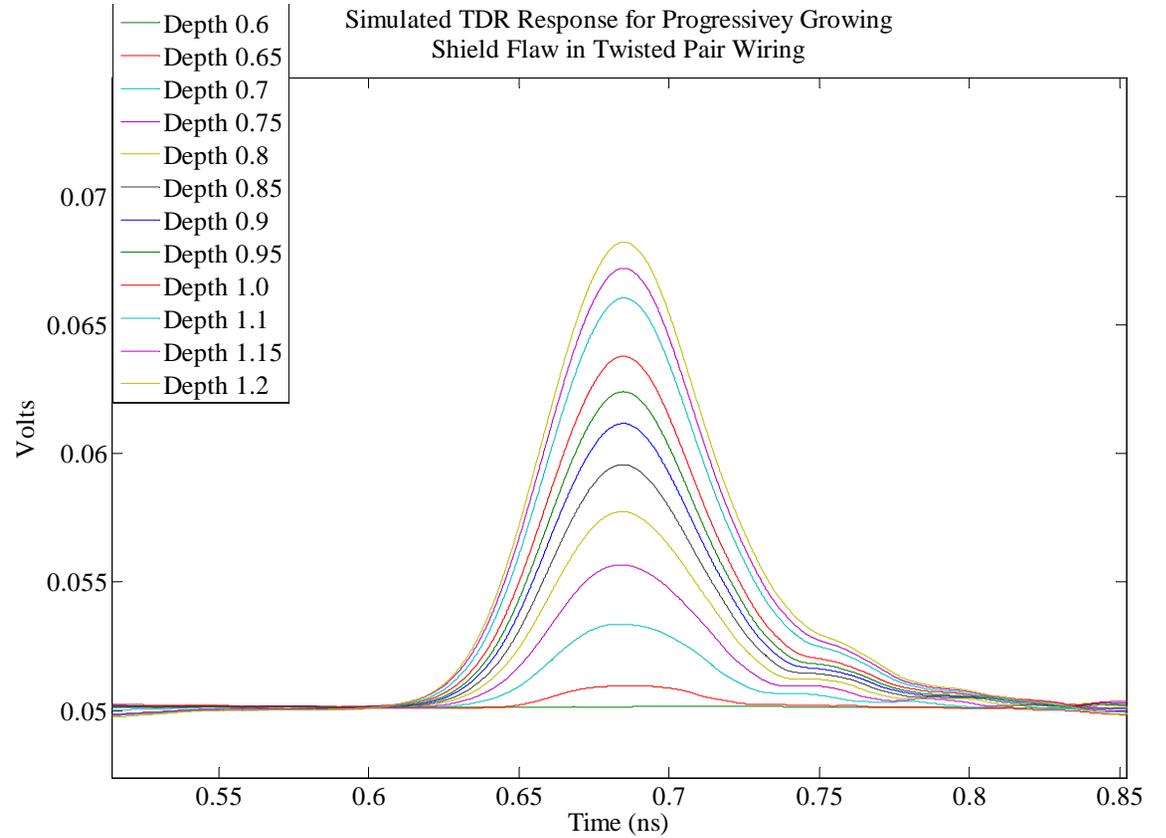
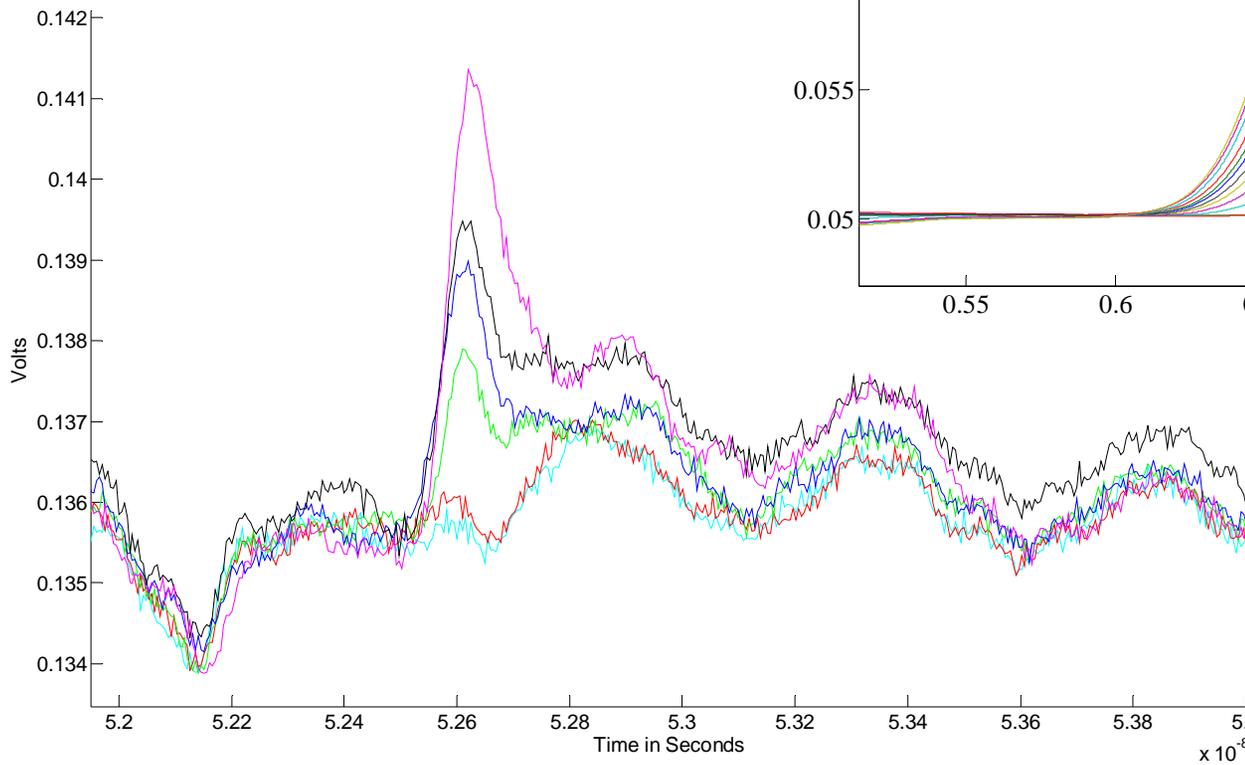


Simulation Results





Reality vs. Simulation





Questions?

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