Non-Destructive Fault Location on Aging Aircraft Wiring Networks Part 1 – Cost-Optimized Solutions

You Chung Chung, Chet Lo, John Mahoney, Jeremy Pruitt, Ryan Hanks, Santi Basava, Cynthia Furse
University of Utah
Center of Excellence for Smart Sensors

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Abstract: Non-Destructive Fault Location on Aging Aircraft Wiring Networks Part 1 – Cost-Optimized Solutions

By: You Chung Chung**, Chet Lo**, John Mahoney**, Jeremy Pruitt**, Ryan Hanks**, Santi Basava**, Cynthia Furse*

Center of Excellence for Smart Sensors
University of Utah* and Utah State University**
50 S. Campus Drive 4120 Old Main Hill
Salt Lake City, Utah 84112 Logan, Utah 84322-4120

Age-related malfunctioning of wiring infrastructure in aircraft, space vehicles, trains, nuclear power plants, high speed data networks, and even the family home and car is an area of critical national and international concern. As these networks age, the wires become brittle and crack, break, or short circuit, sometimes dangerously, sometimes with annoying intermittents. Millions of man hours are spent each year trying to locate these faults, and costs from this maintenance and the associated down time run into the billions of dollars. The problem of locating the faults is notoriously frustrating. When a car will not start in the morning, is it a dead battery, corroded connector, broken battery cable, alternator, or electrical connection to the alternator? Merely debugging this very simple system will take a significant amount of time and a few cases of trial and error. Imagine when the complexity of this system is multiplied a hundred-fold, and the fault is buried deep within several miles of power distribution wire on an aircraft scheduled to depart for Chicago in twenty minutes.

This paper describes a set of cost-effective sensors that are being applied to handheld fault location meters and in situ testing systems for pre-flight fault detection and location. Three specific sensor families are described – a Frequency Domain Reflectometer, a set of Capacitance sensors, and a new class of Correlation sensors. Several advanced signal processing methods are compared for accuracy, efficiency, and applicability to realistic, noisy, ill-matched, lossy aircraft cables with complex loads. A comparison of accuracy, cost, complexity, and functionality reveals the most cost-effective solution depending on the system requirements.

These sensors and associated algorithms are tested and compared on a variety of realistic wiring platforms including the US Navy's F-18, P3, E-2C, and C2 aircraft. The system-level design considerations are included to begin to understand the most effective method of deploying an in situ network health monitoring system.

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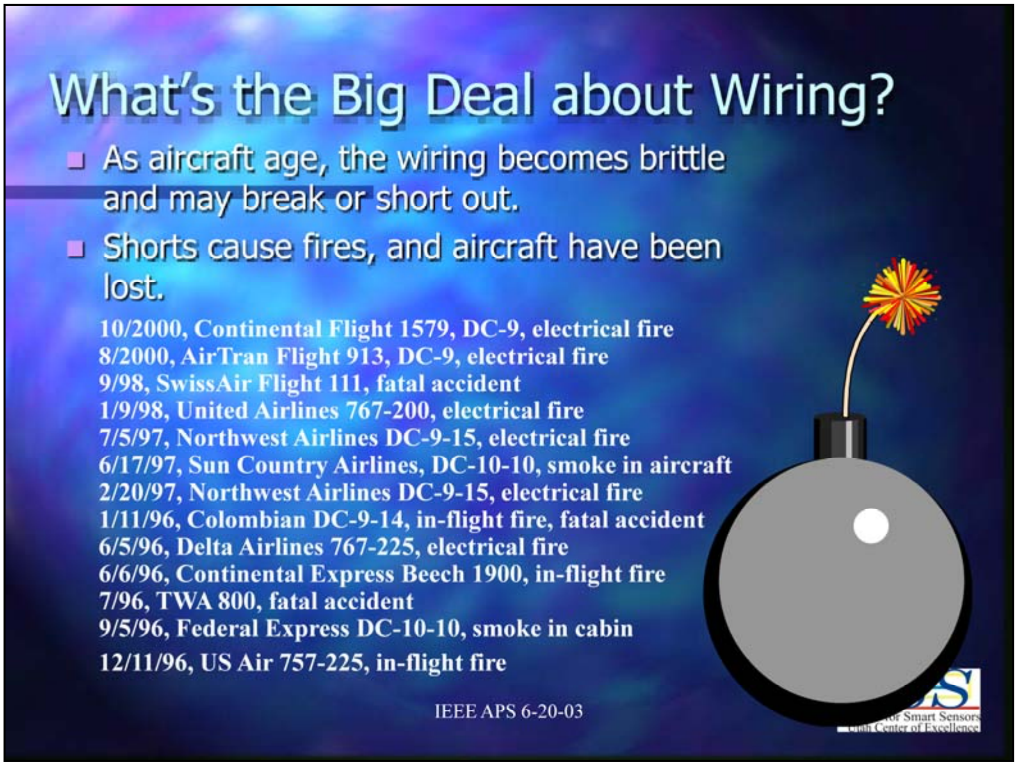
What's the Big Deal about Wiring?
As aircraft age, the wiring becomes brittle and may break or short out.
Shorts cause fires, and aircraft have been lost.
10/2000, Continental Flight 1579, DC-9, electrical fire
8/2000, AirTran Flight 913, DC-9, electrical fire
9/98, SwissAir Flight 111, fatal accident
1/9/98, United Airlines 767-200, electrical fire
7/5/97, Northwest Airlines DC-9-15, electrical fire
6/17/97, Sun Country Airlines, DC-10-10, smoke in aircraft
2/20/97, Northwest Airlines DC-9-15, electrical fire
1/11/96, Colombian DC-9-14, in-flight fire, fatal accident
6/5/96, Delta Airlines 767-225, electrical fire
6/6/96, Continental Express Beech 1900, in-flight fire
7/96, TWA 800, fatal accident
9/5/96, Federal Express DC-10-10, smoke in cabin
12/11/96, US Air 757-225, in-flight fire
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Wire Technology

% Probability of Failure of the Worst Polyimide Insulated Wire in each USN P-3 "Aircraft Location vs. Time"
As of 5/7/95

Location	Years: 1	2	5	10	20
	% Failures				
Bomb Bay	0	0	0	24	33
Wing, Outboard Trailing Edge	0	0	0	28	53
Galley/Aft Cabin	0	0	0	41	61
Wing,Center Leading Edge	0	0	15	23	30
Forward Electrical Load Center	0	0	24	35	48
Avionics Bay C1	0	0	43	57	68
Wing, Inboard/Root, Leading Edge	15	20	32	46	60
Avionics Bay H1	21	23	40	46	78
Hydraulic Service Center, Under Deck	20	26	39	56	64
Main Wheel Well	38	42	50	72	100
Nose Wheel Well	31	57	89	100	100
Wing, Center, Trailing Edge	0	74	91	100	100

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Industry Composite

	Total Aircraft	Avg IOC > 10 years	Avg IOC > 20 years
Major US Airlines	3696	90%	41%
International Airlines	3646	83%	36%
US Cargo Carriers	982	97%	81%
International Cargo	95	96%	84%
Air Force	4421	71%	42%

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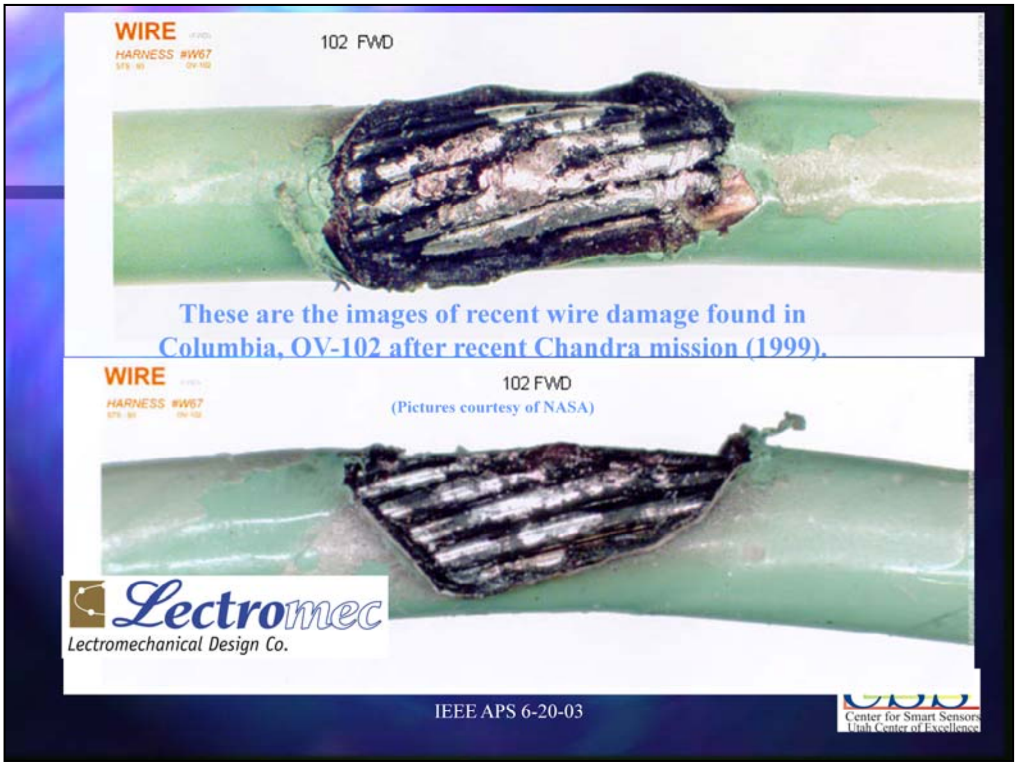
WIRE
HARNESS #W67
102 FWD
These are the images of recent wire damage found in Columbia, OV-102 after recent Chandra mission (1999).
WIRE
HARNESS #W67
102 FWD
(Pictures courtesy of NASA)
Lectromec
Lectromechanical Design Co.
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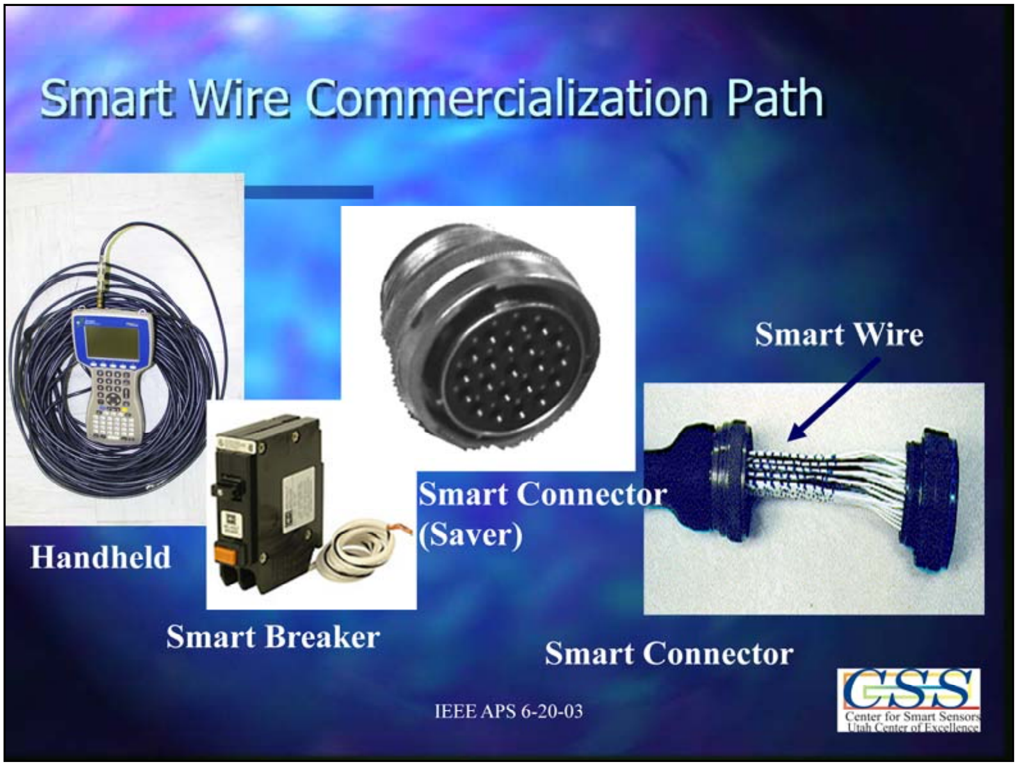


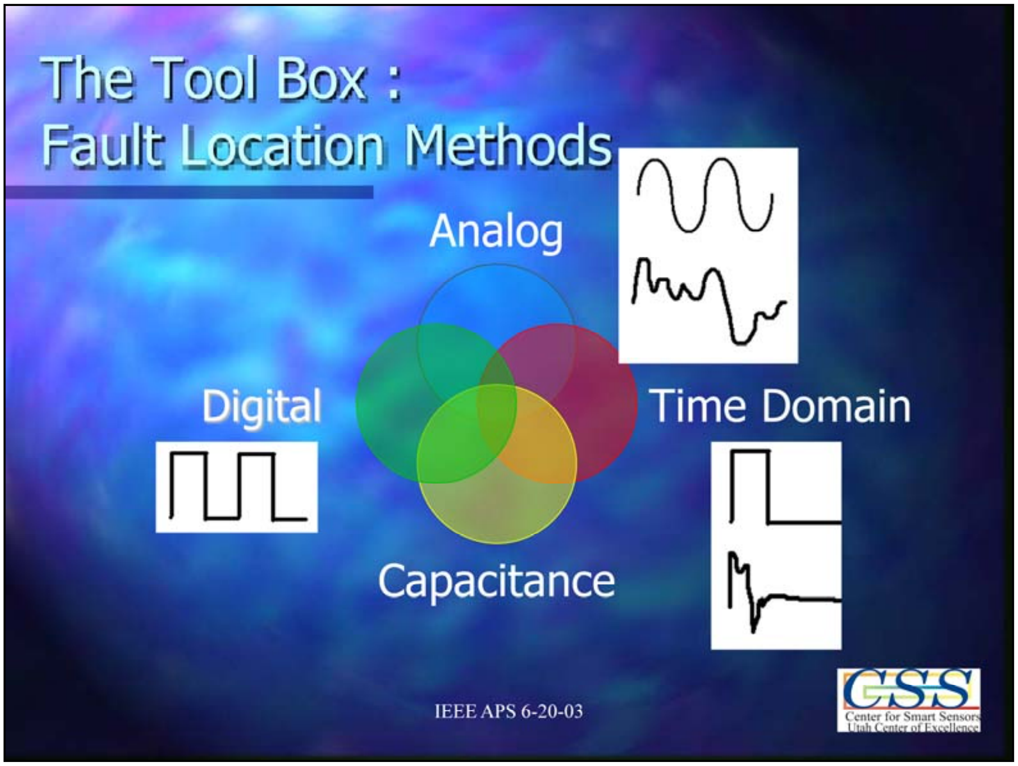
Maintaining aging aircraft wiring can be a difficult and frustrating task. Several emerging technologies hold promise for reducing the time, effort, and difficulty of locating faults in wiring systems.

Handheld testers can be used to determine the length of a wire, and to map out a small network. This can be compared to diagrams of known wire systems to determine where a fault exists. Most often these handheld test units would be used after a fault is identified, to locate the fault precisely (typically within 2-6 inches).

The University of Utah is using this ruggedized handheld PC from Juniper Systems to test and develop a wide range of technologies.

The next application of these emerging technologies is the Smart Breaker. Existing thermal circuit breakers trip only when there is a large excess current. If a small arc occurs on the wire, the wire will be severely damaged before the breaker blows. New Arc Fault Circuit Interrupters (AFCI) are digital breakers designed to trip when the noise associated with an arc is detected. Typically this lasts just a few milliseconds and results in minimal observable damage to the wire. This is a very exciting technology for reducing in-flight fires, but it leaves behind a maintenance nightmare. The maintainer is called in to handle a tripped breaker with damage that is extremely difficult or impossible to find. Emerging technologies that can run live and in flight hold promise for locating these intermittent arcs while they occur, and directing the maintainer to the correct location for repair.

The next application of these technologies is in a Smart Connector or connector saver, that contains electronics and data analysis hardware to determine where faults are live and in flight in all types of wiring.



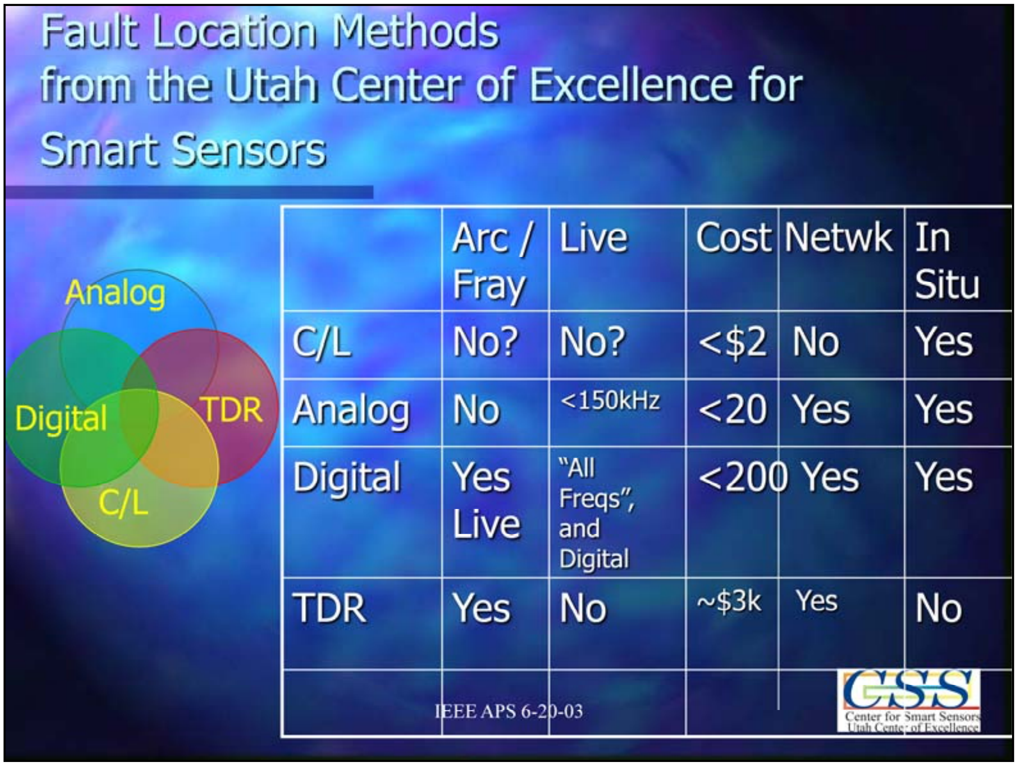
There are a wide variety of test methods, and this talk is focused on those that hold promise to become inexpensive miniature sensors for widespread use.

Probably the simplest and least expensive of these technologies is the capacitance sensor. The total capacitance (or inductance in th case of a short circuited wire) is proportional to the total length of the wire. This method is highly effective for locating faults, however it cannot be used on a network of wires. The far end of the wire must be disconnected, which is OK for handheld use but not OK for live in situ application.

Time Domain Reflectometry (TDR) is a traditional wire testing method. It sends a short pulse down the wire and recieves a reflection (or echo) from the far end of the wire. The time between incident and reflected signals tells the length of the wire.

Analog reflectometry sends a sine wave down the wire and receives the reflected sine wave echo. The phase difference between these two waves tells the length of the cable. This method can be used on a network of cables, but in most cases, the wire cannot be live at the time.

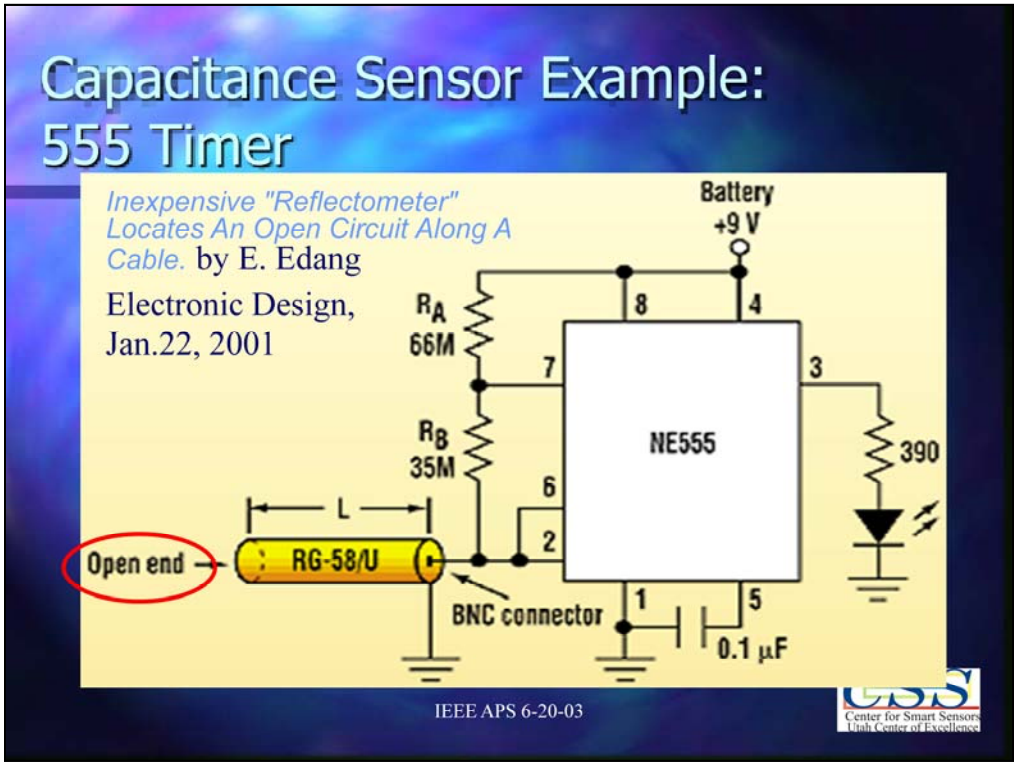
Digital reflectometry methods are among the newest of the emerging technologies. This method sends a digital code down the wire and correlates the echo and incident signals. This method can work on live cables without interferance and is suitable for networks of wires.



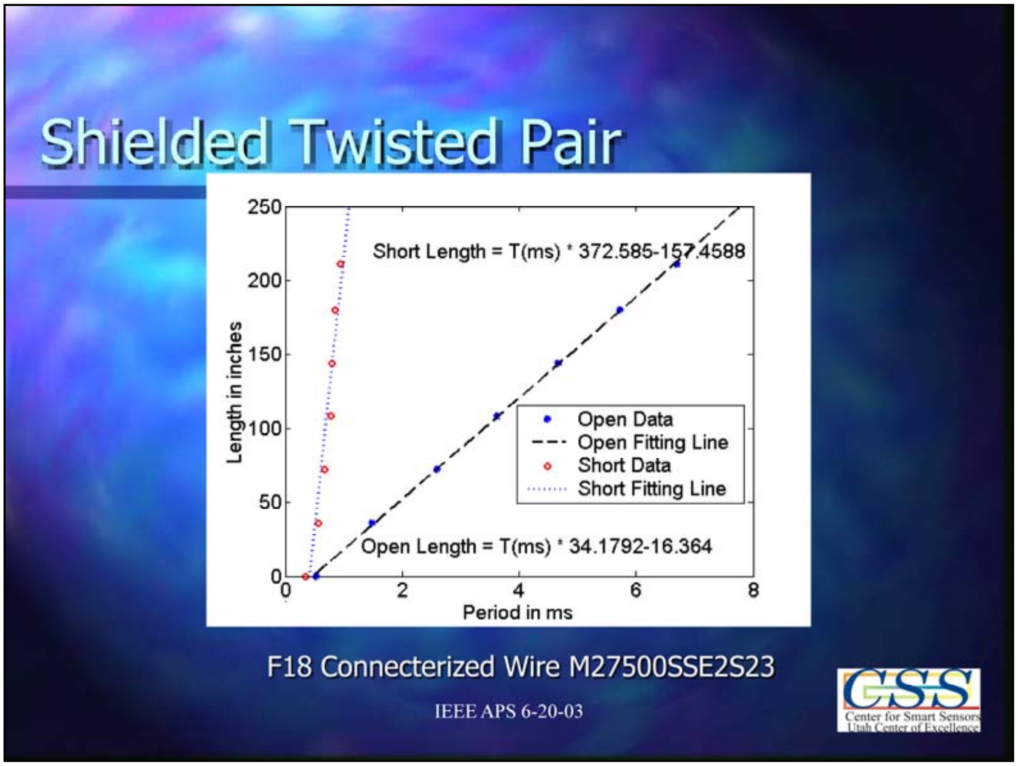
	Arc / Fray	Live	Cost	Netwk	In Situ
C/L	No?	No?	<$2	No	Yes
Analog	No	<150kHz	<20	Yes	Yes
Digital	Yes Live	"All Freqs", and Digital	<200	Yes	Yes
TDR	Yes	No	~$3k	Yes	No

Each class of wire testing technologies has advantages and disadgantages.

(discuss tradeoff matrix)

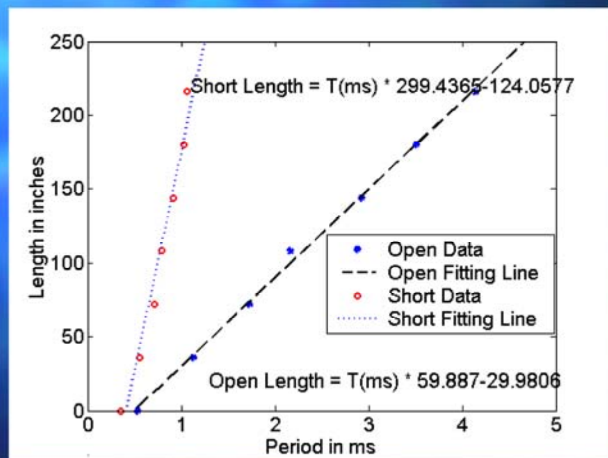


This 555 timer is a simple example of a capacitance measurement circuit. The wire acts as the capacitor in an astable multivibrator configuration. As the wire decreases in length, the capacitance decreases, and the output frequency is decreased. This frequency of oscillation can be found using a simple “counter” or a frequency to voltage converter.



Data from the 555 timer are very linear and accurate to within 2-6 inches. Shielded cables are the most accurate.

Unshielded Twisted Pair



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Here is the handheld tester built with the 555 timer circuit and an associated circuit for measuring short circuited wires.

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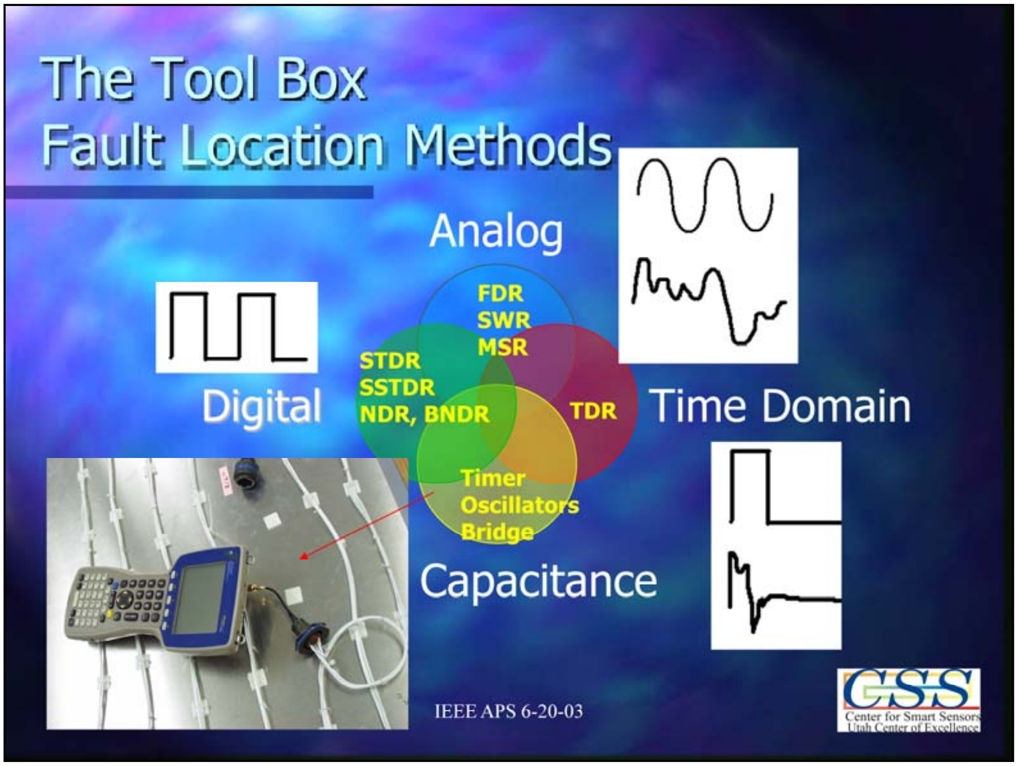
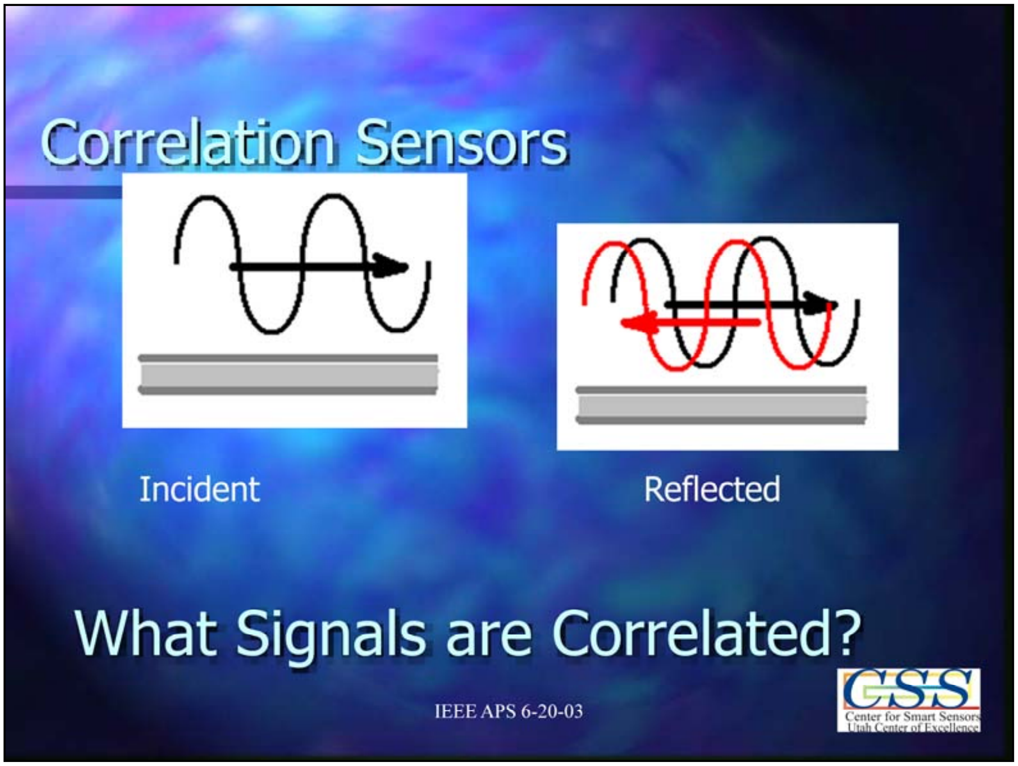


Several specific technologies from each family are available for use in wire testing or are emerging.

The top three methods have something in common. They are all correlation methods.


Correlation Sensors
Incident
Reflected
What Signals are Correlated?
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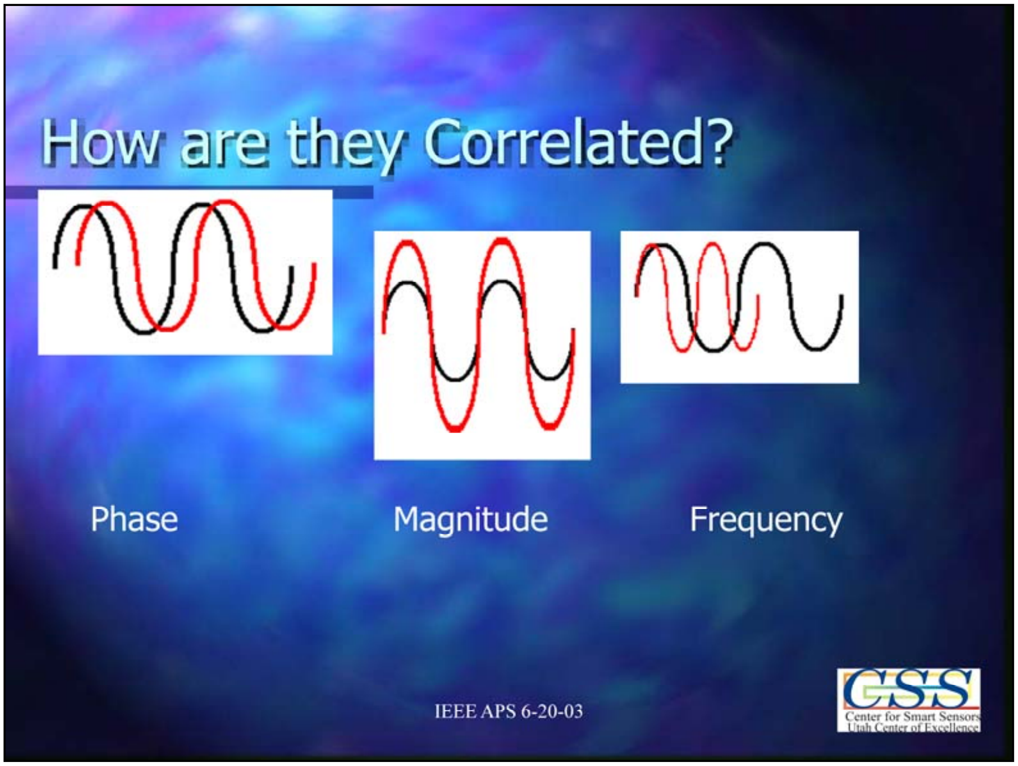


There are three aspects of a signal that you can correlate.

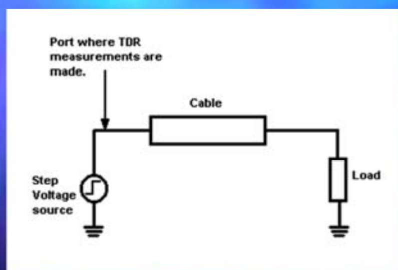
Amplitude correlation determines the length of the wire from its loss. This is fraught with error, as many factors contribute to this loss, not all of which are controllable.

Time domain correlation looks at time history to determine when signals match up.

Phase correlation is highly effective for finding wire length.

Frequency correlation would only apply if the incident signal was not kept constant in frequency during the test.

Time Domain Reflectometry (TDR)



A stepped voltage source sends a pulse down a cable. The reflections are measured at the source end.

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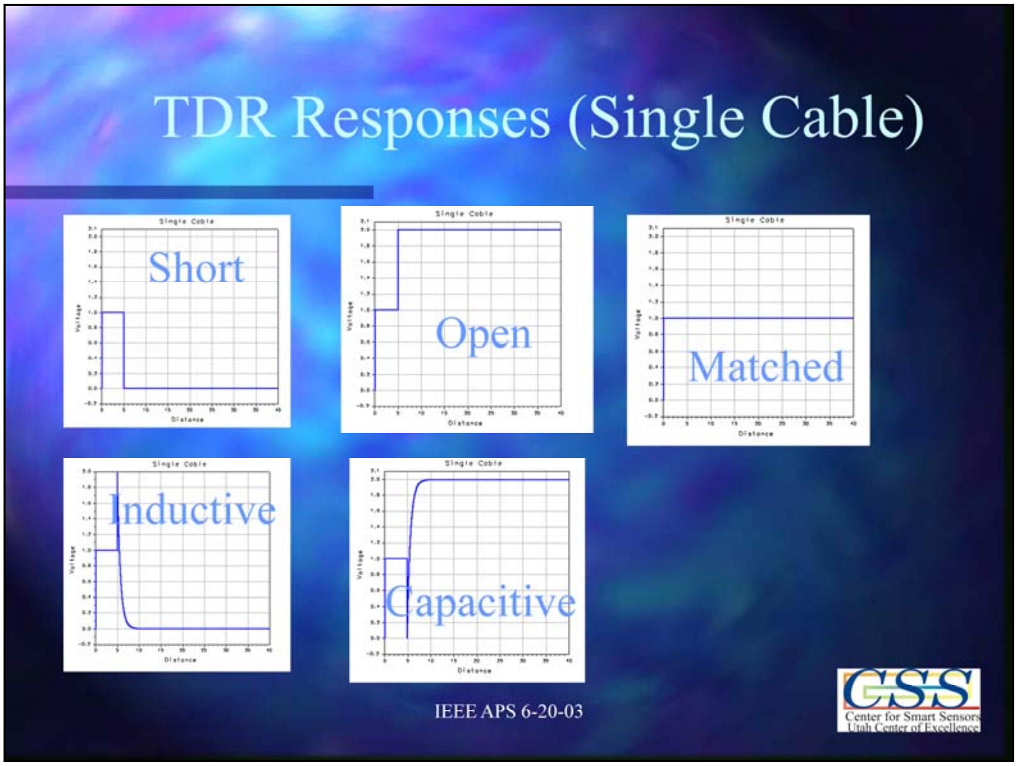
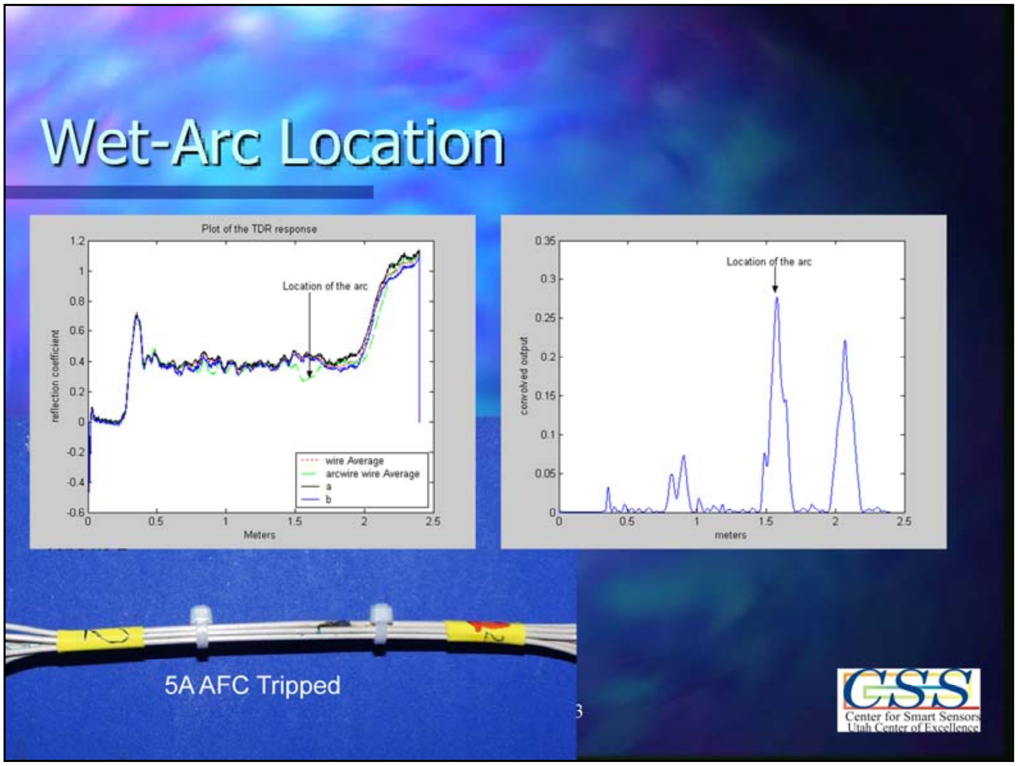


Since this is a time domain method, the TDR requires a fast rise time pulse and a fast time domain sampler.


Wet-Arc Location
Plot of the TDR response
Location of the arc
reflection coefficient
Meters
wire Average
arcwire wire Average
a
b
Location of the arc
convolved output
meters
5A AFC Tripped
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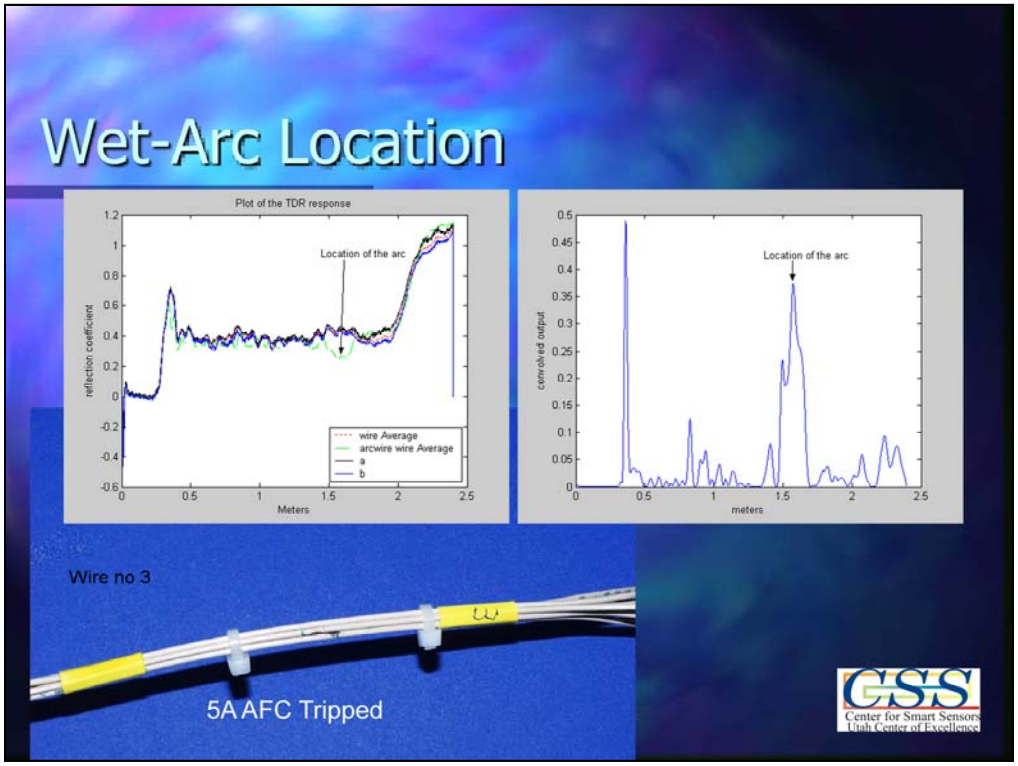
Wet-Arc Location
Plot of the TDR response
Location of the arc
reflection coefficient
Meters
wire Average
arcwire wire Average
a
b
convolved output
meters
Location of the arc
Wire no 3
5A AFC Tripped
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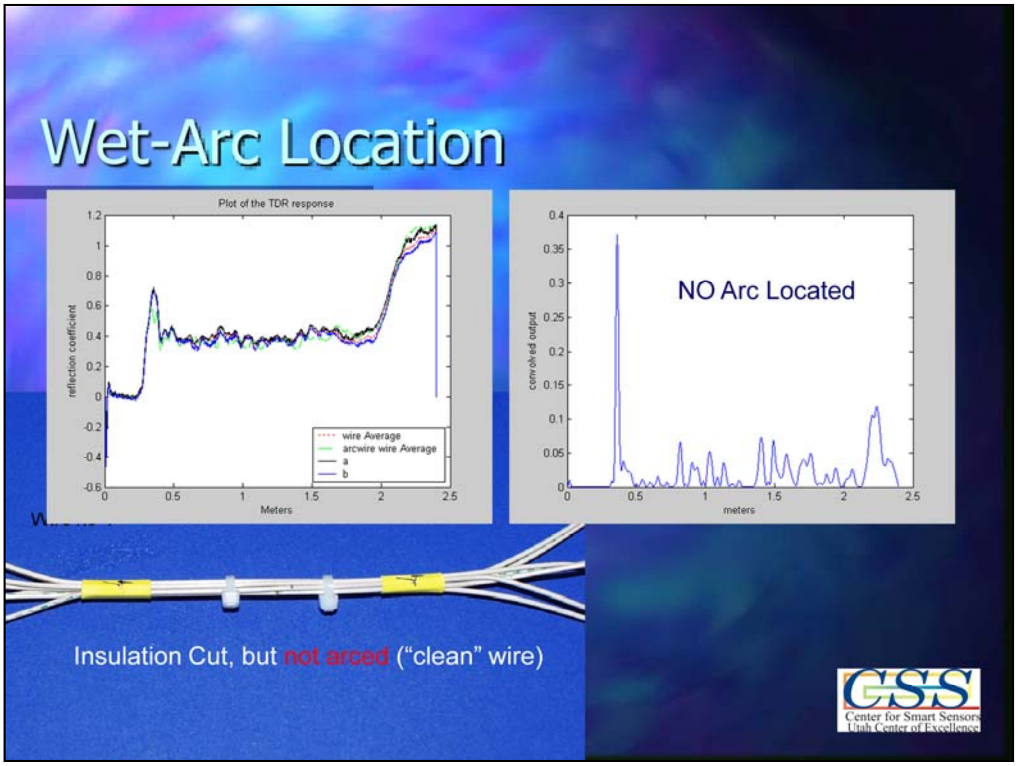
Wet-Arc Location
Plot of the TDR response
reflection coefficient
Meters
wire Average
arcwire wire Average
a
b
convolved output
meters
NO Arc Located
Insulation Cut, but not arced ("clean" wire)
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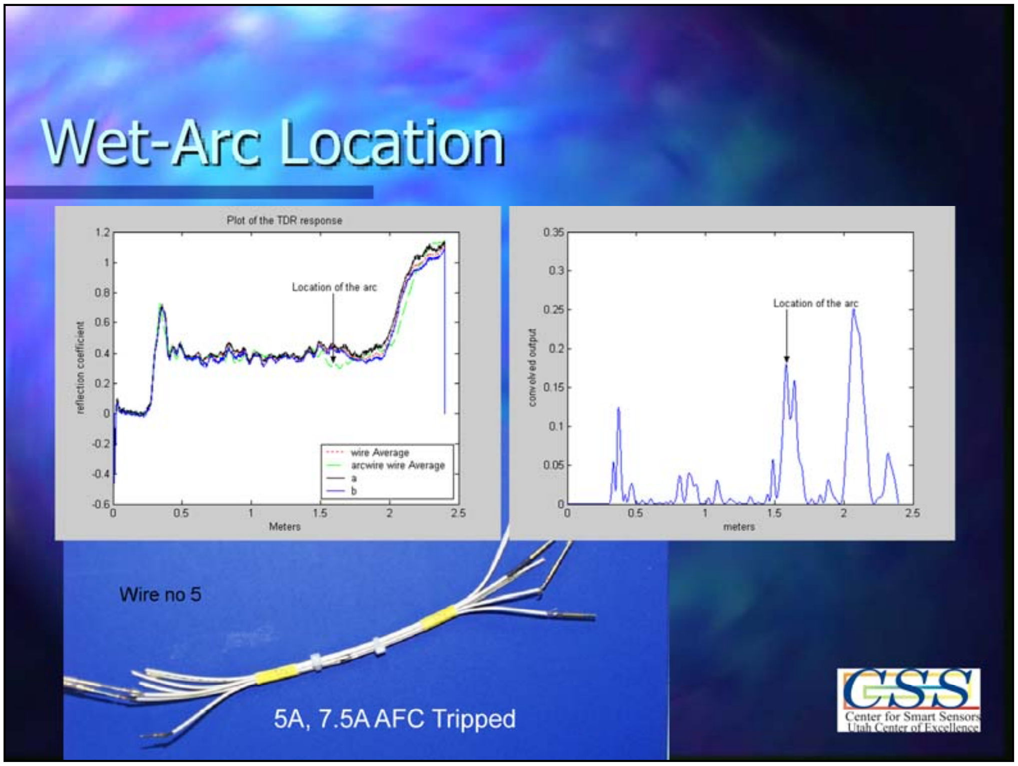
Wet-Arc Location
Plot of the TDR response
Location of the arc
reflection coefficient
Meters
wire Average
arcwire wire Average
a
b
Location of the arc
convolved output
meters
Wire no 5
5A, 7.5A AFC Tripped
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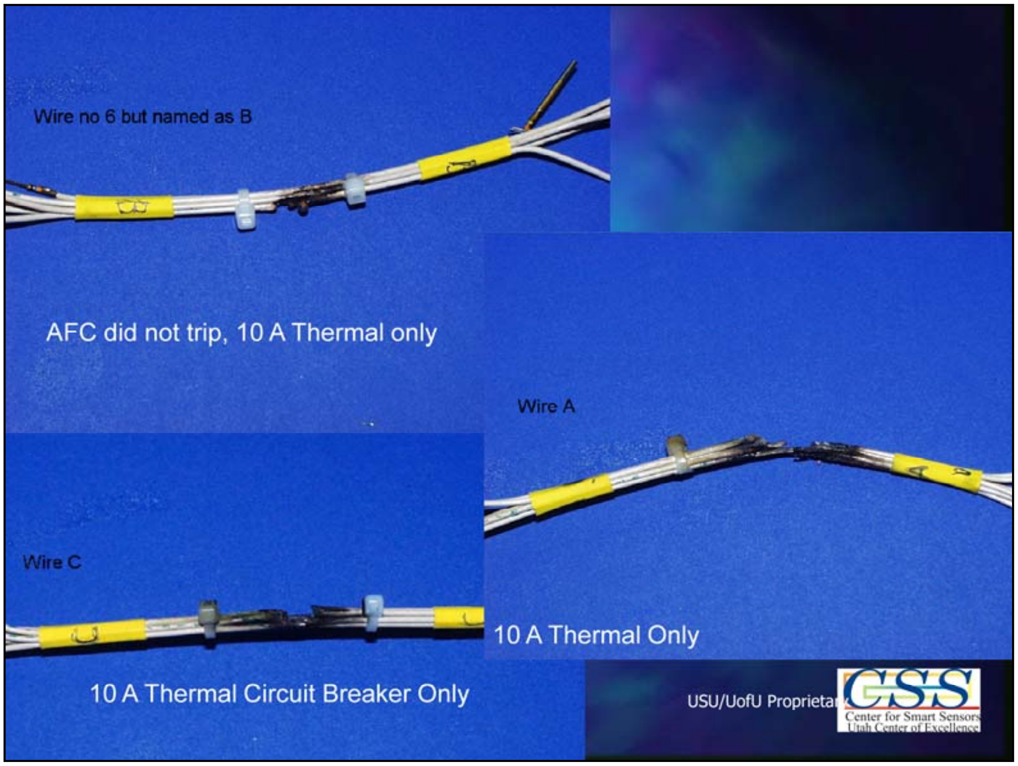
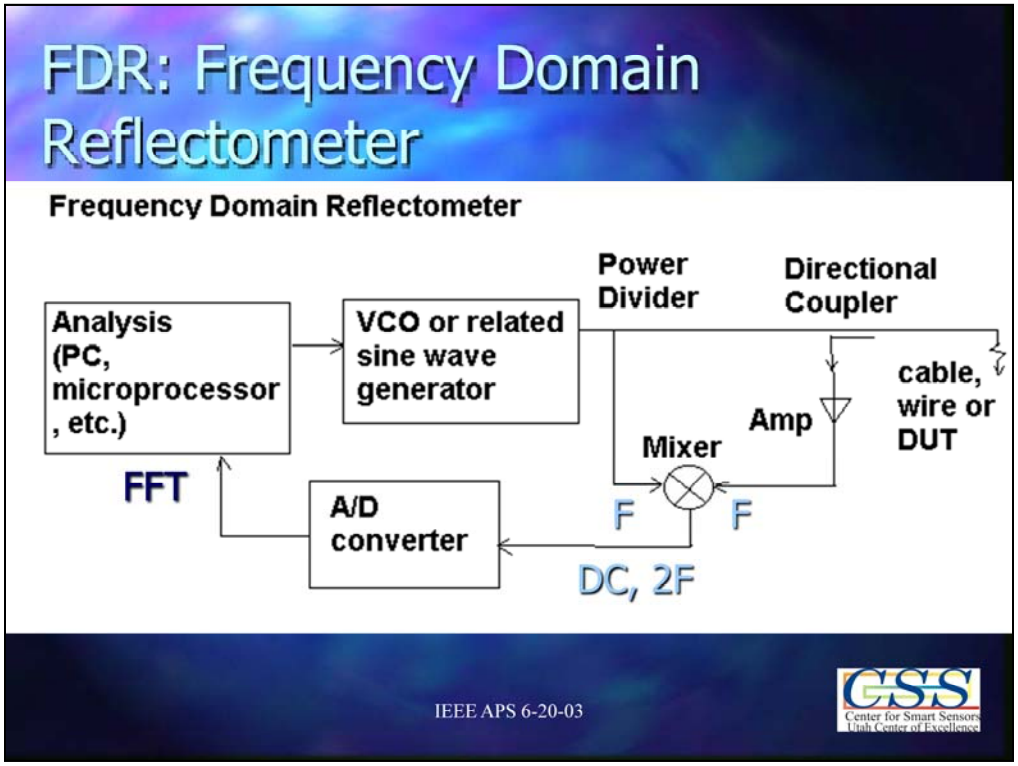


These wires did not have the protection of the arc fault circuit interrupter. The wire are either open or short circuited, depending on the wire.

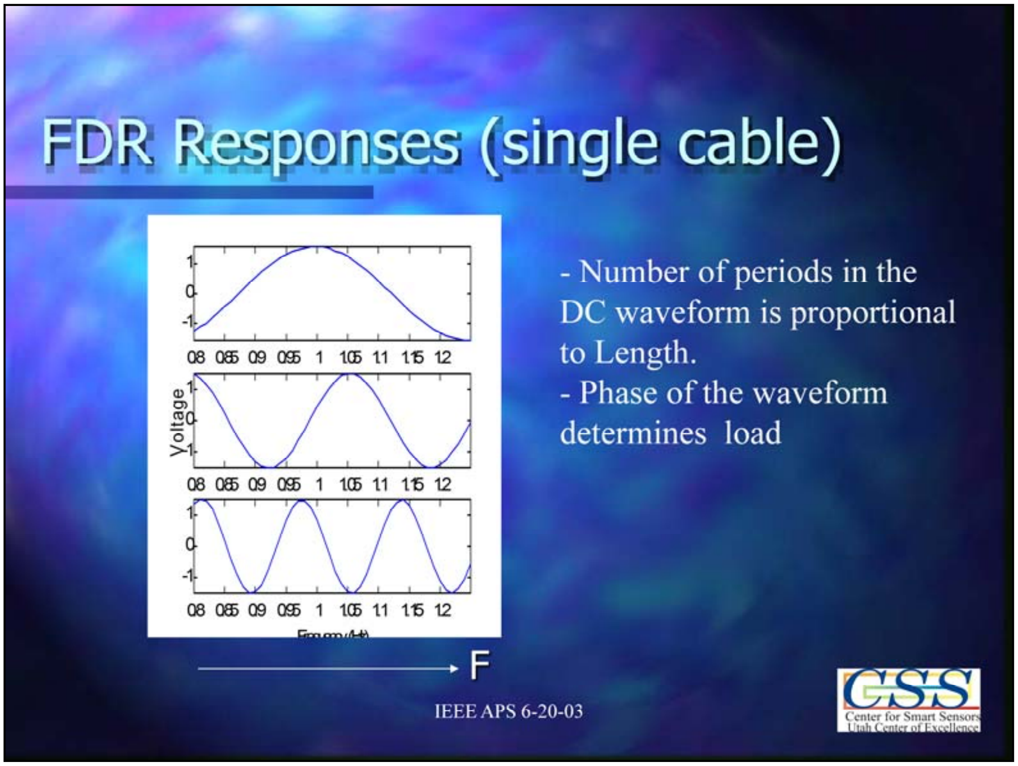


Sends a set of stepped frequency sine waves down the cable

Size of steps and number of frequencies can be adapted to control resolution and maximum length

Reflected field is separated from incident field

DC voltage is measured

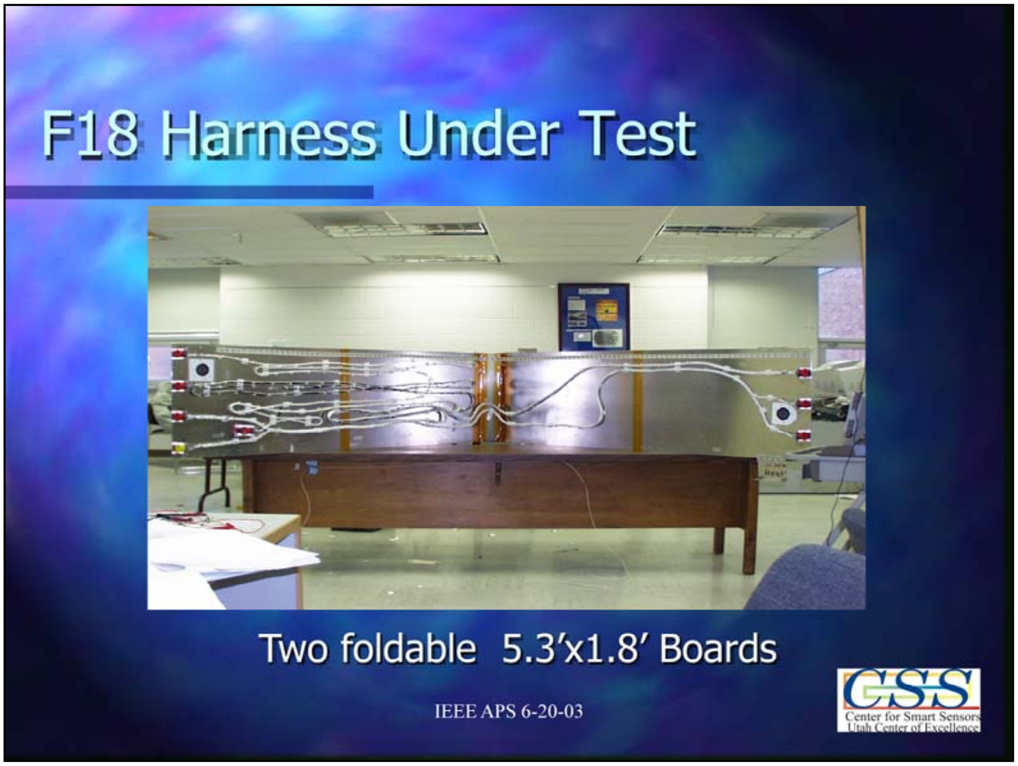


The FDR is like an abbreviated version of the TDR. The TDR includes "all" frequencies, and the FDR includes a subset of these frequencies. The FDR data at these frequencies is virtually identical to the results that the TDR would give at those frequencies. The FDR advantage is that it does not require a fast-rise time pulse or a fast sampler, so the electronics are smaller and less expensive, making it a good candidate for in situ inspection.

Wire Types: 9 different Wires in 4 Types

- Shielded(1, 2, 3, 4), Filtered Cable
- Twisted Pair, Single Strand

← FDR Good ——————→ FDR not good


F18 Harness Under Test
Two foldable 5.3’x1.8’ Boards
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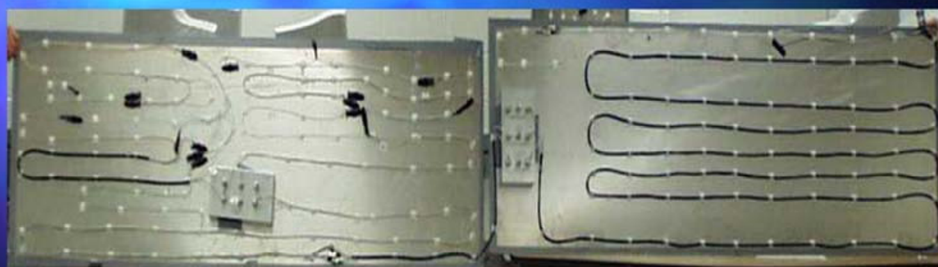
C-2 Fuel Quantity Indicating System Picture



Two of 2’ x 4’ Boards

Most of Single strand and 1-shielded

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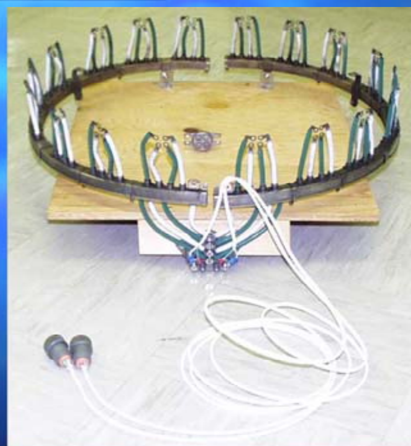
P3C Harness and Sensor



R = 23 inches

2 x 9sensors in P3C

Temperature Sensor

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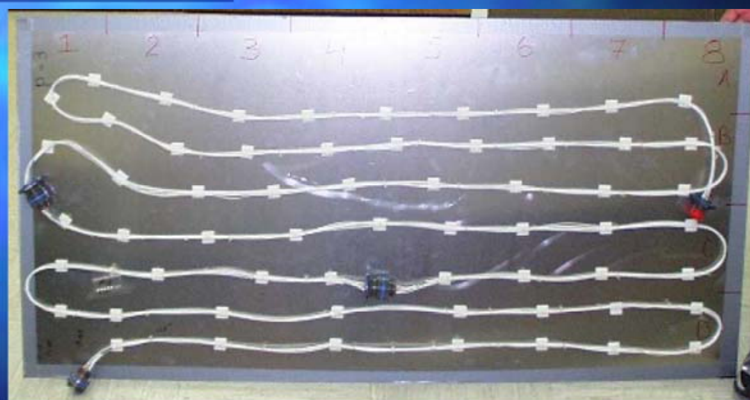
P3 Harness



2'x4' Board, Single Strand Wire Bundle

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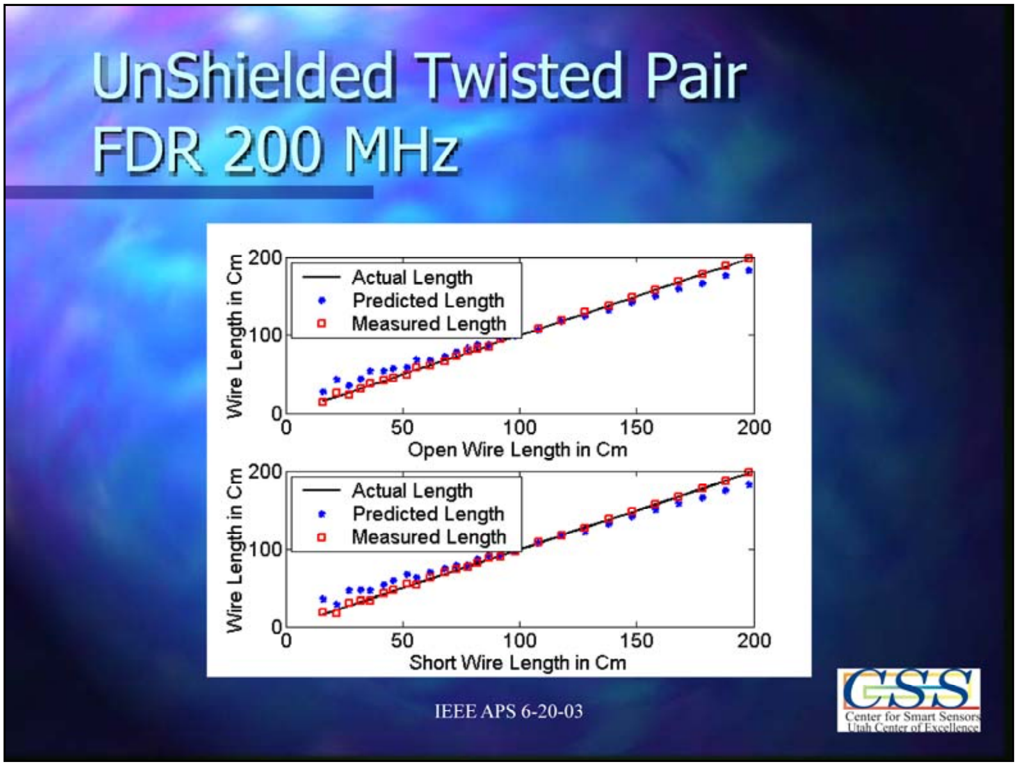

UnShielded Twisted Pair
FDR 200 MHz
Actual Length
Predicted Length
Measured Length
Wire Length in Cm
Open Wire Length in Cm
Short Wire Length in Cm
0
50
100
150
200
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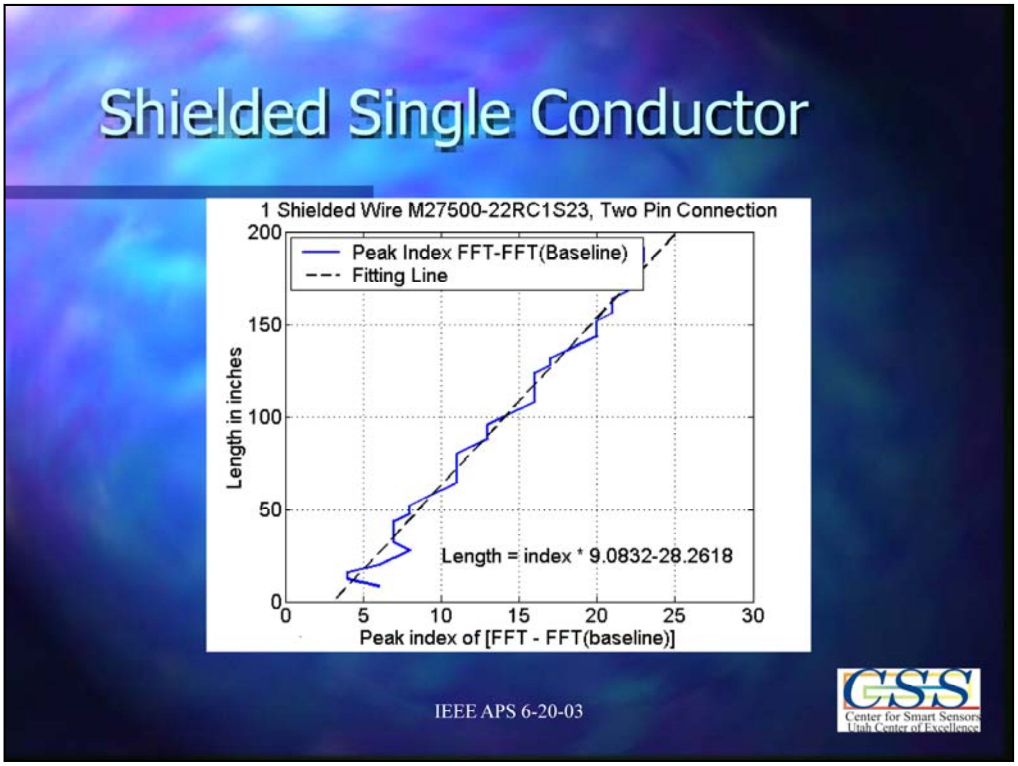
Shielded Single Conductor
1 Shielded Wire M27500-22RC1S23, Two Pin Connection
Peak Index FFT-FFT(Baseline)
Fitting Line
Length in inches
Length = index * 9.0832-28.2618
Peak index of [FFT - FFT(baseline)]
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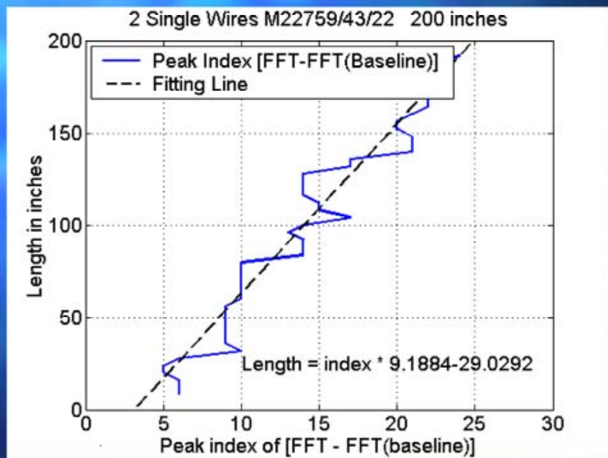
Pair of Single Conductors, Untwisted, Side-by-Side contact



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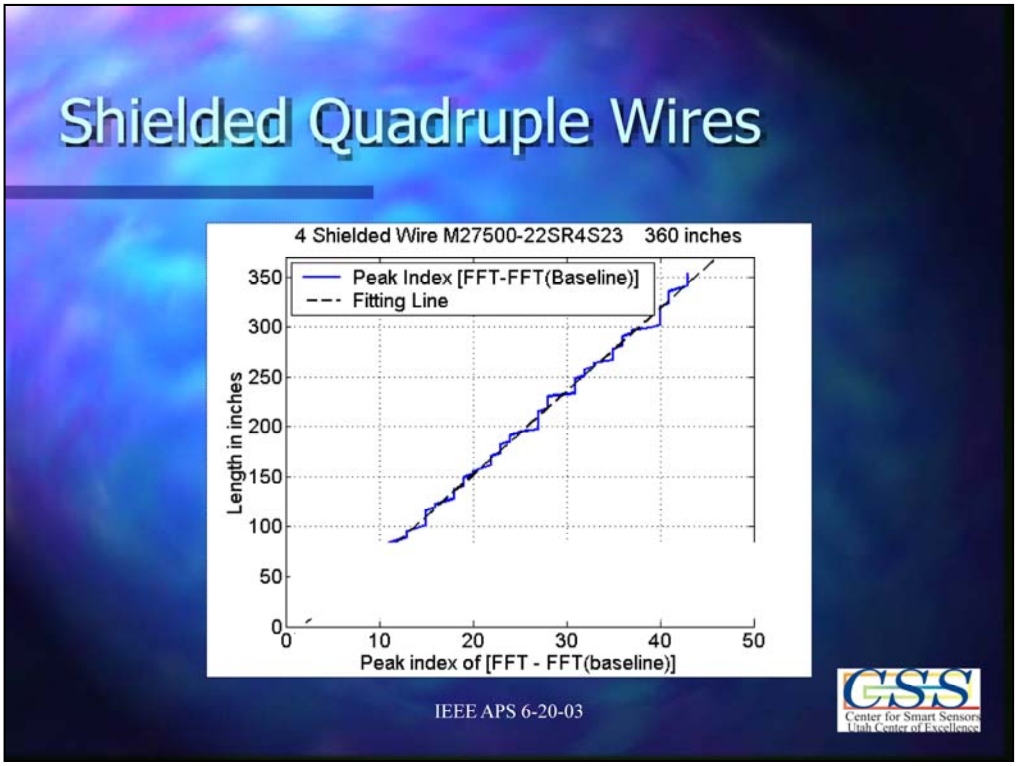
Shielded Quadruple Wires
4 Shielded Wire M27500-22SR4S23 360 inches
Peak Index [FFT-FFT(Baseline)]
Fitting Line
Length in inches
Peak index of [FFT - FFT(baseline)]
0
50
100
150
200
250
300
350
0
10
20
30
40
50
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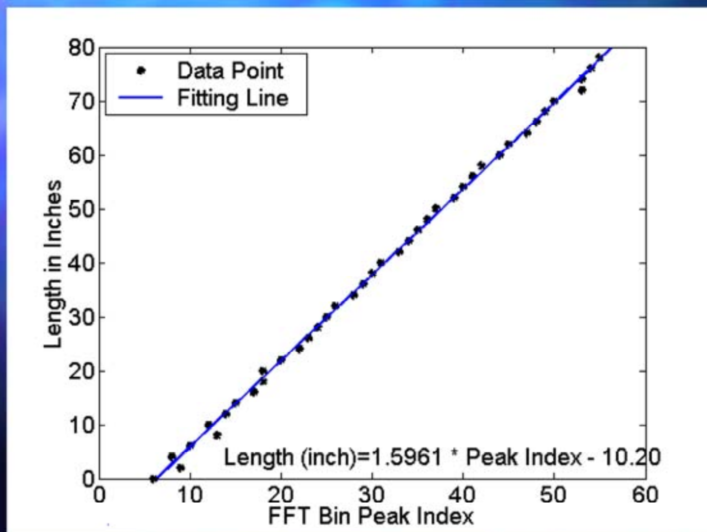
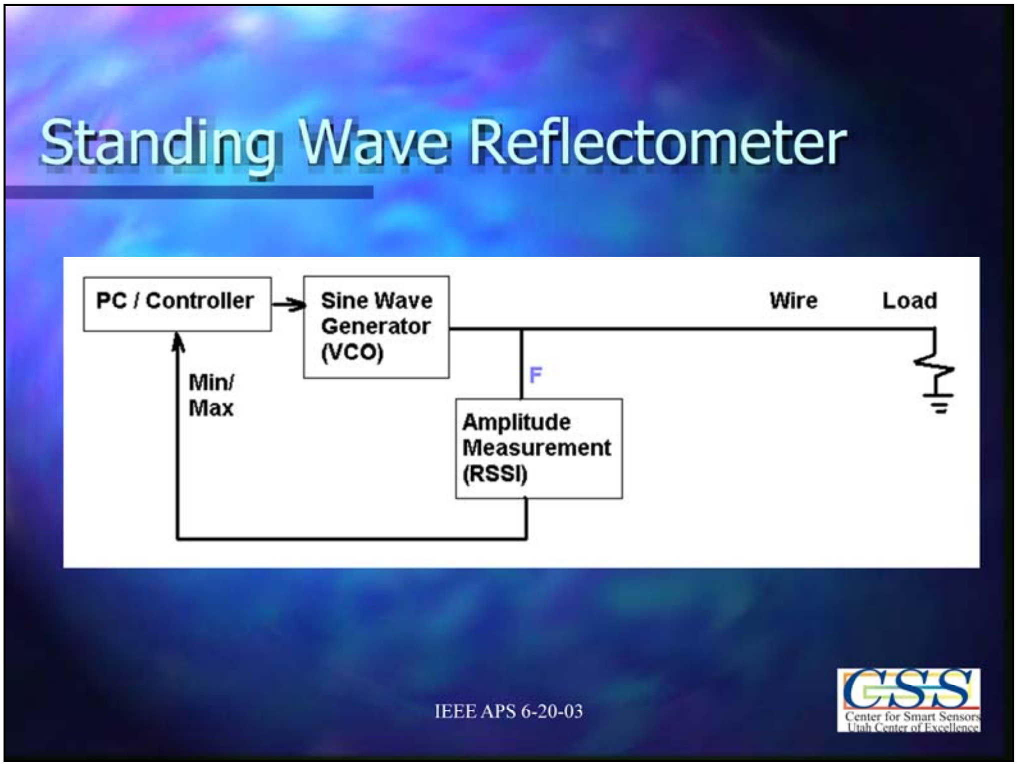
Shielded Triple Wires

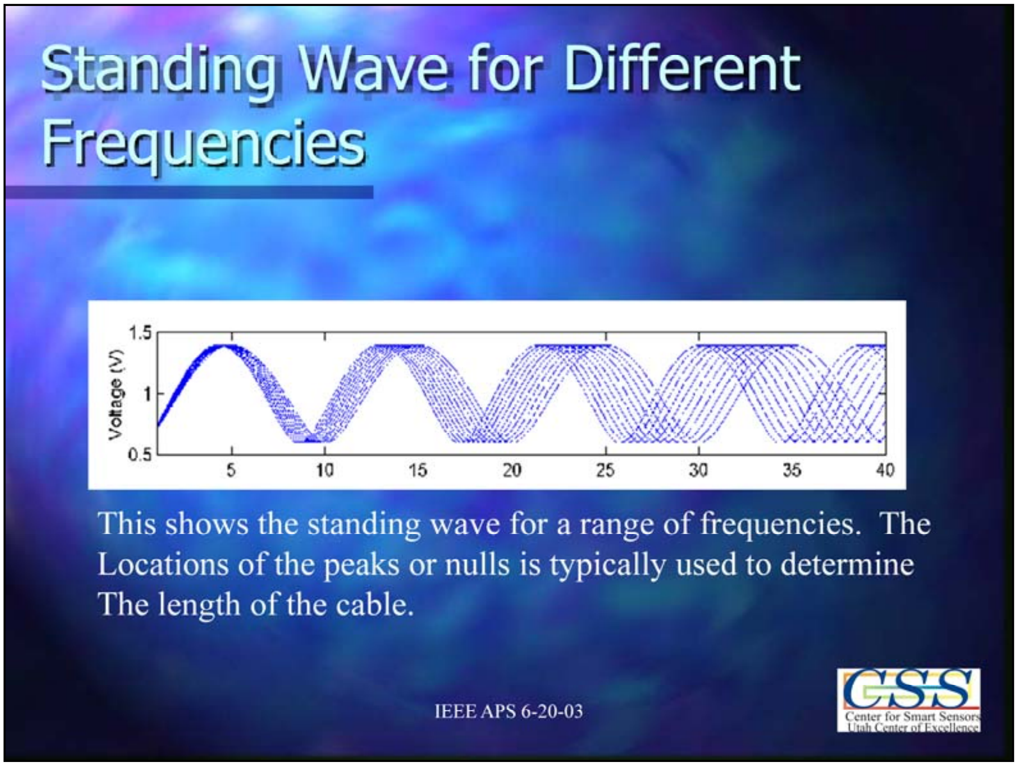




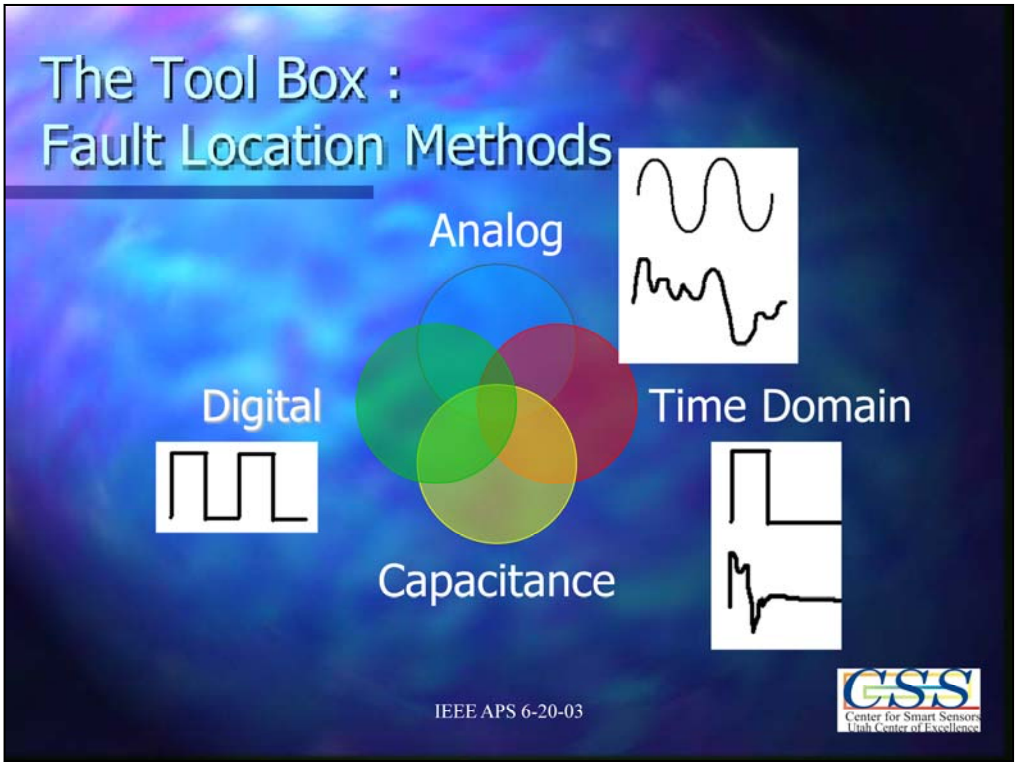
Sends a set of stepped frequency sine waves down the cable

Reflected field is added to incident field to produce a standing wave

Voltages at the incident frequencies (normally a few 100s of MHz to a few GHZ) are measured to map the standing wave



This data comes from a system to measure the height of fluid in a reservoir by measuring the length of a cable in water. The resolution is about 1 mm.



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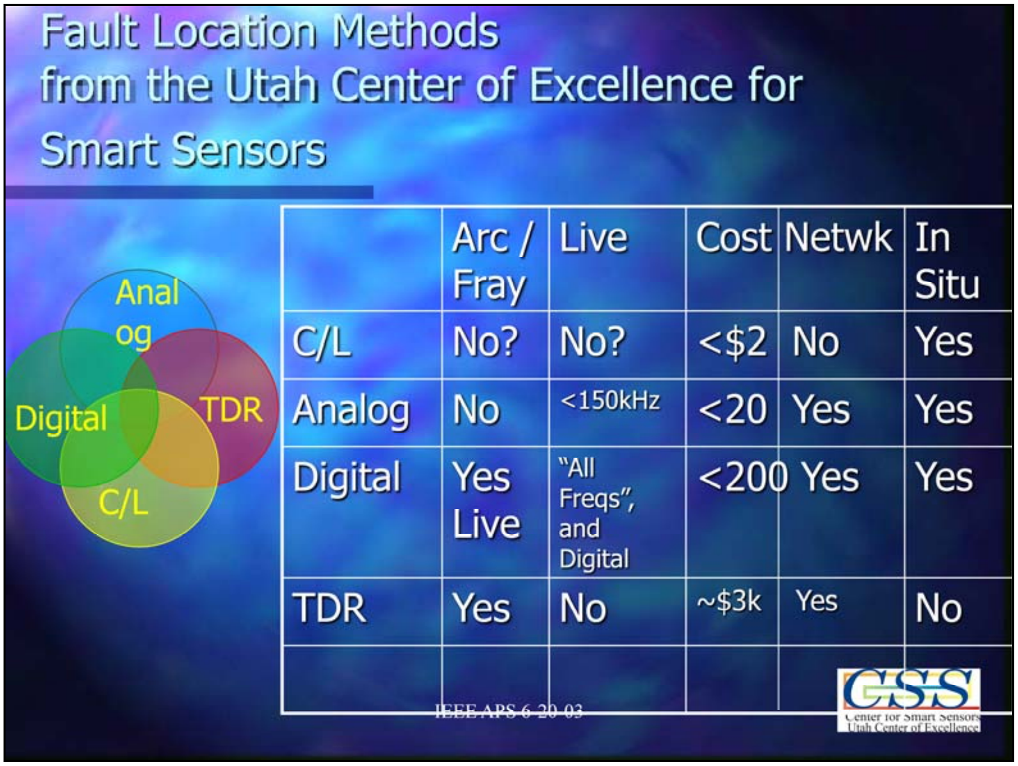
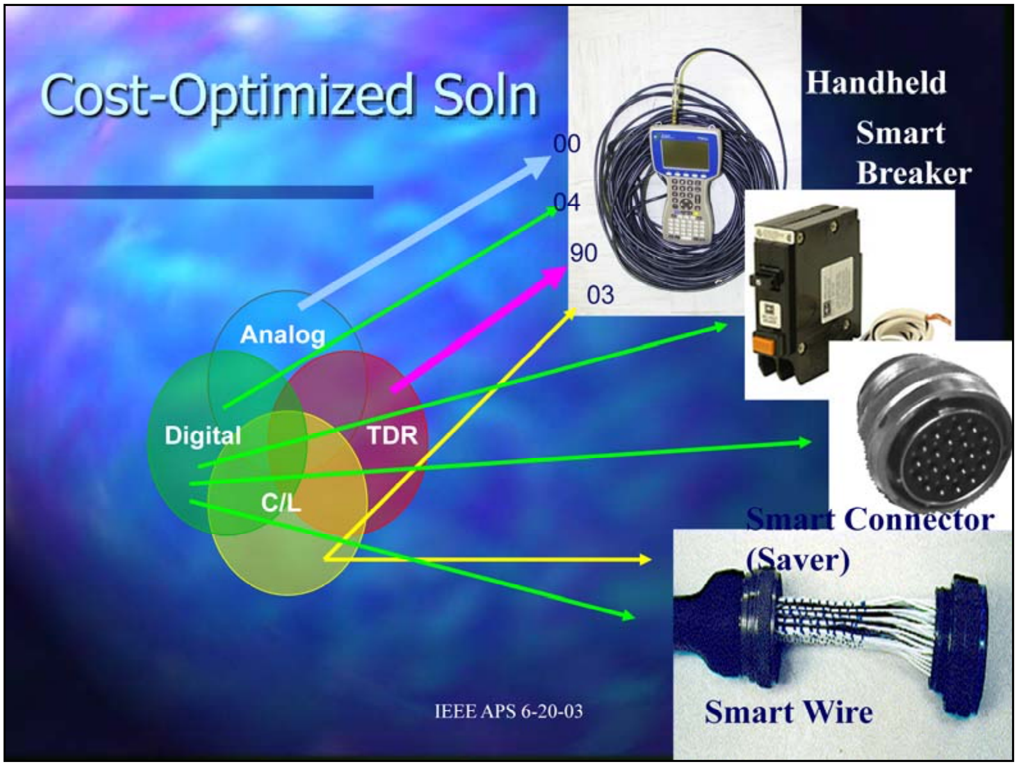


Each class of wire testing technologies has advantages and disadgantages.

(discuss tradeoff matrix)



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Dr. Cynthia Furse

www.ece.utah.edu/~cfurse

cfurse@ece.utah.edu

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