Noncontact Probes for Wire Fault Location With Reflectometry

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***Abstract*—This paper describes an approach to locate wire faults using reflectometry without physical contact with the wire conductor. This noncontact method is capable of locating faults on both dead and live powered wires with today's reflectometry technologies, and it does not require any modification or disconnection of the existing wiring system. With proper configuration, this method can detect wire faults with an accuracy of 3 in, which is comparable to direct connection systems.**

***Index Terms*—Capacitive coupling, inductive coupling, reflectometry, wire fault location.**

I. INTRODUCTION

AGING WIRE has been identified as a major risk factor in aircraft [1], [2]. Numerous disasters have been linked to wire failures, such as the crashes of TWA flight 800 in 1996 and Swissair flight 111 in 1998 [3]. In addition to safety concerns, aging electrical wiring systems are very expensive to maintain.

Various reflectometry methods have been developed for wire testing applications, including frequency-domain reflectometry [4], [5], mixed-signal reflectometry (MSR) [6], time-domain reflectometry (TDR) [4]–[9], sequence TDR (STDR) [10], [11], spread-spectrum TDR (SSTDR) [10], [11], and noise-domain reflectometry (NDR) [12]. Each method sends different types of signals down the wire and evaluates the reflected echo in one of several different ways.

Typical reflectometry measurements require direct contact with the conductor of the wire under test. Thus, disconnecting the wire from the load or signal source is necessary. In addition to the inconvenience, a part of the system needs to be offline to hook the probes onto the wire. This makes it impossible to locate intermittent faults that occur only when the aircraft is functional. Furthermore, multiple disconnect/connect cycles weaken the connector and may also induce new damage in the brittle wires, especially on the aged aircraft where most wiring problems exist.

Testing of inactive wires can locate only a small portion of the wire faults requiring repair [13]. Therefore, live system testing becomes critical. "Hard" open and short circuits can be found one of several ways today. The more challenging problems that take the majority of maintenance technician time are the intermittent faults. They are generally referred to as "no fault found" conditions because the maintenance crew checks out the system and reports that no fault is found on the ground. The plane may then return to duty, only to be grounded again and again by the same intermittent problem. In addition to being exasperating, this is potentially very dangerous. As the fault is repeated, the wire is likely to be more and more damaged until catastrophic failure results. Therefore, a method capable of testing live wires is essential for today's aerospace industry.

This paper introduces a connection method that provides a practical and feasible noninvasive test method for real-world solution. Instead of using a hard-wired connection such as those used in [4]–[12], a capacitive interconnection system is used for the injection and detection of the reflectometry signal. These capacitive probes are capable of performing electrically noncontact and nonintrusive wire measurements on unshielded wires. Although the STDR [10], [11] is chosen to verify the results in this paper, the noncontact probes can be used with most existing reflectometry technologies, including [4]–[12]. (The correlation done in this system is slightly different than classic STDR [10], [11]. The correlation is that of NDR [12], using an unmodulated PN code (STDR) signal as the source "noise.") This method is especially applicable to a handheld device that may be used for troubleshooting the aircraft wiring system when it is live and functioning.

II. WIRE FAULT LOCATION WITH NONCONTACT PROBES

A. STDR Basics

As shown in Fig. 1, a baseband pseudonoise (PN) code is sent down the electrical wire. The signal reflects off the impedance mismatch or fault and returns to the tester.

After autocorrelating the sum of incident and reflected signals present on the wire, the distance between the major correlation peak and the secondary peaks of the resulting function represents the time difference between the incident and reflected signals. This time difference can than be translated to the fault location.

B. Capacitive Coupler

When measuring live powered wires with the STDR, a capacitor is placed between the wire and the test circuit [10].

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Color version of Figs. 6, 8, 9, and 11–13 are available online at http://ieeexplore.ieee.org.

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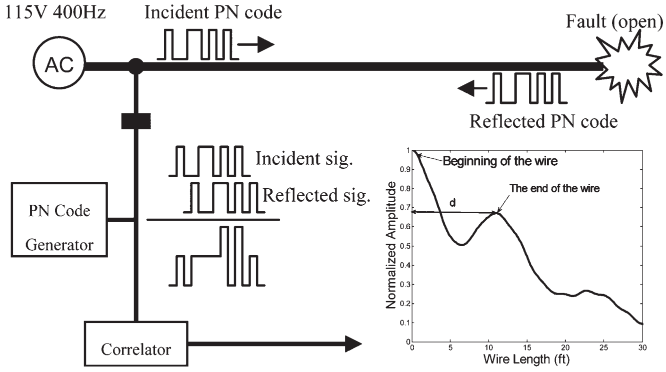


Fig. 1. Simplified STDR system block diagram.

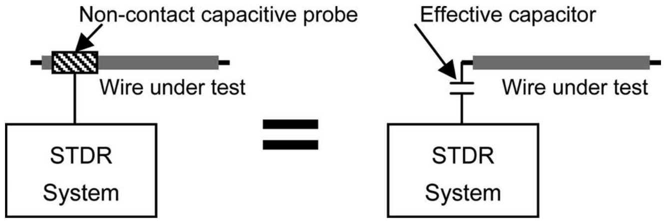
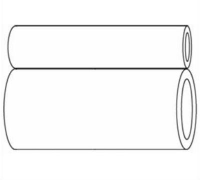
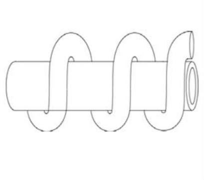
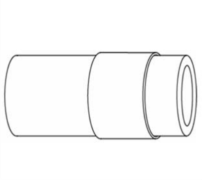


Fig. 2. Noncontact capacitive probe equivalent circuit.

TABLE I
DIFFERENT TYPES OF NONCONTACT CAPACITIVE COUPLING PROBES

Parallel Wire	Spiral	Cylinder
		
0.7 pF/cm (calculated)	0.7 pF/cm (calculated)	3.8 pF/cm (calculated)
0.5 pF/cm (measured)	0.5 pF/cm (measured)	3.0 pF/cm (measured)

This capacitor isolates the low-voltage test circuits to prevent the live signal from damaging them. It also provides a coupling path that allows the high-frequency PN signal to pass onto the wire. Typically, this capacitance is several hundred picofarads to a few nanofarads. A 510-pF capacitor was used in [10].

As shown in Fig. 2, the noncontact capacitive probe described in this paper creates an equivalent capacitance between the PN code generator and the wire. The capacitance created by this noncontact probe is much smaller than the lumped-element capacitor used in the direct contact measurement.

There are several ways of capacitively coupling the PN code onto the wire. The lumped-element capacitor used as circuit protection still requires direct contact with the conductor of the wire under test. Alternatively, a noncontact capacitive coupler such as those shown in Table I can be used. As shown in Table I, the cylindrical probe offers the highest capacitance per unit length [14], [15]. Therefore, this type of capacitive probe is selected for noncontact measurements in this paper.

C. Filtering and Attenuation Effects

The capacitance between the noncontact probe and the wire creates an equivalent high-pass filter or a simple differentiator. The smaller the capacitance, the higher its cutoff frequency. As shown in Fig. 3, the PN code signal is induced on the wire via a single cylindrical probe at point A, and the sum of incident and reflected signals is picked up by the same probe at point B. During the transmission from A to B, the PN signal is being high pass filtered twice. Thus, most of the higher frequency components of the original PN code are being transmitted and detected, while the majority of the lower frequency components that contain most of the signal energy are being suppressed. The signals at point A and point B are somewhat different and therefore have diminished correlation. This problem can be improved by using a longer PN code to increase the processing gain [10].

In addition to the filtering effect, the signal at B is attenuated. Since the correlation is proportional to the similarity of the amplitudes of A and B [14], this significantly reduces the magnitude of the reflected correlation peak, which may place it below the threshold of detection.

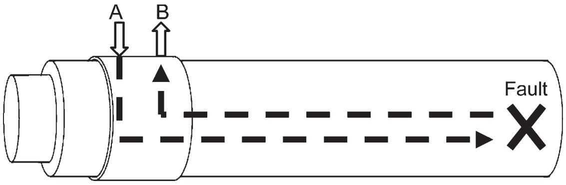


Fig. 3. Inducing the PN code onto the wire via a single cylindrical noncontact probe.

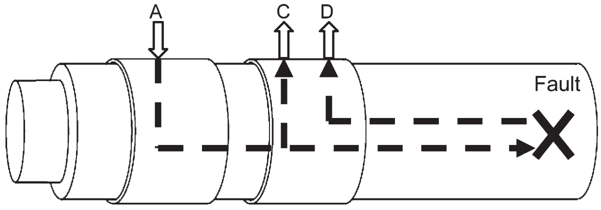


Fig. 4. Dual cylindrical noncontact probe solution.

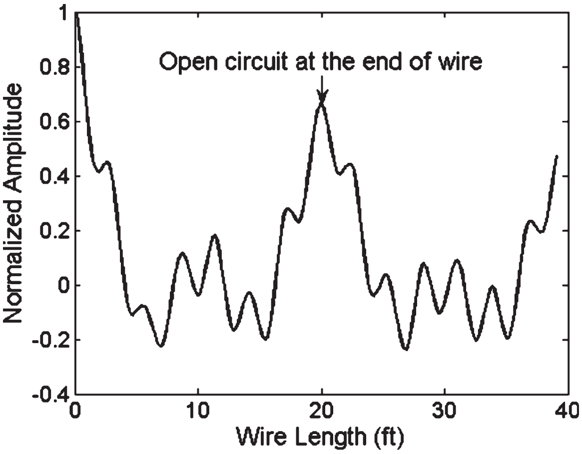
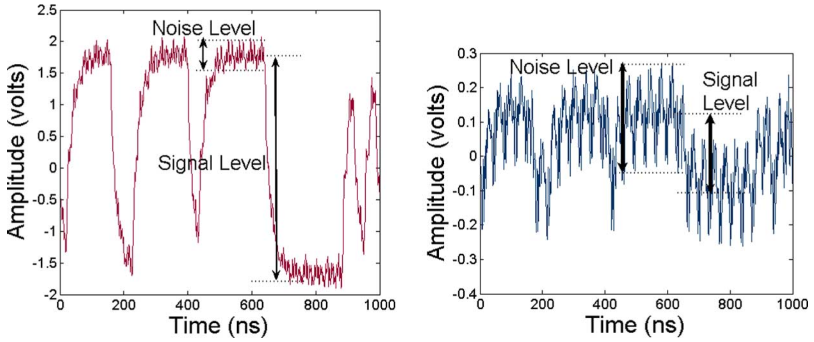


Fig. 5. Dual-probe measurement result on a 20-ft-long wire using 3-cm-long dual cylindrical probes.

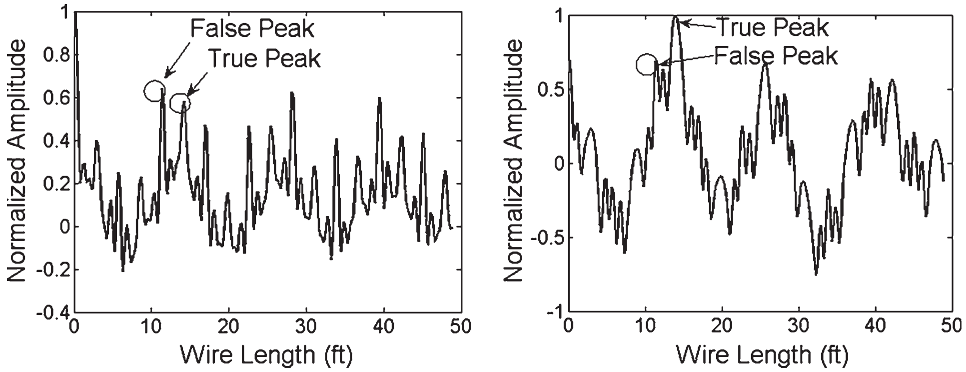
D. Dual-Probe Solution

A solution to the filtering effect and signal attenuation is to utilize a dual-probe system shown in Fig. 4. The PN signal is



(a) (b)

Fig. 6. (a) Original PN code. (b) After being filtered twice.



(a) (b)

Fig. 7. (a) Before and (b) after using signal compensation.

induced at point A of the first probe, and it is filtered once going onto the wire. While traveling down the wire, the PN signal is detected at point C of the second probe, which means it is filtered twice. The signal reflects off the fault and is picked up at point D. Without considering the external noise, signal dispersion, and transmission loss, the signals at C and D should be identical except for a short time delay (which represents the fault location) since they are both being high pass filtered twice by the same probes. The signals at C and D are then correlated, and the results are shown in Fig. 5.

The correlation shown in Fig. 5 is from a 127-chip maximum-length PN code transmitted on an 18-gauge lamp cord using a pair of 3-cm-long copper tape segments as the probes. The wire is open ended at 20 ft. The peak of the correlation shown in Fig. 5 correctly identifies the end of wire. The periodic spikes in Fig. 5 are caused by the filtering effect of the capacitive probes. The original (relatively noisy) PN signal is shown in Fig. 6(a). The same signal after being high pass filtered twice is shown in Fig. 6(b). For longer wires, smaller faults, or shorter probes, these periodic spikes can overshadow the correct peak and cause an error in the fault location measurements.

III. IMPROVED MEASUREMENTS

There are several ways to reduce the periodic spikes shown in Fig. 5 and increase the measurement accuracy of the system. One method is to use higher capacitive coupling by using longer cylindrical probes. These will be limited to a few centimeters for practical applications. Minimizing the noise in the PN code generator also helps. Other methods are described below.

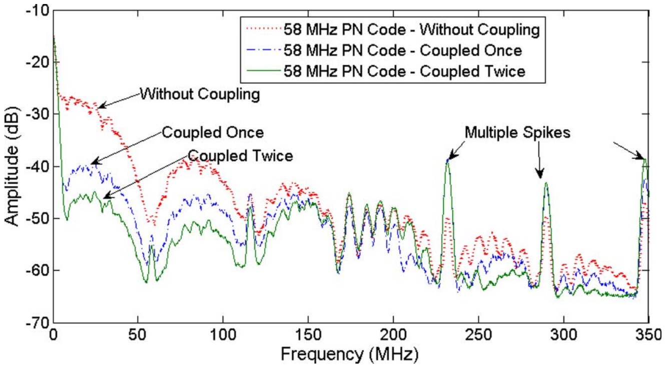
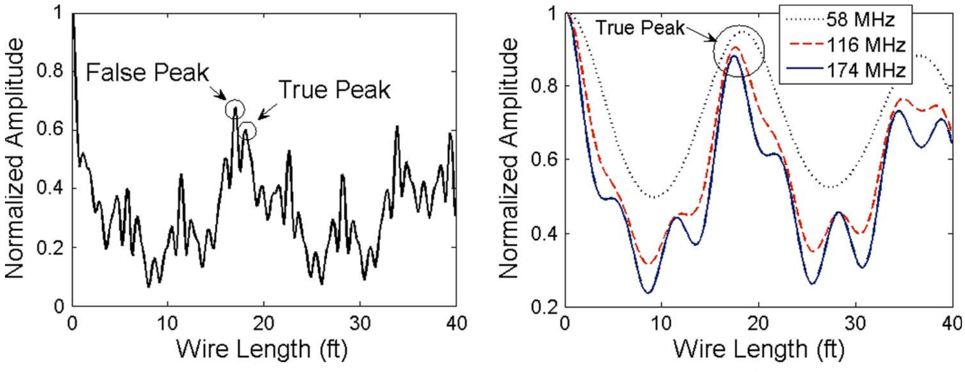


Fig. 8. Spectra of the PN code signals.

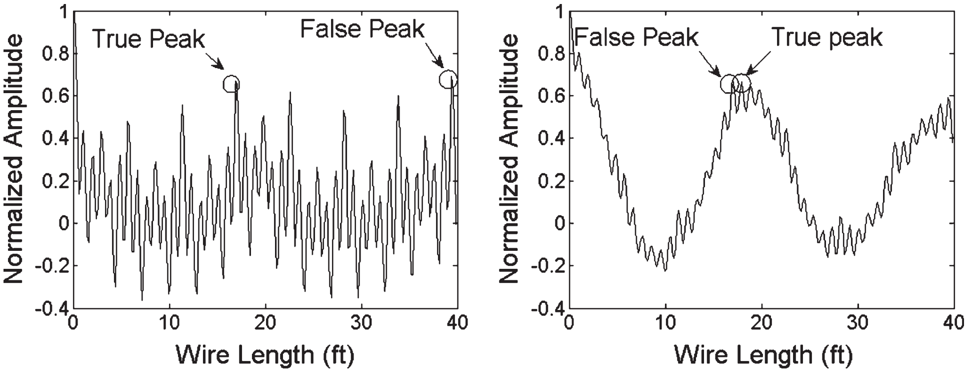
A. *Signal Compensation*

The spikes caused by an imperfect PN signal are periodic and predictable. By measuring a long wire, we can duplicate these spikes and use them as a noise baseline. In this paper, the result of a 61-ft-long open-ended wire is used as the noise baseline, and a 13-ft-long open-ended wire is the wire under test. By subtracting the result of the 61-ft wire from the result of the 13-ft wire, the periodic spikes will be cancelled out. Fig. 7(a) shows that the false peak dominates the true peak in the original correlation response. The false peak is significantly reduced by subtracting the 61-ft response from the 13-ft response as shown in Fig. 7(b).



(a) (b)

Fig. 9. (a) Before and (b) after using a low-pass software filter.



(a) (b)

Fig. 10. (a) Before and (b) after using an inline choke inductor.

B. Software Filter

In the real world, it may not be possible to obtain a long wire with the same characteristics as the wire under test. Another way to deal with the multiple spikes is to utilize a software filter. By evaluating the high-pass-filtered PN signal on a spectrum analyzer, the frequency spectra of the spikes were observed. As shown in Fig. 8, the majority of the unwanted spikes are at higher frequencies, especially at multiples of the PN code chip rate. These unwanted high-frequency spikes can be removed by using a software low-pass filter. Although a high-order filter is not required, a 20th-order equal-ripple finite impulse response low-pass filter with 58/116/174 MHz cutoff frequencies and 40-dB suppression was designed with the Filter Design Toolbox in Matlab. As shown in Fig. 9(a), an incorrect fault location is detected with a pair of 3-cm cylindrical probe on a 17-ft open-ended wire. Fig. 9(b) shows the result after the software filter is applied. Although a lower cutoff frequency filter gives a smoother result, some of the useful information is also removed. Therefore, the accuracy is not as good as higher cutoff frequency filters.

C. Hardware Filter

The software filter gives smooth results, but it requires significant computing resources that may not be available in all applications. An alternative solution is to use a hardware low-pass filter such as an inline choke inductor. The result of measuring an 18-ft open-ended wire is shown in Fig. 10(a) and (b). The dual-probe measurement result can be improved dramatically with a simple choke inductor. It can be further improved with a higher order filter, which is not covered in this paper.

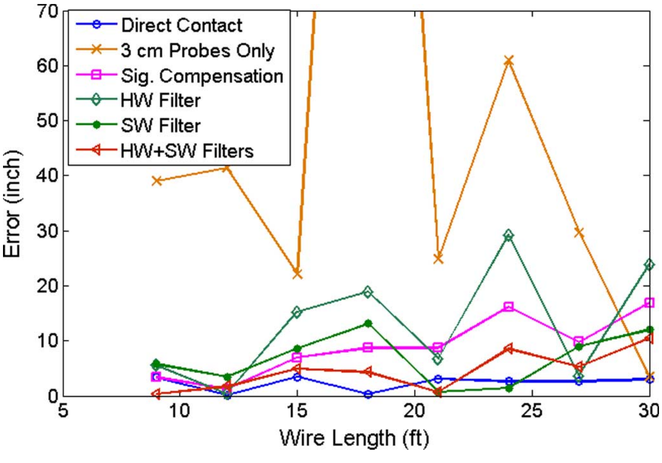


Fig. 11. Error of different measurement methods using a pair of 3-cm cylindrical probes.

IV. RESULTS

To convert the correlation peak location to wire length, the velocity of propagation is used. Fig. 11 shows a comparison

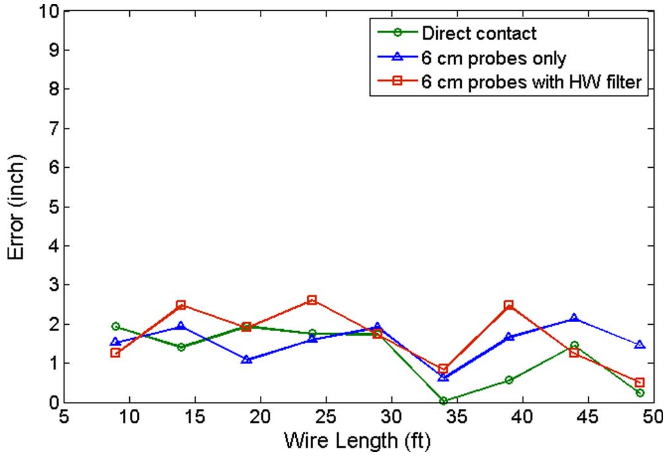


Fig. 12. Error of different measurement methods using a pair of 3-cm cylindrical probes.

of the error in wire length obtained using different coupling methods. It is clear that the direct contact method gives the smallest error, less than 3 in over 3 ft of wire. Using 3-cm probes with the hybrid method (hardware filter plus software filter) results in an error less than 12 in.

In the case where longer probes are acceptable, the accuracy can be improved significantly. As shown in Fig. 12, 6-cm probes with the hardware filter alone can give accuracy of 3 in over 50 ft of wire, which is comparable to direct contact measurement. With sufficient coupling, the filters may not be needed, as shown in Fig. 12.

As stated previously, STDR system can be used on live wires. A sinusoidal wave signal 17 dB (root mean square) higher than the PN code was placed on the wire. The system was able to correctly identify the 11-ft open-ended wire when the sinusoidal signal was less than about 200 kHz. The direct contact method was able to measure the same wire carrying signal up to about 500 kHz [14].

The noncontact probe can also be used with TDR. A traditional method of interpreting the TDR result is to identify the location where the maximum slope occurs. This applies for both the beginning and the end of the wire. Mathematically, the maximum slope can be found with differentiation of the function. Since the noncontact probe acts as a high-pass filter or a basic differentiator, the noncontact probe is suitable for wire fault location with a TDR system. The TDR signal can be induced and detected via a single noncontact probe without any system modification. Fig. 13 shows the comparison between the direct contact TDR and noncontact (3-cm copper tape) TDR measurements on an 8-ft-long open-ended wire. Rather than looking for the location of maximum slopes in the direct contact method, the location of the signal peak indicates the fault location.

V. CONCLUSION

This paper shows that it is possible and feasible to locate wire faults using reflectometry without physical contact with the conductor. With proper configuration and signal handling, the noncontact method is capable of locating faults with an error comparable to the direct contact method (less than 3 in). Although the demonstrated data were obtained by using the TDR and STDR, the noncontact probes can also be used for SSTDR, MSR, NDR, or other reflectometry systems.

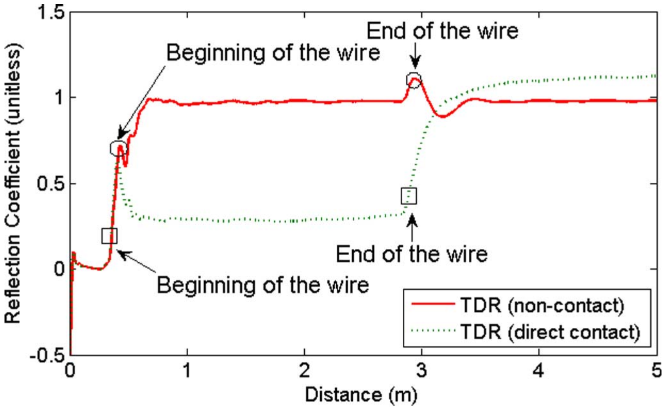


Fig. 13. Direct contact and noncontact TDR measurement.

The noncontact probes offer many benefits over the traditional techniques that require direct contact with the wire conductor, including ease of use, light weight, and no maintenance. The convenience can be further improved by integrating the dual probes into a single clamp. The thickness of the copper tape is only 1.2 mils, and the weight is negligible.

The probe does not need an additional power source. The noncontact probe works on live wires and is capable of detecting wire faults without disconnection of the power or the load. Due to this advantage, this method is ideal for portable or handheld test equipment. The noncontact probe method can be integrated with existing systems with minimal modification.

This method can eliminate the need to create a compatible connector to attach to each of the thousands of specialized connectors in the aircraft. This method does not work on shielded wires, however. The noncontact probes described in this paper offers a significant opportunity for the development of easier to use handheld maintenance equipment for wire fault location.

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