

# **RADICAL EXTENSION OF TIME DOMAIN REFLECTOMETRY FOR DETECTION AND LOCATION OF FLAWS IN AIRCRAFT WIRING SYSTEMS**

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**Abstract-** This paper proposes a novel and radical extension of Time Domain Reflectometry (TDR) as applied to the detection and location of flaws in wiring systems. The proposed approach merges two methods most commonly used for the inspection of conducting structures: TDR, and Eddy Current Testing (ECT). In many ways, TDR and ECT appear to be orthogonal methods. By combining them, key advantages of both (testing at distance for TDR, and sensitivity for ECT) are retained while avoiding some of their limitations. The proposed TDR technology, which uses high speed digital signals for probing the wires, has the following improvements over state of the art: (1) higher sensitivity to soft faults such as insulation chafing, (2) unambiguous localization of faults on branched-wiring harnesses, and (3) mitigates the problem of uncontrolled impedance.

## **Introduction**

As today's military and commercial aircraft age, the many miles of wiring buried deep within their structures become brittle and crack, break, or develop short circuits. Some of these faults are intermittent, occurring only sporadically as the physical vibration, stresses, temperatures, electrical loads, moisture condensation, etc. change throughout the flight [1]. When the plane is on the ground, no fault can be found. These types of problems are among the most frustrating for aircraft maintainers, resulting in a typical "no fault found" incident taking tens or even hundreds of hours to locate. As the system ages, wiring faults, arc faults on power wires in particular, have been implicated in a variety of smoke incidents, in flight fires, and crashes. Some planes even remain grounded for extended periods of time until basic electrical systems can be fully replaced at great cost and labor. One of the greatest hazards of these systems is that they may forebode a more serious in flight hazard as a small fault grows, yet the system check does not result in any anomaly detection.

In recent years, inspection methods have increased both in number, and capabilities. In particular, Time Domain Reflectometry (TDR) methods have improved greatly in their ability to detect and locate hard faults on simple wiring circuits [2]. State of the art TDR can now locate such faults within inches on wires of tens or hundreds of feet of length, without a base line. The TDR developed at Intelligent Automation, Inc. (IAI) was validated at the AANC at SANDIA for these capabilities.

However, there are currently no methods available that can reliably detect and localize soft faults, such as insulation damage, or frays<sup>1</sup>. The detection of such faults is important because they are often precursors to arc faults or other serious faults later on. Secondly, wiring in actual aircraft, unlike that in the laboratory is not simple. In particular, such wires are often branched, challenging the ability of traditional TDR practices (which only measure the time of flight to the defect) to unambiguously locate the fault.

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<sup>1</sup> If a baseline measurement is available, we can reliably detect and localize most soft faults with our current hardware [3].

The work discussed in this paper is an improvement on traditional TDR methods that has the potential to improve the state of the art for both localization of soft faults, and the localization of faults in branched wiring circuits. Our method is based on combining aspects of TDR, with an apparently orthogonal method: Eddy Current Testing (ECT).

### **Time Domain Reflectometry**

The basic method of TDR is that a short (compared to the time of flight through the entire wire) duration pulse is injected in to a wire, and the reflections of any discontinuities, including flaws and the end of the wire are detected and analyzed. Because many wires of interest are only 10ft long, the pulse duration should be in the order of ns, or shorter, corresponding to frequencies 100MHz-1GHz. The time it takes the reflection to complete the roundtrip corresponds directly to the distance to the scattering discontinuity, and the magnitude of the scattered wave indicates the severity of the flaw. The polarity and other characteristics of the reflection yield further detail on the nature of the scattering defect. TDR is compatible with one-side access, but is only sensitive to defects which backscatter or reflect; purely absorbing defects can only be detected by their effect on reflections which lie beyond them.

### **Eddy Current Testing**

Another widely used method for the inspection of conducting structures is Eddy Current Testing (ECT). The basic method of ECT is that a coil carrying a strong AC current (typically 10Hz-10KHz) is passed off the Unit Under Test (UUT) (say an airplane wing). In the metal surface of the wing, currents are induced, scatter of cracks, and other defects. A collocated small pickup coil detects the magnetic fields indicative of the induced current. As the probe scans the surface of the wing, an image of scattering discontinuities can be formed. ECT is extremely sensitive, and is used to monitor critical systems. Its key drawback for wiring testing is its small standoff distance (the probe needs to be within a few mm of the UUT, which is incompatible with one-sided access).

Typical TDR signals used for wire inspection cause induced signals of magnitude comparable to those used for ECT. While frequencies used for TDR are about three orders of magnitude higher than those for ECT, currents used in TDR (mA) are about three orders of magnitude smaller than those in ECT. The standoff distance used in ECT is similar or larger than those between neighboring wires in a harness subjected to TDR. The magnitude of induced signals is proportional to frequency and current, and inversely proportional to standoff distance. This means that when a typical TDR signal is injected into a wire, significant signals are induced on neighboring wires in the same wiring harness.

Current practice to detect wire-to-wire defects with TDR is to connect the signal wire of the TDR to one wire, and the ground pin of the TDR to the second wire. Then, as a probe signal is injected in a wire, the voltage on the same line is digitized to detect reflections from any impedance discontinuities. For inductive testing the second wire is not grounded. Rather, we inject the signal in one wire of a harness, and listen for induced signals on the neighboring wire. As we show below, these induced signals are much more sensitive to damage to the wiring insulation, and also allow for localization of faults in branched wiring harnesses.

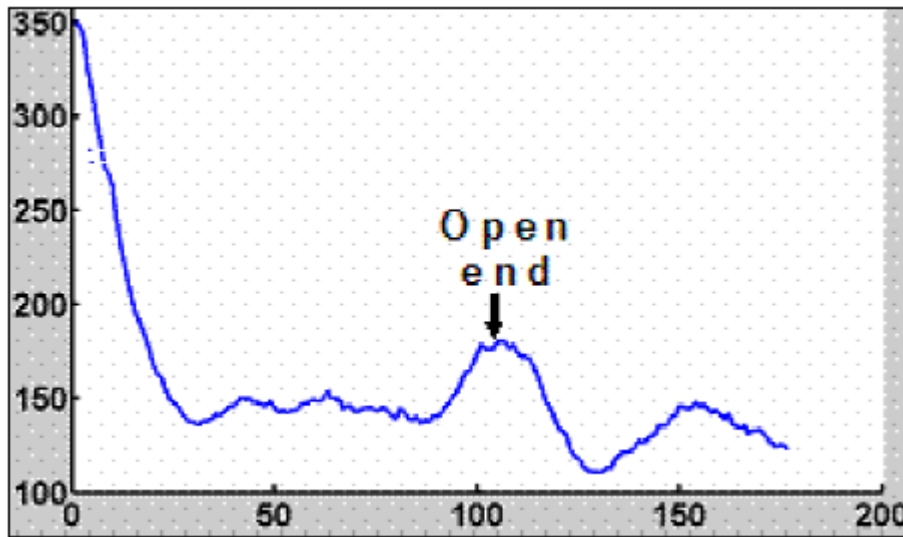
While our approach could be implemented with any TDR scheme, we will build on a particular implementation of TDR, which is based on so called Pseudo Random Binary Sequences (PRBS) [3].

### **Pseudo Random Binary Sequences**

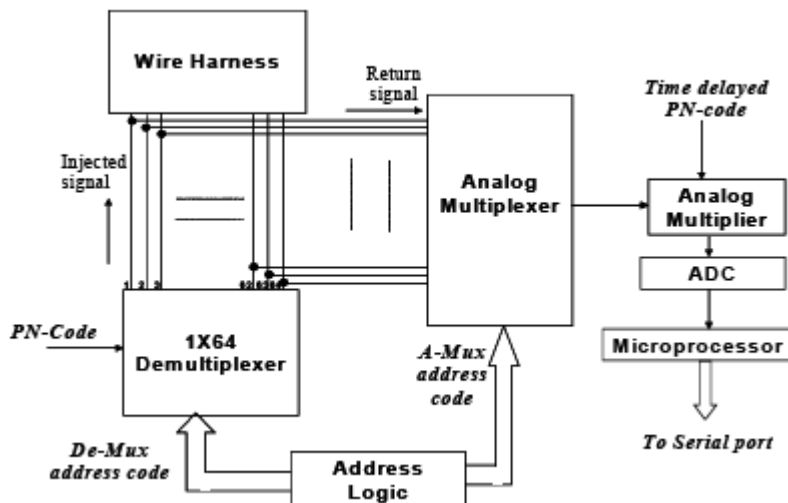
A Pseudo Random Binary Sequence (PRBS) is a sequence of bits (0 or 5V) with several desirable properties for wire testing:

- Since PRBS are used in spread-spectrum communications, GPS receivers, and other hardware, low-cost hardware is available to generate such sequences in the ~100 MHz -10 GHz regimes.
- In addition, PRBS have very desirable correlation properties for TDR: the correlation of the exact PRBS input with the signal received due to reflections gives the impulse response of the circuit. That impulse response completely characterizes the transfer function of the cable, including the analog properties of connectors as well as wires, including its frequency and phase characteristics over a wide frequency range.

If the cable changes due to a high resistance point, leakage, changing capacitance to a shield or to another conductor in the cable, its transfer function will change, which can be detected, diagnosed, localized. Similarly, discontinuities which cause signal reflections are detected and diagnosed. An example of an experimentally obtained cross-correlation for an open-ended wire is shown in Figure 1.

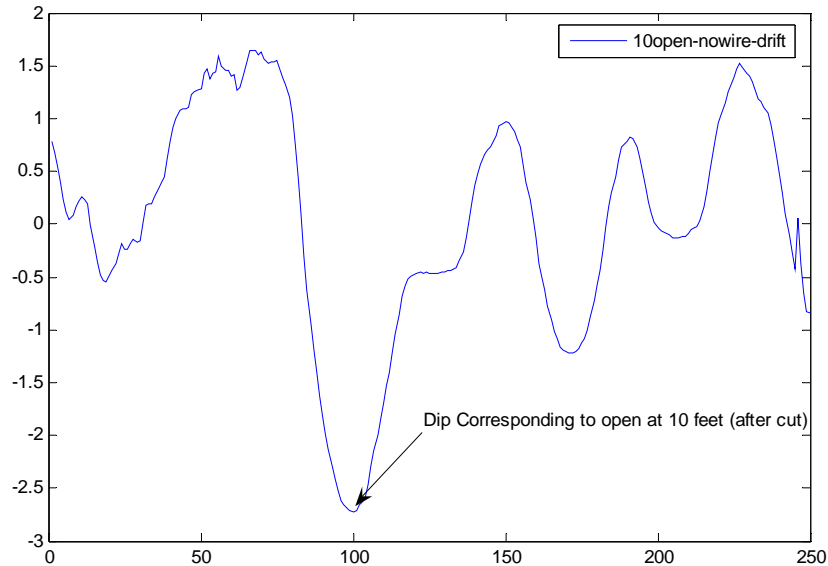


**Figure 1:** Cross-correlation plot of healthy, open-ended wire. Vertical axis: cross-correlation in arbitrary units. Horizontal axis: time-of-flight in units of  $\frac{1}{2}$  ns.



**Figure 2: Block diagram of the hardware to inspect wires using PRBS approach developed at Intelligent Automation Inc.**

In Figure 2, we show a block diagram of a PRBS-based TDR capable of testing multiple wires. The hardware was realized at Intelligent Automation, Inc., and capable of testing up to eight wires sequentially. The address provided to the digital multiplexer selects what wire the test signal will be injected to. The address provided to the analog multiplexer determines on what wire the TDR will detect reflections and correlate them with the input signal. In traditional TDR, these two addresses are identical. In inductive TDR, we also allow all combinations of non-identical addresses.



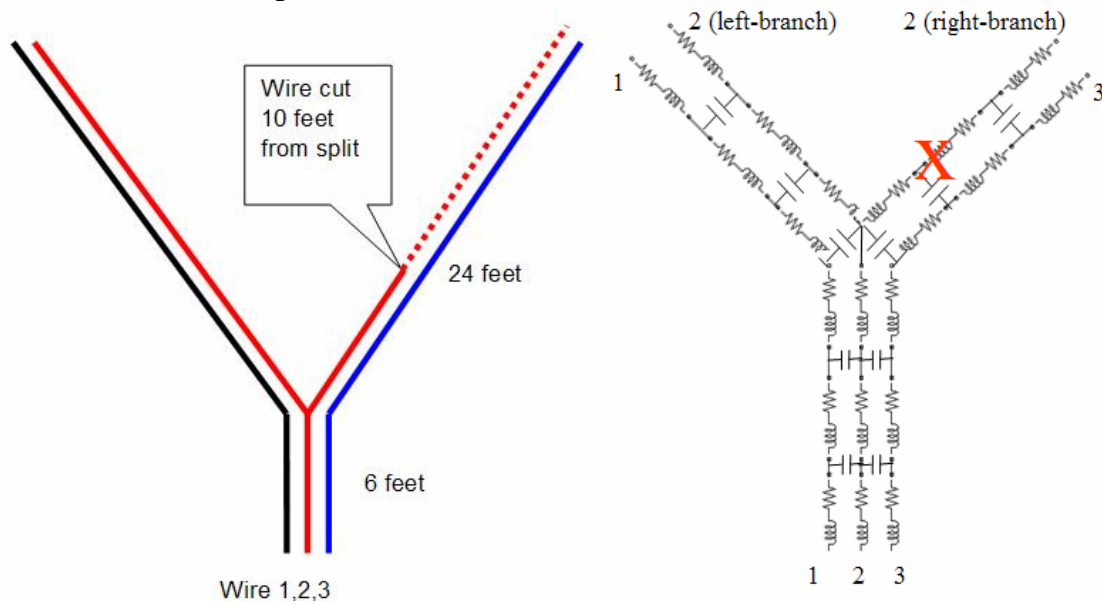
**Figure 3: Induced correlation due to cut wire (open) on neighboring wire. Vertical axis: cross-correlation in arbitrary units. Horizontal axis: time-of-flight in units of  $\frac{1}{2}$  ns.**

In Figure 3, we show the induced correlation for an open at 10ft in a neighboring wire. These measurements are taken on a 15ft wiring harness consisting of 8 single unshielded 20AWG wires of a type commonly used in aircraft. As expected, the induced peak due to the reflection from the cut is negative, opposite to the reflection shown in Figure 1.

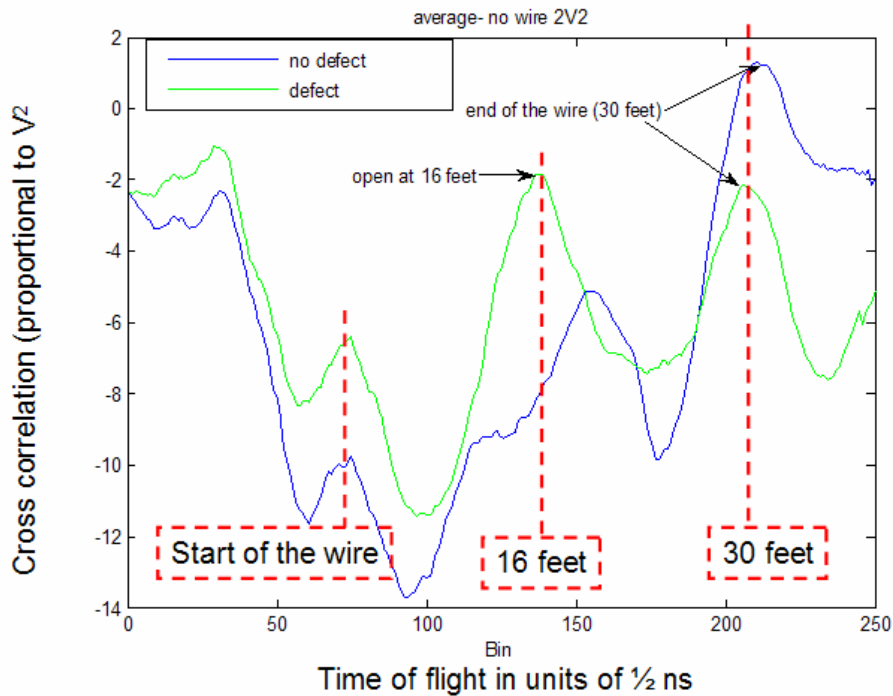
The usefulness of induced signals for the localization of faults on branched wiring circuits lies in the fact that in many cases, wires do not branch off individually. Rather, several wires will branch off at the same time (for instance, a control and power wire for the same device). A simple example of such a harness is shown in Figure 4. A harness consisting of three wires is shown, with the center wire branching in to two wires. From the figure it is clear that the symmetry of the harness will not allow unambiguous localization of the defect. If the two branches are of unequal length, an approach based on detection of multiple reflections as proposed by Furse et al [3] would suffice, although multiple reflections suffer from poor SNR due to the attenuation of the signal as it propagates along the wire. An alternative approach proposed by Furse [4], which entails applying an additional TDR past the branching point could also unambiguously localize the defect but would need access to multiple points along the harness. In contrast, inductive measurements can all be performed by accessing one side of the harness.

We implemented and tested a simple algorithm to unambiguously detect an open in a 30ft, 20AWG harness with the symmetry depicted in Figure 4. We measure all direct and induced correlations  $C_{ij}$ ,  $i, j=1,2,3$ . We use the direct measurements to detect, and measure the time of flight to the defect (Figure

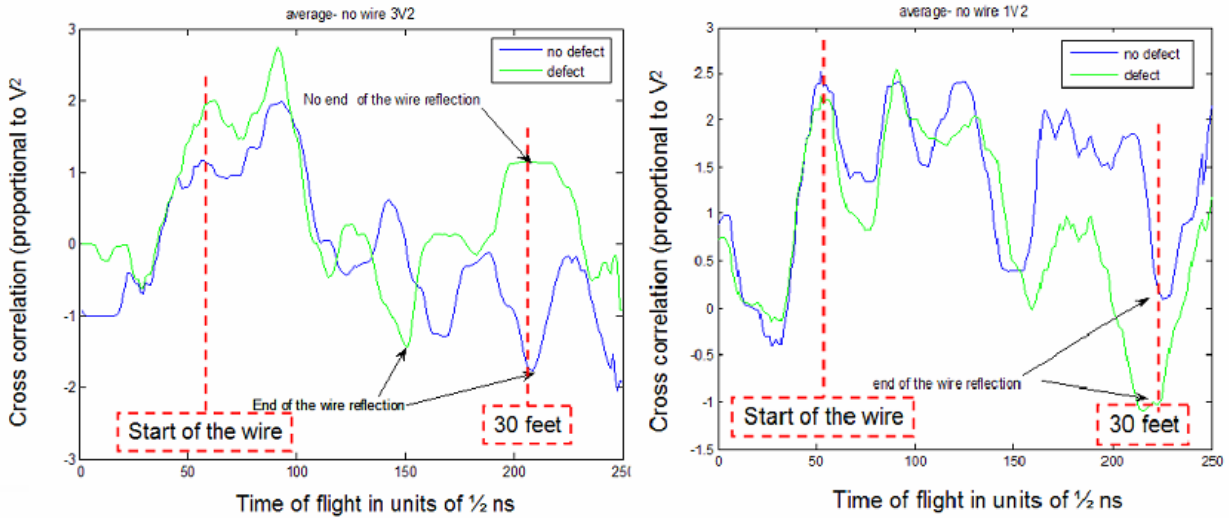
5). Next, we used the induced correlations to determine what branch the fault is located. Specifically, the induced signal due to the end of wire reflections in the branched circuits clearly indicate what side of the branched circuit is affected (Figure 6).



**Figure 4 Defect on a simple branched circuit. Reflection from defect (X) in right branch of wire 2 induces signal in wire 3, but not in wire 1.**



**Figure 5: Work with the direct signals to identify the type of fault and the distance. Signal is injected in wire 2 and the reflection is measured in wire 2.**



**Figure 6: Work with the induced signals to identify the branch and uniquely confirm the location** (a) the left figure shows that for the defective branch we do get end of wire reflection at 30 feet. Signal is injected in wire 3 and the induced reflection is measured in wire 2. (b) Right figure for the healthy branch shows the end of wire reflection at 30 feet. Signal is injected in wire 1 and the induced reflection is measured in wire 2.

### Detection and Localization of Insulation Chafing

In Figure 7, we show results of a side by side comparison of detection and localization of chafed insulation with direct (traditional) TDR, and inductive TDR. The data on the left show that the direct measurements show very little sensitivity to the chafe. This is not an expected result, Waddoups et al [5] argued that small, insulation defects are comparable to the small discontinuities present on non-impedance controlled wiring, and hard to detect without a baseline measurement. However, the change due to the chafe is 10dB larger for the inductive measurements. We find similar results for other levels of chafing, gauges AWG 16-22, twisted and untwisted pairs, and several other wiring configurations. These results indicate that inductive TDR is more sensitive to chafing than direct TDR. Surprisingly, we do not observe increased sensitivity to breaking wiring strands. We speculate the higher sensitivity to chafes is due to the changed coupling between the wires at the chafing point, rather than a small change in the local impedance. We are now investigating this assertion further using Finite Element simulations.

We have also developed a novel method of detection and localization of insulation chafing in a harness by creating an artificial baseline. Here we work on the assumption that majority of the wires in the harness are healthy. It can be seen in Figure 8 that this method succeeds in detecting and locating the chafe in a harness. This method mitigates the problem of uncontrolled impedance. The steps involved are listed below.

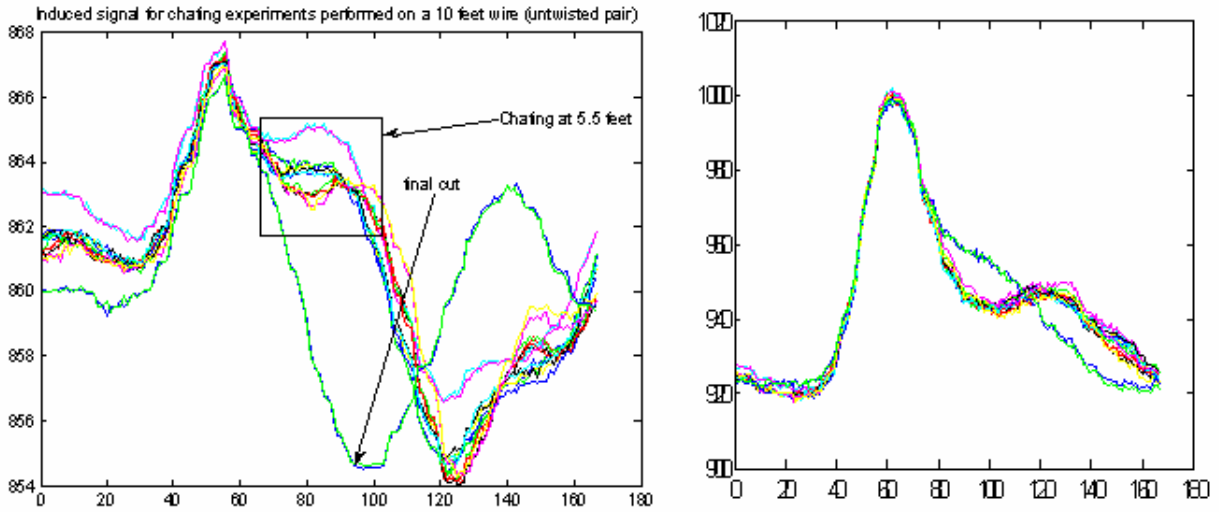
#### 1. Preprocessing

- I. Wavelet based smoothing algorithms
- II. Induced effect averaged over all wires in the harness

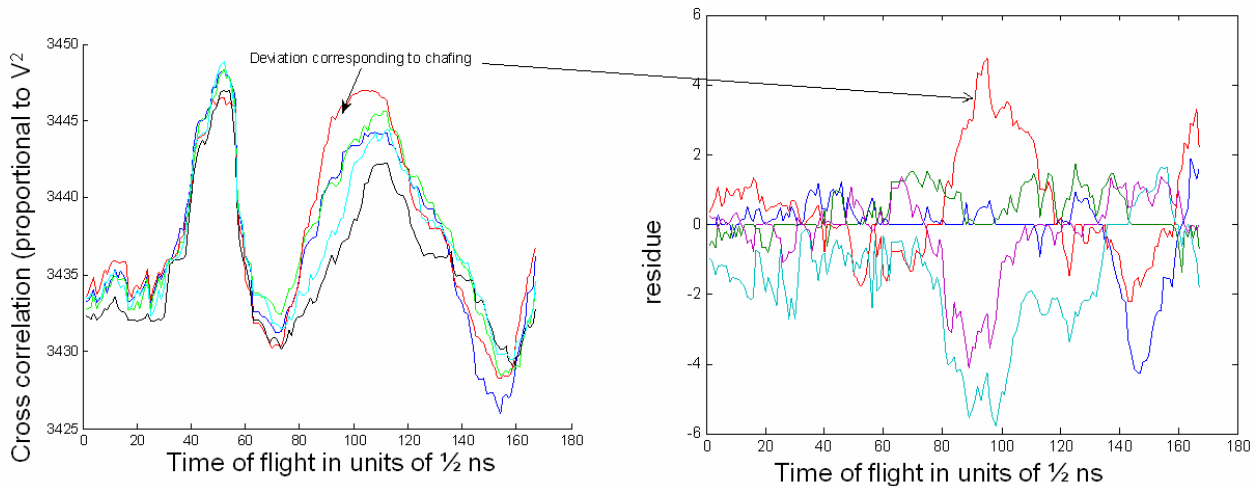
#### 2. Outlier detection

- I. Compute the median of the scans. (Median rather than the mean, since the median is robust under the presence of outliers). This is our artificial baseline
- II. Identify the index corresponding to the beginning and the end of the wire
- III. For each wire square the difference between the median and each individual scan. This is the residual scan.

IV. We sum the residual scan. A large value of this sum indicates big deviations from the artificial baseline, and an increased likelihood of a fault.



**Figure 7 Comparison of induced and direct signals for chafing experiment : Detection and localization of 1" insulation chafe on single unshielded AWG 20 wiring. Right: Crosscorrelation vs. time-of-flight (0.5ns). The curves that deviate most correspond when the wire is cut. The largest group of wires corresponds to healthy wires, and wires with increasing amounts of chafing. Left: Induced measurements result for same experiment. The horizontal index 85 corresponds to the round trip time-of-flight to the chafing location.**



**Figure 8: Chafing experiments on harnesses Left: Induced data: Sum of all induced scans with respect to a particular wire in the harness. The scan corresponding to the defective wire is marked. Right: Residue corresponding to the induced scans.**

## Conclusions

We have developed a novel tool for wiring diagnostics that can detect and locate hard faults within inches. Our method show much greater sensitivity to soft faults than traditional TDR methods. In addition, induced signals can be used to unambiguously localize detect defects on branching wiring

circuits with greater SNR than methods based on the detection of multiple reflections. In ongoing work, we are extending our approach to the inspection of fiber optics.

### **Acknowledgment**

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